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Détermination de la composition de l'acide aminé pour le géochronologie des sols enfouis du mont Kenya, Afrique de l'Est

Bestimmung der Amino-Säure als Geochronometer der begrabenen Böden auf dem Mount Kenya, Ost-Afrika

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Résumé de l'article

On a identifié et daté, au radiocarbone et à l'aide de techniques de datations à l'acide aminé, des paléosols enfouis et de surface afin de comprendre l'évolution quaternaire de la région. Les datations au radiocarbone des paléosols enfouis varient de 900 à plus de 40 000 BP. Les sols se sont développés dans des dépôts glaciaires et périglaciaires de différentes textures, constitués de fragments de roches détritiques, de phonolite, de basalte et de syénite. Tous les paléosols, sauf deux, sont situés dans la zone afroalpine (au-dessus de 3200 m). On a déterminé par racémisation les rapports D/L des acides aminés dans les horizons Ab en vue d'évaluer leur fiabilité pour la datation des âges relatifs. On a fait l'analyse de l'alaline, de l'acide aspartique, de l'acide glutamique, de la leucine, de la valine et du phénylalaline. L'acide aspartique, comme dans d'autres cas, a donné des résultats particulièrement satisfaisants, les quotients plus élevés correspondant aux âges les plus anciens. D'autres acides montraient des tendances bien distinctes, mais moins convaincantes que dans le cas de l'acide aspartique. Ainsi, dans la plupart des cas, les relations quotients/âges de l'acide aspartique étaient corroborées par les datations au radiocarbone. Les rapports D/L de l'acide aspartique variaient d'environ 0,07 pour les échantillons modernes à environ 0,45 pour les échantillons de plus de 40 000 ans.

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EVALUATION OF AMINO ACID COMPOSITION AS A GEOCHRONOMETER IN BURIED SOILS ON MOUNT KENYA, EAST AFRICA*

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ABSTRACT A sequence of surface and buried paleosols from the slopes of Mount Kenya, East Africa, has been identified and dated by radiocarbon and amino acid dating techniques in order to elucidate the Quaternary history of the area. Buried paleosols vary in radiocarbon age from 900 to > 40,000 yrs BP. They have developed in glacial and periglacial deposits of variable texture, consisting of a high percentage of clasts of phonolite, basalt and syenite. All but two paleosols are located in the Afroalpine zone (above 3200 m). D/L ratios of amino acids in Ab horizons were determined in order to establish their reliability for relative age dating. Alanine, aspartic acid, glutamic acid, leucine, valine, and phenylalanine were routinely analyzed. Aspartic acid, as in other cases, proved reliable yielding remarkably consistent results, with higher ratios corresponding to increasing age. Other acids analyzed showed distinct trends, although not as convincing as aspartic acid. In most cases, the aspartic acid ratio/age relationships were supported by radiocarbon dates. D/L ratios of aspartic acid varied from approximately 0.07 for modern samples, to approximately 0.45 in samples > 40,000 years old.

RÉSUMÉ *Détermination de la composition de l'acide aminé pour le géochronologie des sols enfouis du mont Kenya, Afrique de l'Est.* On a identifié et daté, au radiocarbone et à l'aide de techniques de datations à l'acide aminé, des paléosols enfouis et de surface afin de comprendre l'évolution quaternaire de la région. Les datations au radiocarbone des paléosols enfouis varient de 900 à plus de 40 000 BP. Les sols se sont développés dans des dépôts glaciaires et périglaciaires de différentes textures, constitués de fragments de roches détritiques, de phonolite, de basalte et de syénite. Tous les paléosols, sauf deux, sont situés dans la zone afroalpine (au-dessus de 3200 m). On a déterminé par racémisation les rapports D/L des acides aminés dans les horizons Ab en vue d'évaluer leur fiabilité pour la datation des âges relatifs. On a fait l'analyse de l'alaline, de l'acide aspartique, de l'acide glutamique, de la leucine, de la valine et du phénylalaline. L'acide aspartique, comme dans d'autres cas, a donné des résultats particulièrement satisfaisants, les quotients plus élevés correspondant aux âges les plus anciens. D'autres acides montraient des tendances bien distinctes, mais moins convaincantes que dans le cas de l'acide aspartique. Ainsi, dans la plupart des cas, les relations quotients/âges de l'acide aspartique étaient corroborées par les datations au radiocarbone. Les rapports D/L de l'acide aspartique variaient d'environ 0,07 pour les échantillons modernes à environ 0,45 pour les échantillons de plus de 40 000 ans.

ZUSAMMENFASSUNG *Bestimmung der Amino-Säure als Geochronometer der begrabenen Böden auf dem Mount Kenya, Ost-Afrika.* Eine Serie von an der Oberfläche liegenden und begrabenen Paläoböden von den Hängen des Mount Kenya, Ost-Afrika, wurde mittels Radiokarbon- und Aminosäuredatierungs-techniken identifiziert und datiert, um die Geschichte dieses Gebiets im Quaternär zu erhellen. Das durch Radiokarbon bestimmte Alter der begrabenen Paläoböden variiert von 900 bis > 40,000 Jahren v.u.Z. Diese Böden haben sich in glazialen und periglazialen Ablagerungen verschiedener Beschaffenheit entwickelt, welche zu einem hohen Prozentsatz aus Trümmern von Phonolith, Basalt und Syenit bestehen. Außer zweien befinden sich alle Paläoböden in der afroalpinen Zone (oberhalb 3200 m). Die D/L Anteile der Aminosäuren in den Ab-Horizonten wurden bestimmt, um ihre Verläßlichkeit bei der relativen Altersbestimmung festzustellen. Alamin, aspartische Säure, Glutamin-Säure, Leuzin, Valin und Phenylalanin wurden laufend analysiert. Wie in anderen Fällen erwies sich die aspartische Säure als verläßlich, indem sie bemerkenswert beständige Ergebnisse ergab, bei denen die höheren Quotienten dem höheren Alter entsprachen. Andere analysierte Säuren zeigten ausgeprägte Trends, wenn auch nicht so überzeugend wie die aspartische Säure. In den meisten Fällen wurden die Beziehungen Quotient/Alter der aspartischen Säure durch Radiokarbondatierungen gestützt. Die D/L Anteile der aspartischen Säure variierten von ungefähr 0.07 für moderne Proben bis ungefähr 0.45 in Proben, die > 40,000 Jahre alt sind.

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* Contribution du premier symposium de la CANQUA, sous la direction de René W. Barendregt

INTRODUCTION

The fate of amino acids in buried paleosols is of considerable interest to Quaternary geologists, particularly since the racemization of aspartic acid and others may provide a means of dating organic-rich horizons. Dated paleosols ranging from 960 to > 42,000 yrs BP have been described on Mount Kenya (Fig. 1a and 1b; 0°10′S; 37°15′E) in several drainage basins between 2990 and 4050 m elevation (MAHANEY, 1979, 1981, 1982a, 1982b, 1983, 1984a, 1984b and 1985). Most soils have developed in transported regolith with different lithologic compositions. We consider this paleosol sequence to provide a convenient field setting in which to test the reliability of using amino acid racemization for age determination, and where the deposits can be calibrated by radiocarbon. Moreover, time stratigraphy refinement of amino acid racemization assists in increasing our understanding of the timing of geologic events before, during, and following the last (Liki) glaciation on Mount Kenya (Fig. 2).

