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# Mires as late Quaternary accumulation basins in Rwanda and Burundi, Central Africa

by Hannu Pajunen

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# MIRES AS LATE QUATERNARY ACCUMULATION BASINS IN RWANDA AND BURUNDI, CENTRAL AFRICA

by

HANNU PAJUNEN

with 62 figures and 13 tables

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The accumulation of both peat and mineral matter is studied in nine mire basins located at 1350 - 1840 m a.s.l. on both sides of the watershed between the Nile and the Zaire in Rwanda and Burundi.The onset of peat deposition in the basins is determined by $^{14}$C dating of basal peat samples. Dry matter, carbon and energy accumulation rates are calculated on the basis of the $^{14}$C ages, dry bulk density, carbon content and net calorific values. The deposition of mineral matter in the mires is studied by field observations and determinations of ash content.

Tectonic movements, volcanic activity and landslides served initially to create basins favourable to paludification. Peat formation was initiated approximately 20 200 B.P. in the oldest mire and approximately 1600 B.P. in the most recent one, and has continued through both dry and humid climatic stages.

The long-term average rates of total dry matter accumulation are in the range 110 - 220 g m$^{-2}$a$^{-1}$ in the Akanyaru area and 150 - 190 g m$^{-2}$a$^{-1}$ in the Rusizi area and are approximately 60 m$^{-2}$a$^{-1}$ in the Virunga area. Accumulation rates have varied in the course of time for both climatic and other reasons. The climatic humidity minimum during the Holocene (after 4