Many varieties of fossils are now routinely analyzed to determine the D/L ratios of amino acids for relative and absolute age dating of sediments. The method has been particularly useful when fossils have experienced similar temperature

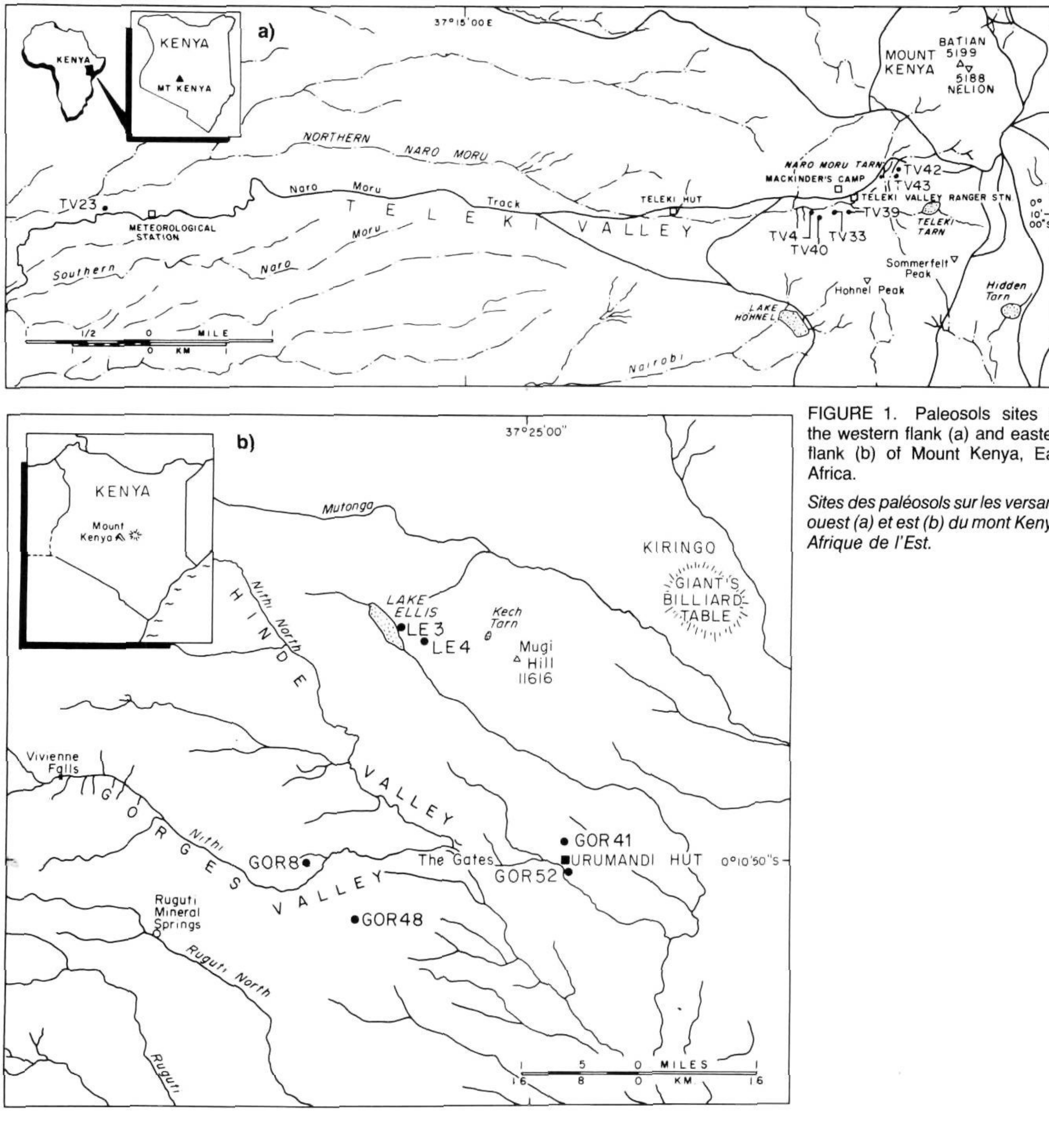


FIGURE 1. Paleosols sites on the western flank (a) and eastern flank (b) of Mount Kenya, East Africa.

Sites des paléosols sur les versants ouest (a) et est (b) du mont Kenya, Afrique de l'Est.

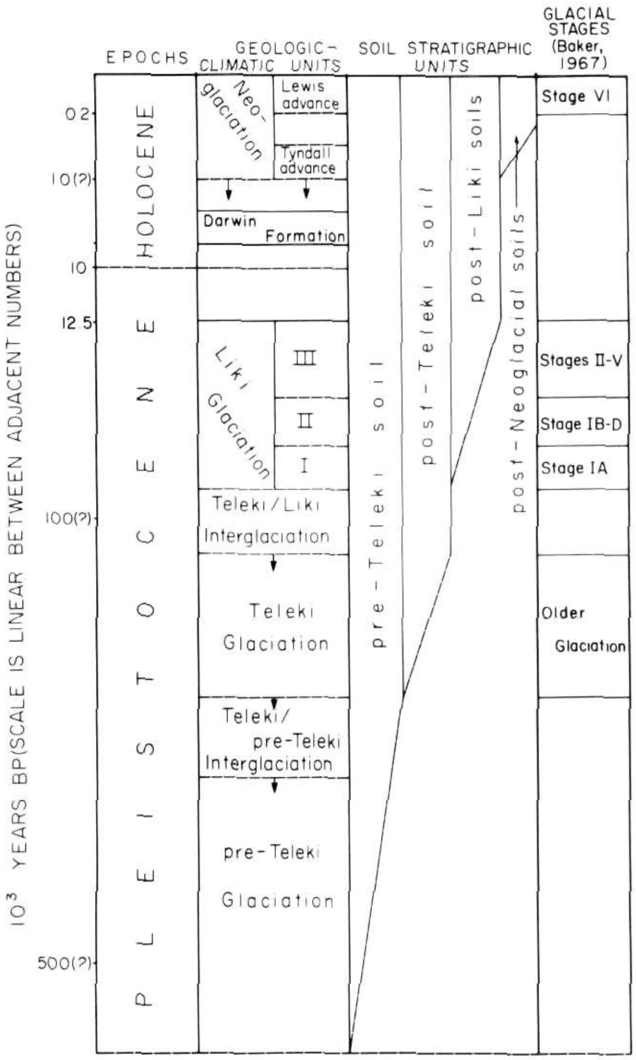


FIGURE 2. Correlation diagram for Pleistocene and Holocene deposits on Mount Kenya. Unit boundaries are based on maximum and minimum dates for glacial and nonglacial sediments. Dashes denote boundaries for which there is no radiometric control. Arrows indicate directions in which boundaries are likely to be shifted when additional dates become available.

Diagramme de corrélation des dépôts pléistocènes et holocènes sur le mont Kenya. Les limites des unités sont fondées sur les dates maximales et minimales de sédiments glaciaires et non glaciaires. Les tiretés identifient les limites qui ne sont pas datées selon des méthodes radiométriques. Les flèches pointent vers les directions que les limites pourront prendre lorsque de nouvelles datations s'ajouteront.

histories and diagenetic conditions. Marine molluscs have been widely utilized and are probably the most successful for age determination, whereas freshwater and terrestrial molluscs offer promise (ANDREWS *et al.*, 1979; BELKNAP and WEHMILLER, 1980; BRIGHAM, 1982, 1983; EMERSON *et al.*, 1981; McCOY, 1980; MILLER, 1982; MILLER and HARE, 1974; MILLER *et al.*, 1977, 1983; MITTERER, 1974, 1975; RUTTER *et al.*, 1980; WEHMILLER, 1982; WEHMILLER *et al.*, 1977). Bone and wood have been useful, although problems have been encountered (BADA, 1972; BADA and HELFMAN, 1975; BADA *et al.*, 1973, 1974, 1979; BENDER, 1974; HARE, 1974; HO, 1965, 1967; LEE *et al.*, 1976; RUTTER and CRAWFORD, 1984). In addition, investigations involving amino acid racemization age dating have been carried out with marine sediments (BADA *et al.*, 1970; KVENOLDEN *et al.*, 1970), foraminifera (KING, 1980; WEHMILLER and HARE, 1971) coral (WEHMILLER *et al.*, 1976, WEHMILLER and HARE, 1970) and with soils (LIMMER and WILSON, 1980).

Racemization (or epimerization) of amino acids in geological specimens is a complex process involving a number of factors. The rates of interconversion processes are dependent upon the species of amino acid, ambient temperatures, types of materials in which the amino acids are embedded (shells, bones, wood, *etc.*), and the state in which the amino acids occur, *i.e.* whether they are terminally bound, internally bound, or free amino acids. In addition, other external diagenetic factors such as moisture content, acidity, and oxidation-reduction conditions can play a role. The accuracy of D/L determinations rests with the care of preparation and the reliability of the analytical methods employed. These factors have contributed to the apparent lack of interest in amino acid D/L ratio determinations of paleosols. The complex nature of soil formation and diagenetic changes that take place at the surface and upon burial compound the problems already inherent in the method. It will be seen, however, that in the present work there is a trend for D/L ratios, of aspartic acid, to increase with age of the paleosol.

FIELD AREA

A number of major deposits of Pleistocene and Holocene age are found in the Afroalpine area of Mount Kenya (Fig. 1a and 1b for location; Fig. 2 for stratigraphy). These glacial and nonglacial deposits have been assigned ages on the basis of topographic position (BAKER, 1967), as well as weathering features, degree of soil expression, and radiocarbon (MAHANEY, 1979, 1980, 1981, 1982a, 1982b).

CLIMATE

The Afroalpine area rises from ~ 3200 m to the summit of Mount Kenya at 5199 m (Fig. 1a). Precipitation derived from the Indian Ocean is delivered by the Tropical Easterly Wind Belt as well as the classical and Atlantic monsoon system. The southeastern slopes are wettest with rainfall reaching 2500 mm (at 2250 m); the northern slopes are driest with ~ 1000 mm annually. On the western flank of the mountain, precipitation rises from ~ 500 mm at Naro Moru (2000 m), to ~ 1000 mm on the high moorland (~ 3500 m), and then drops in the central peaks areas (~ 4300 m) to 750-800 mm (COETZEE, 1967). Temperature extrapolations (COE, 1967; THOMPSON, 1966) suggest that temperatures at 4200 m average 3.1 to 3.6°C (from observations taken during two periods in 1948; COETZEE, 1967; HEDBERG, 1964). The depth of frost penetration in Afroalpine sites while limited to a few centimetres, is diurnal in nature, and controlled largely by variations in thermal conductivity of different cover sediments. Variations in subsurface (~ 1.0 m depth) temperatures, as they might affect racemization rates of amino acids are considered small even between Pleistocene cold periods and warmer Holocene climate. Frost penetration in surface deposits in the Bamboo Forest, while nil at present, may have occurred to depths of a few centimetres during the last glaciation when ice limits reached ~ 3100 m. As in the Afroalpine zone, however, paleoclimatic variations in surface temperature did not affect buried paleosols insofar as racemization rates are concerned.

VEGETATION

Below timberline the subalpine forest consists of Hagenia Woodland dominated by *Hagenia abyssinica* and Bamboo Forest (*Arundinaria alpina*). Above the heather zone at timberline (~ 3200 m) the lower Afroalpine zone, dominated by *Senecio brassica*, extends upwards to ~ 3700 m where it merges with the upper Afroalpine zone characterized by *Senecio keniodendron*. The Upper Afroalpine zone merges with vegetation of the nival zone at ~ 4500 m (COE, 1967; HEDBERG, 1964). The probability that different species produce variable ratios of amino acids was considered to affect the amount of each L-form amino acid that might be present in a paleosol at time zero, although not the D/L ratios which should be close to zero.

METHODS

Selected horizons were sampled in sections in a variety of glacial and nonglacial deposits in several topographic situations ranging from well- to poorly-drained. Samples were collected from each paleosol horizon described in the field following the nomenclature of the SOIL SURVEY STAFF (1951, 1975; and BIRKELAND, 1984). Particle size analyses were performed on the < 2 mm fractions; coarse grade sizes (> 63 μm) were calculated by sedimentation following procedures established by BOUYOUCOS (1962) and DAY (1965).

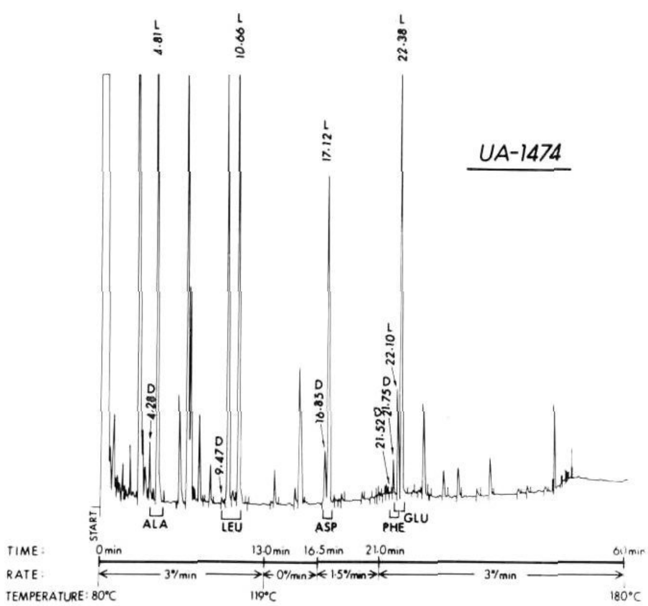
Amino acids were determined at the University of Alberta and at York University. Once in the laboratory, samples were prepared for D/L ratio determinations using the following procedures. Large samples of between 1 and 2.5 grams of organic material were weighed directly into clean vials. It was not possible to clean the samples by the usual method of rinsing and sonicating in HCl and double distilled water because whole-soil samples were utilized.

The samples were hydrolyzed for 24 hours at 108°C in 5.5M HCl. The hydrolyzate was decanted, then dried under vacuum in a rotary biodryer. The dried residue was then taken up in double distilled water and placed on a cation exchange resin. Samples were eluted with 3M NH_4OH and again dried under vacuum. Esterification was accomplished by adding acidified isopropanol and heating for 15 minutes at 100°C. After drying the samples were acylated with pentafluoropropionic anhydride in methylene chloride. The samples were then heated for 5 minutes at 100°C and evaporated to remove any excess PFPA. After being washed with CH_2Cl_2 the samples were dried over potassium carbonate. Later samples were filtered and the filtrate injected into a 25 metre x 0.3 mm Chriasil-Val capillary column installed in a Hewlett-Packard 5840A Gas Chromatograph equipped with an FID detector. A chromatograph and report of a typical Mount Kenya soil are shown in Figures 3a and 3b respectively.

RESULTS AND DISCUSSION

PALEOSOLS

The samples were collected from dated paleosols (Appendices I-XI for descriptions; Fig. 2 for stratigraphy) in the Mount Kenya Afroalpine and Bamboo Forest zones. Radiocarbon dates for the buried soil horizons are from whole-soil samples collected in the center of each horizon and are given in Table I; particle size determinations are in Table II. The youngest buried soil (site TV42) was collected from a prominent debris flow in upper Teleki Valley (Fig. 1a; Appendix I). The buried soil formed in pebbly and cobbly material which was subsequently buried by debris from renewed mass wasting activity that probably coincided with the end of the Tyndall advance (MAHANEY 1984a, 1985).



CHROMATOGRAPH REPORT OF SELECTED AMINO ACIDS

UA-1474
TV33-Ab (lower)

HP RUN # 58 JAN/05/84 TIME 13:59:07
AREA %

	RT	AREA	AREA %	D/L RATIO
ALA	4.01	762	0.615	
ALA	4.28 D	1418	1.138	0.0758
ALA	4.51	422	0.341	
ALA	4.81 L	18610	15.022	
LEU	9.47 D	120	0.097	0.0096
LEU	9.89	11420	9.218	
LEU	10.24	294	0.237	
LEU	10.66 L	12520	10.106	
ASP	16.85 D	1770	1.429	0.1586
ASP	17.12 L	11160	9.008	
PHE	21.52 D	32	0.026	0.0128
PHE / GLU	21.75 D	800	0.646	0.0681 (GLU)
PHE / GLU	22.10 L	2508	2.024	
GLU	22.38 L	11740	9.476	

FIGURE 3. a) Amino acid spectrum for sample TV33 — Ab (lower) (UA1474), and b) chromatograph report of selected amino acids.

a) Spectre des acides aminées de l'échantillon TV33 — Ab (inférieur) (UA1474) et b) chromatographie de quelques acides aminés.

In order of increasing age the next oldest soil was described in a valley train deposit in upper Teleki Valley (site TV4a; Fig. 1a; Appendix II). This buried paleosol of clayey silty composition was covered by pebbly sandy alluvium approximately 1940 ± 100 yr BP (Gak-8273; Table I) radiocarbon years ago; the Ab horizon in the buried profile has been dated by thermoluminescence at 1300 ± 300 yr BP (MAHANEY, 1985; pers. comm., D. Huntley, 1985).

Alluvial fans representing the Darwin Formation (MAHANEY, 1984a, 1985) formed between 4000 and 7000 radiocarbon years ago. Profile TV33 (Fig. 1a; Appendix III) consists of an Inceptisol (ground soil) over three buried Entisols that radiocarbon date between 3400 ± 170 yr BP (Gak-11322) to 3610 ± 180 yr BP (Gak-11320) to (Table I). The lowermost Ab horizon in this sequence radiocarbon dates at 3400 ± 170 yr BP (Gak-11322) and is known to be contaminated by microorganisms (BOYER and MAHANEY, 1985). Profile TV39 (Fig. 1a for location; Appendix IV for morphology) contains an Inceptisol (ground soil) over a buried soil in slopewash. The Ab horizon was covered by slopewash 4540 ± 130 yr BP (Gak-11241; Table I).

On the eastern slopes profile GOR8 (Fig. 1b; Appendix V) in Liki I Till was covered with alluvium at 5110 ± 120 yr BP (Gak-11570; Table I). Profile GOR52 in Gorges Valley (Fig. 1b; Appendix VI) contains alluvium deposited sometime in the late Pleistocene or early Holocene. An Entisol forming in this sediment was covered by younger alluvium 5100 ± 100 yr BP (Beta-10821; Table I).

The LE3 profile (Fig. 1b; Appendix VII) is a compound paleosol with the buried component formed in loess over till. The Ab horizon radiocarbon dates at > 43,210 yr BP (Beta-9085; Table I). This buried paleosol overlies a truncated unweathered deposit consisting of lake sediment which probably predates the Teleki Glaciation (Fig. 2). The surface paleosol is formed in outwash and loess of late Teleki age. Both the ground and buried paleosols are Inceptisols, which are common above timberline on Mount Kenya. Coarse textures prevail in the ground paleosol suggesting only slight weathering; however, in the buried soil a silty loam texture (loess) grades downward into till with sandy loam textures. The cemented lower paleosolum and subsoil in the buried soil are common in older pre-Pleniglacial paleosols on Mount Kenya. The coarse-textured surface paleosol and finer-textured and cemented buried paleosol probably result from wetter conditions following emplacement of Teleki Till. Since the paleosol formed in buried till and loess is weathered to a depth of 100 cm, at least several thousand years would be required to produce the buried paleosol. The surface paleosol must have formed under a dry climate throughout the late Pleistocene and Holocene.

Soil profile TV23 (Fig. 1a; Appendix VIII) consists of a compound buried paleosol overlain with a ground paleosol with somewhat similar characteristics (BOYER and MAHANEY, 1985). Both the buried and surface paleosols are Alfisols, which are more common below timberline on Mount Kenya. Heavy textures in the B2t horizons (Appendix VIII) are the result of downward movement of clay in profiles, which directly

TABLE I

D/L ratios for amino acids in buried soils and radiocarbon dates on Mount Kenya, East Africa

Site[a] and Field sample Number	U. of Alberta Number	Alanine	Aspartic Acid	Glutamic Acid	Leucine	Phenyla lanine	Valine	^{14}C Date	
TV40-A1	(UA-1475)	.05	.07	.07	.01	.03	—	modern	
TV4-A1	(UA-1468)	.10	.08	.12	.02	.03	.02	modern	
TV43-A1	(UA-1477)	.11	.10	.12	.01	.04	—	modern	
TV42-A1	(UA-1476)	.10	.08	.11	.01	.03	.02	modern	
TV42-Ab	(UA-1610)	.19	.18	.14	—	—	.03	920 ± 100	(GaK-11240)
TV4a	(UA-1469)	.09	.09	.09	.01	.01	.01	1940 ± 100	(GaK-8273)
TV33-Ab(upper)	(UA-1472)	.11	.13	.09	.02	—	—	3610 ± 180	(GaK-11320)
TV33-Ab(lower)	(UA-1474)	.08	.16	.07	.01	.02	.02	3400 ± 170	(GaK-11322)
TV39-Ab	(UA-1636)	.20	.16	.13	.12	—	.08	4540 ± 130	(GaK-11241)
GOR8-Ab	(UA-1608)	.21	.26	.22	.04	—	.15	5110 ± 120	(GaK-11570)
GOR52-Ab	(UA-1635)	.27	.29	.21	—	—	—	5100 ± 100	(Beta-10821)
LE3-Ab	(UA-1612)	.22	.45	.22	.29	—	—	>43,210	(Beta-9085)
TV23-Ab	(UA-1663)	—	—	—	—	—	—	40,000	(GaK-11319)
LE4-Ab	(UA-1633)	.23	.33	.21	.05	—	.13	42,629	(Beta-9086)
GOR48-carbon in B2 horizon	(UA-1638)	.21	.27	.19	.08	—	.18	b	
GOR41-Ab	(UA-1584)	.21	.32	.17	.10	—	—	b	

a. Sites are located on Figures 1a and 1b.

b. Not available

— Nil

influences the development of blocky structures. Reddish colors in this profile result partly from the chemical composition of the parent material which is ultrabasic in nature and high in iron (MAHANEY 1982a, 1984b). The surface paleosol in Teleki Till, and the buried paleosol formed in older till of pre-Teleki age, are representative of paleosols formed in older tills of pre-Teleki age found elsewhere along the western flank of Mount Kenya. On the northern and eastern flanks of the mountain, tills of similar age occur in the same stratigraphic position, but the prevailing vegetation is Alpine Moorland, not Bamboo Forest. Despite a dark color (Appendix VII) in the IIIAb horizon, attempts at radiocarbon dating provided only a infinite age of > 40,000 yr BP (Gak-11319). Dating by thermoluminescence places this horizon at 64 ± 24 x 10^3 yrs ago (personal communication, G. Berger, January 1985).

Site LE4 (Fig. 1b; Appendix IX), located on a moraine ridge at 3520 m, contains pre-Teleki Till and outwash over bedrock. The ground paleosol forming in loess and outwash to a depth of 54 cm is an Inceptisol. Between 54 and 126 cm depth the buried paleosol represents weathered pre-Teleki Till, the Ab horizon of which gives an infinite radiocarbon age of > 42,629 yr BP (Beta-9086) (Table I). The data (Appendix IX) suggest that following emplacement of pre-Teleki Till a paleosol formed in cobbly material upon which 18 cm of loess was deposited. Because this paleosol contains a finer texture throughout it must have been exposed at the surface for a considerable time following till emplacement and prior to the deposition of the outwash body.

Profile GOR48 (Fig. 1b; Appendix X), located in pre-Teleki Till in Gorges Valley does not contain any buried paleosols. However, cemented subsoil horizons together with its topographic position provide evidence for considerable age. BAKER (1967) considered this surface as representing the earliest glaciation on the mountain.

Site GOR41 (Fig. 1b; Appendix XI) is situated on the highest strath terrace in the Nithi River Basin along the eastern slopes of Mount Kenya. The lowermost paleosol in the sequence was formed from bedrock emplaced ~ 2.0 Ma. If was later buried by stream activity, presumably during the pre-Teleki Glaciation (> 0.7 x 10^6 yrs).

AMINO ACID RACEMIZATION

As mentioned earlier, soils are probably one of the least desirable materials to analyze for D/L ratios of amino acids because they are subject to so many biogeochemical influences. Indeed, some aspects of contamination are reported by LIMMER and WILSON (1980) in allophanous soils of New Zealand. Besides the complex nature of their formation, and later diagenetic changes that take place at the surface and upon burial, organic matter is difficult to isolate for analysis using gas chromatography. This is clearly illustrated for profile TV33-Ab (lower) (Fig. 3a and 3b) where some peaks of anomalous material are present. To determine the amount of biogeochemical contamination we studied the overall depth distributions of extractable Ca/Mg and pH to elicit information on downward movements. While some downward translocations occurred in profiles on the western flanks of the mountain, very little occurred on the eastern flanks, presumably in response to drier climate there. In all cases where we found downward translocations they occurred mainly in ground paleosols, leaving the buried paleosols unaffected and with apparently valid radiocarbon dates as well as amino acid values.

The D/L ratios for aspartic acid (Table I) were plotted against time (Fig. 4) revealing an overall trend from ~ 0.10 to ~ 0.45 over the late Pleistocene and Holocene. A factor that may contribute to consistent results is that samples are from the same geographical area with similar climatic (especially temperature) and vegetation histories. In other words, close proximity to the equator has tended to minimize the effect of the depth of frost penetration as a factor influencing the rate of racemization. Therefore, amino acid D/L ratios appear to pro-

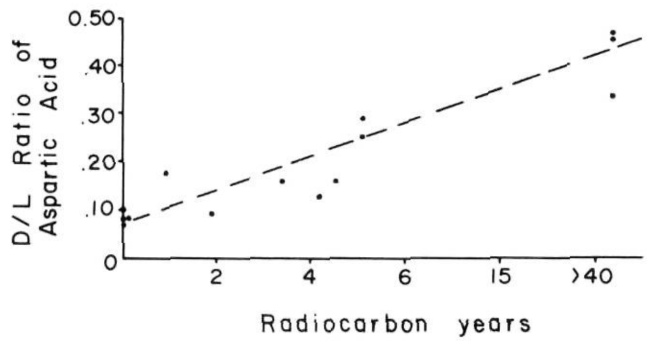


FIGURE 4. Radiocarbon age vrs. D/L ratios for aspartic acid in the Mount Kenya Quaternary sequence.

Datations au radiocarbone et rapports D/L de l'acide aspartique de la séquence quaternaire du mont Kenya.

TABLE II

Particle distributions for the buried paleosol horizons in the Mount Kenya Quaternary Sequence

Sample[a]	Depth (cm)	<2 mm Sand % (2mm-63μm)	Silt % (63-2μm)	Clay % (<2μm)
TV42-Ab	25-29	47.0	36.0	17.0
TV4-Ab	63-67	37.4	45.6	17.0
TV33-Ab (upper)	71-78	52.2	33.8	14.0
TV33-Ab (lower)	140-144	61.7	29.3	9.0
TV39-Ab	142-146	69.4	22.7	7.9
GOR8-Ab	40-45	—	—	—
GOR52-Ab	105-121	50.6	39.4	10.0
LE3-Ab	63-69	37.6	59.2	3.2
TV23-Ab	176-186	45.5	40.0	14.5
LE4-Ab	53-71	17.1	64.9	18.0
GOR48 (carbon in B horizon)	3-25	81.8	18.0	0.2
GOR41-Ab	79-92	72.8	27.0	0.2

— not available

a, Sites are located on Figures 1a and ab.

vide relative age dates for buried soils. In addition, D/L ratios can provide a useful criterion for acceptance or rejection of radiocarbon dates.

Other amino acids (Table I) show variable trends with time that appear useful in age determination. In particular, alanine, glutamic acid, and leucine produced D/L ratios that increased in progressively older samples. Still others, such as phenylalanine and valine, increase slightly or not at all in older buried paleosols, suggesting little utility as a geochronometer.

PARTICLE SIZE

We investigated the possibility that particle size might influence amino acid values either by clay adsorption or by influencing moisture retention. The data in Table II reveal rather wide variations in percentages of sand, silt and clay, reflecting differences in origin. Even percentages of clay vary widely among the buried A horizons in the paleosol sequence, and although some amounts are essentially nil (*e.g.* GOR48 and 41) we found no apparent relationship with the height of amino acid peaks.

CONCLUSIONS

Paleosols on Mount Kenya have been dated by radiocarbon and amino acid dating techniques. D/L ratios of amino acids, as determined for these samples, proved useful for relative age determinations and as an important crosscheck on the validity of radiocarbon dates. Aspartic acid proved remarkably reliable as an age indicator giving progressively higher ratios for most samples of increasing age. Several other amino acids including alanine, glutamic acid, and leucine showed distinct age-dependent trends, although not as convincing as aspartic acid. The aspartic acid ratio/age relationships, verified by radiocarbon controls, allow construction of an aspartic acid time diagram that can be used to date samples ranging from a few hundred to $>$ 42,000 yrs BP. Further work is needed to add more radiocarbon control points and aspartic acid values to this diagram.

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APPENDICES

APPENDIX I

Paleosol Profile TV42[a] in a debris flow, Upper Teleki Valley

Elevation: 4170 m
Age: postglacial
Vegetation: Upper Afroalpine

Horizon	Depth (cm)	Description[b]
01	1 ½-0	
A1	0-5	Brownish black (10YR 2/3m) (10YR 3/2d) sandy loam, slight granular structure, friable, nonplastic and nonsticky
Cox	5-25	Dark brown (10YR 3/3m) and grayish yellow brown (10YR 5/2d) sandy loam, massive structure, very friable, nonplastic and slightly sticky
Ab	25-29	Dark brown (10YR 3/4m) and grayish yellow brown (10YR 3/4m) and grayish yellow brown (10YR 4/2d) loam, massive structure, very friable, non plastic and nonsticky
C1oxb	29-65	Brownish black (10YR 3/2m) and dull yellowish brown (10YR 5/3d) loam, massive structure, very friable, slightly plastic and slightly sticky
C2oxb	65-80	Dull yellowish brown (10YR 4/3m) (10YR 5/3d) loam, massive structure, friable, slightly plastic and slightly sticky
D	80+	Open network of cobbles and pebbles

a. Soil site is located on Figure 1a.
b. Soil descriptions follow Birkeland (1984) and Soil Survey Staff (1951, 1975). Colors were taken from Oyama and Takehara (1970) in the moist(m) and dry(d) states. Consistence is given in the moist state.

APPENDIX II

Soil Profile TV4a[a] in late Holocene alluvium, upper Teleki Valley

Elevation: 4155 m
Age: postglacial
Vegetation: Upper Afroalpine

Horizon	Depth (cm)	Description[b]
A1	0-6	Brownish black (10YR 2/3m, 3/2d) silt loam, weak granular structure, friable consistence, plastic and sticky
B2	6-26	Brown (7.5YR 4/4m) and dull yellowish brown (10YR 5/3d) pebby loamy sand, weak blocky structure, loose consistence, nonplastic and nonsticky
Cox	26-54	Grayish brown (7.5YR 5/2m), dark reddish brown (5YR 3/3m) and grayish yellow brown (10YR 6/2d) clay loam, massive, firm consistence, plastic and sticky
Cu	54-63	Yellowish gray (2.5Y 4/1m) pebbly sandy loam, massive, friable consistence, slightly plastic and slightly sticky
Ab	63-67	Brownish black (10YR 2/3m) and grayish yellow brown (10YR 5/2d) loam, granular structure, firm to friable consistence, plastic and slightly sticky. ^{14}C dated at 1940 ± 120 yrs BP (Gak-8273).
Cb	67-70	Grayish yellow brown (10YR 4/2m, 6/2d) clay loam, massive, friable consistence, plastic and slightly sticky
Cub	70-86	Dark grayish yellow (2.5Y 4/2m) and grayish yellow (2.5Y 6/2d) sandy loam, massive, friable consistence, plastic and slightly sticky.

a. Soil site is located on Figure 1a.
b. Parent material (Cu) is based on criteria established by Hodson (1976).

APPENDIX III

Soil Profile TV33[a] in a middle Holocene alluvial fan, Upper Teleki Valley

Elevation: 4160 m
Age: postglacial
Vegetation: Upper Afroalpine

Horizon	Depth (cm)	Description[b]
01	2-0	Black (10YR 2/1m)
A11	0-7	Dark brown (10YR 3/3m) and brownish black (10YR 3/1d), loam, granular structure, friable consistence, nonplastic and nonsticky
A12	7-20	Dark brown (10YR 3/4m) and grayish yellow brown (10YR 5/2d) pebbly loam, granular structure, friable consistence, plastic and slightly sticky
B2	20-40	Brown (10YR 4/4m) and (7.5YR 4/6d) pebbly sandy loam, blocky structure, friable consistence, nonplastic and slightly sticky
Cox	40-71	Mottled dull yellowish brown (10YR 5/4m), brown (10YR 4/4d) pebbly sandy loam, massive, firm consistence, nonplastic and slightly sticky
Ab	71-78	Brownish black (10YR 3/1m) and grayish brown (7.5YR 5/2d) fine sandy loam, massive, friable consistence, nonplastic and nonsticky
Coxb	78-109	Yellowish gray (2.5Y 4/1m) and grayish yellow brown (10YR 6/2d) pebbly clay loam, massive, firm consistence, plastic and nonsticky
Ab	109-118	Dark brown (10YR 3/3m) and grayish yellow brown (10YR 5/2d) sandy loam, massive, firm consistence, plastic and sticky
Coxb	118-140	Yellowish gray 2.5Y 4/1m) and grayish yellow brown (10YR 6/2d) pebbly sandy loam, massive, firm consistence, plastic and sticky
Ab	140-144	Brownish black (10YR 3/2m) fine sandy loam, massive, friable consistence, slightly plastic and slightly sticky
Coxb	144+	Dull yellow orange (10YR 6/3m) pebbly sandy loam, friable consistence, slightly plastic and nonsticky

a. Soil site is located on Figure 1a.
b. See Appendix II.

APPENDIX IV

Paleosol Profile TV39[a] in a middle Holocene alluvial fan, Upper Teleki Valley

Elevation: 4160 m
Age: postglacial
Vegetation: Upper Afroalpine

Horizon	Depth (cm)	Description[b]
A1	0-8	Dark brown (10YR 3/3m) and brown (7.5YR 4/3d) loam, granular structure, friable, nonplastic and nonsticky
B2	8-22	Brown (7.5YR 4/4m) and dull brown (7.5YR 5/3d) loam, blocky structure, friable, plastic and sticky
C1ox	22-44	Dull brown (7.5YR 5/3m) (7.5YR 6/3d) sandy loam, massive structure, friable, nonplastic and sticky
C2ox	44-90	Dark brown (10YR 3/4m) and dull brown (7.5YR 5/3d) sandy loam, massive structure, very friable, slightly plastic and slightly sticky
C3ox	90-110	Brown (7.5YR 4/6m) and dull yellow orange (10YR 6/3d) sandy loam, massive structure, very friable, nonplastic and nonsticky
C4ox	110-142	Dull yellowish brown (10YR 5/4m) and yellowish brown (10YR 5/6m) (10YR 5/6d) sandy loam, massive structure, friable, nonplastic and sticky
Ab	142-146	Yellowish gray (2.5Y 4/1m) and dull yellowish brown (10YR 5/3d) sandy loam, massive structure, friable, nonplastic and slightly sticky
Cub	146+	Dark grayish yellow (2.5Y 4/2m) and dull yellow orange (10YR 6/3d) sandy loam, massive structure, friable, nonplastic, nonsticky

a. Soil site is located on Figure 1a.
b. See Appendix II.

APPENDIX V

Paleosol Profile GOR8[a] in Liki I Till, Gorges Valley

Elevation: 3475 m
Age: Liki Till
Vegetation: Ericaceous Zone

Horizon	Depth (cm)	Description[b]
A1	0-11	Grayish yellow brown (10YR 4/2m) silty loam, granular structure, friable, nonplastic and nonsticky
IIB2	11-31	Brown (10YR 4/6m) loamy sand, massive structure, friable, nonplastic and nonsticky
IIC	31-40	Dull yellowish brown (10YR 5/3m) sandy loam, massive structure, friable, nonplastic and slightly sticky
IIIAb	40-45	Black (10YR 2/1m) silty loam, granular structure, friable, nonplastic and nonsticky
IVD	45+	Till consisting of an open network of pebbles, cobbles, and boulders containing basalt, phonolite and kenyte

a. Soil site is located on Figure 1b.
b. See Appendix II.

APPENDIX VI

Paleosol Profile GOR52[a] in outwash, Gorges Valley

Elevation: 3050 m
Age: Liki Outwash
Vegetation: Timberline Ecotone

Horizon	Depth (cm)	Description[b]
A11	0-16	Black (10YR 1.7/1m) and brownish black (10YR 2/1d) loam, granular structure, friable, slightly plastic and nonsticky
A12	16-35	Black (7.5YR 2/1m) and dark brown (10YR 3/3d) sandy loam, granular structure, friable, nonplastic and nonsticky
IIB2	35-49	Dull reddish brown (5YR 4/4m) and dull yellowish brown (10YR 5/3d) sand, massive structure, loose, nonplastic and nonsticky
IIC1ox	49-81	Brown (10YR 4/6m) and dull yellow orange (10YR 6/3d) loamy sand, massive structure, loose, nonplastic and nonsticky
IIC2ox	81-105	Yellowish brown (10YR 5/6m) and dull yellow orange (10YR 6/4d) loamy sand, massive structure, loose, nonplastic and nonsticky
IIAb	105-121	Brownish black (7.5YR 3/2m) and brown (10YR 4/4d) loam, massive structure, firm, plastic and sticky
IICbox	121+	Brown (10YR 4/6m) and dull yellow orange (10YR 7/4d) silty clay, massive structure, firm, plastic and sticky

a. Soil site is located on Figure 1b.
b. See Appendix I.

APPENDIX VII

Soil Profile LE3[a] in Teleki Till and outwash, Lake Ellis

Elevation: 3050 m
Age: Teleki Till
Vegetation: Lower Afroalpine

Horizon	Depth (cm)	Description[b]
01	1-0	Brownish black (10YR 3/1m)
A1	0-12	Brownish black (7.5YR 2/2m) and grayish brown (7.5YR 4/2d) sandy loam, granular structure, friable consistence, nonplastic and nonsticky
IIB21	12-25	Brown (7.5YR 4/3m) and dull yellowish brown (10YR 5/4d) loamy sand, massive structure, loose to very friable, nonplastic and nonsticky
IIB22	25-36	Brown (7.5YR 4/6m) and dull yellow orange (10YR 6/4d) loamy sand, massive structure, loose, nonplastic and nonsticky
IIC1ox	36-55	Dull orange (7.5YR 6/4m) and dull yellowish brown (10YR 5/3d) sand, massive structure, loose, nonplastic and nonsticky
IIC2ox	55-63	Orange (7.5YR 6/6m) bright brown (7.5YR 5/6m) dull yellowish brown (10YR 5/3d) loamy sand, massive structure, loose, nonplastic and nonsticky
IIIAb	63-69	Black (7.5YR 1/1m) and brownish black (10YR 3/2d) silty loam, granular structure, friable, slightly plastic and nonsticky
IVB21bm	69-83	Grayish brown (7.5YR 4/2m) and grayish yellow brown (10YR 6/2d) sandy loam, massive structure, friable, nonplastic and nonsticky
IVB22bm	83-97	Brownish gray (7.5YR 4/1m), grayish brown (7.5YR 5/2m) and grayish yellow brown (10YR 6/2d) sandy loam, massive structure, loose, nonplastic and nonsticky
IVC1boxm	97-127	Grayish brown (7.5YR 4/2m), grayish yellow brown (10YR 6/2d) silty loam, massive structure, friable, nonplastic and nonsticky
IVC2boxm	127-142	Grayish brown (7.5YR 4/2m) and dull yellow orange (10YR 6/3d) sandy loam, massive structure, friable, nonplastic and nonsticky
IVC3boxm	142-163	Brownish gray (7.5YR 4/1m), dull brown (7.5YR 5/3m) and dull yellow orange (10YR 6/4d) silt, massive structure, friable, nonplastic and nonsticky
VCub Lacustrine sediment	163+	Grayish brown (7.5YR 5/2m), dull brown (7.5YR 5/3m) and grayish yellow brown (10YR 6/2d) massive structure, firm, plastic and sticky

a. Soil site is located on Figure 1b.
b. See Appendix II.

APPENDIX VIII

Soil Profile TV23[a] in Teleki and pre-Teleki Tills, lower Teleki Valley

Elevation: 2990 m
Age: Tills of Teleki and pre-Teleki ages
Vegetation: Bamboo Forest — Hagenia Woodland Transition Zone

Horizon	Depth (cm)	Description[b]
A11	0-18	Brownish black (10YR 2/3m; 3/3d) and dark brown (10YR 3/3d) silty clay loam, granular structure, friable, slightly plastic, and slightly sticky
A12	18-38	Brownish black (10YR 4/3d) clay, granular structure, firm, plastic and sticky
B21t	38-91	Dark reddish brown (5YR 3/3m) and brown (7.5YR 4/4d) clay, blocky structure, firm, plastic and sticky
B22t	91-104	Brown (7.5YR 4/4m) and dull brown (7.5YR 5/4d) clay, blocky structure, firm, plastic and sticky
IIClox	104-168	Reddish brown (5YR 4/6m), bright reddish brown (5YR 4/5m) and orange (7.5YR 6/6d) clay, massive, friable, plastic, and slightly sticky
IIC2ox	168-176	Dull reddish brown (5YR 4/4m) and bright brown (7.5YR 5/6d) clay, massive, firm, plastic, and sticky
IIIAb	176-186	Black (10YR 1.7/1m), yellowish brown (10YR 5/6m) and dull brown (7.5YR 5/3d) loam, massive, firm consistence, plastic, and sticky
IIIB21t	186-199	Yellowish brown (10YR 5/6m), black (10YR 1.7/1m) and dull yellow orange (10YR 6/4d) clay, massive, firm, plastic, and sticky
IIIB22tb	199-217	Brown (10YR 4/4m) and dull yellow orange (10YR 7/3m) clay, massive, firm, plastic and very sticky
IIIB23tb	217-247	Brown (7.5YR 4/4m; 10YR 6/4d) and dull yellow orange (10YR 6/4d) clay, massive structure, firm, plastic and sticky
IVC1oxb	247-277	Brown (10YR 4/6m) and bright yellowish brown (10YR 6/6d) clay, massive, firm, very plastic, and sticky
IVC2oxb	277+	Brown (10YR 4/6m) some light gray (10YR 8/2m) and dull yellow orange (10YR 6/4d) clay, massive, very firm consistence, very plastic and sticky

a. Soil site is located on Figure 1a.
b. See Appendix I.

APPENDIX IX

Soil Profile LE4[a] in pre-Teleki Till and outwash, Lake Ellis

Elevation: 3490 m
Age: pre-Teleki
Vegetation: Lower Afroalpine

Horizon	Depth (cm)	Description[b]
01	1-0	Brownish black (10YR 4/1m)
A11	0-13	Black (7.5YR 1/1m) and brownish black (7.5YR 2/2d) sandy loam, granular structure, friable, nonplastic and nonsticky
IIA12	13-21	Brownish black (7.5YR 2/2m) and dull yellowish brown (10YR 4/3d) sandy loam, granular structure, very friable, nonplastic and nonsticky
IIB2	21-33	Dull reddish brown (5YR 4/4m) and dull yellow orange (10YR 6/3d) silt, massive structure, loose, nonplastic and nonsticky
IIC1ox	33-42	Brown (7.5YR 4/4m), dull brown (7.5YR 5/3m) and dull brown (7.5YR 5/4d) sandy loam, massive structure, loose, nonplastic and nonsticky
IIC2ox	42-53	Dark brown (7.5YR 3/4m), brown (7.5YR 4/3m) and dull yellow orange (10YR 6/4d) sandy loam, massive structure, friable, nonplastic and slightly sticky
IIIAb	53-71	Black (7.5YR 2/1m) and very dark brown (7.5YR 2/3d) silty loam, granular to massive structure, firm, plastic and slightly sticky
IVB2b	71-85	Grayish brown (7.5YR 4/2m), grayish brown (7.5YR 5/2m) and dull yellow orange (10YR 6/4d) silty loam, blocky structure, firm, plastic and sticky
IVCb	85+	Dull Brown (7.5YR 6/3m), dull brown (7.5YR 5/4m) and dull yellow orange (10YR 7/3d) silty loam, massive structure, friable, nonplastic and nonsticky
R	85+	

a. Soil site is located on Figure 1b.
b. See Appendix I.

APPENDIX X

Paleosol Profile GOR48[a] in pre-Teleki Till, Gorges Valley

Elevation: 3610 m
Age: pre-Teleki Till
Vegetation: Lower Afroalpine

Horizon	Depth (cm)	Description[b]
01	3-0	Black (10YR 1.7/1m)
A1	0-3	Grayish brown (7.5YR 5/2d) sandy loam, granular structure, friable, nonplastic and nonsticky
B21	3-25	Dull brown (7.5YR 6/3d) loamy sand, massive, very friable, nonplastic and nonsticky
B22	25-33	Dull orange (7.5YR 6/4d) sandy loam, blocky structure, firm consistence, slightly plastic and slightly sticky
C1m	33-69	Light brownish gray (7.5YR 7/1d) loamy sand, massive, friable consistence, nonplastic and nonsticky
C2m	69+	Light brownish gray (7.5YR 7/1d) sandy loam, massive, friable consistence, nonplastic and nonsticky

a. Soil site is located on Figure 1b.
b. See Appendix I.

APPENDIX XI

Paleosol Profile GOR41[a] in pre-Teleki outwash, Gorges Valley

Elevation: 3110 m
Age: pre-Teleki outwash
Vegetation: Timberline Ecotone

Horizon	Depth (cm)	Description[b]
Ab	0-14	Black (7.5YR 1.7/1m) and dull yellowish brown (10YR 4/3d) sandy loam, granular structure, very friable, nonplastic and nonsticky
B21	14-28	Dark brown (7.5YR 3/3m) and dull brown (10YR 4/3d) sandy loam, blocky structure, loose, nonplastic and nonsticky
B22	28-41	Dark brown (7.5YR 3/4m) and dull brown (7.5YR 5/4d) loamy sand, weak blocky structure, loose, nonplastic and nonsticky
C1ox	41-63	Brown (7.5YR 4/6m) and dull brown (7.5YR 5/4m) (7.5YR 5/4d) sand, massive structure, very friable, nonplastic and nonsticky
C2ox	63-79	Dull yellowish brown (10YR 5/3m) (10YR 4/3m) and dull brown (10YR 5/3d) loamy sand, massive structure, loose, nonplastic and nonsticky
Ab	79-92	Black (7.5YR 2/1m) and brown (7.5YR 4/3d) loamy sand, massive to single grain structure, firm, plastic and sticky
B2b	92-103	Dull yellowish brown (10YR 5/3m) (10YR 4/3m) and dull yellow orange (10YR 7/3d)silt loam, weak blocky structure, firm, plastic and sticky
C1oxb	103-128	Dull yellowish brown (10YR 5/4m), brownish gray (10YR 6/1m), yellow orange (7.5YR 7/8m) and dull yellow orange (10YR 7/2d) silt loam, massive, firm, plastic and sticky
C2oxb	128-155	Reddish brown (5YR 4/6m), grayish yellow brown (10YR 6/2m) and dull yellow orange (10YR 6/4m) (10YR 7/4d) silt loam, massive structure, firm, plastic and sticky
C3oxb	155-175	Dull brown (7.5YR 5/4m), bright brown (7.5YR 5/6m), grayish brown (7.5YR 6/2m) and dull yellow orange (10YR 6/3d) silt loam, massive structure, firm, plastic and sticky

a. Soil site is located on Figure 1b.
b. See Appendix I.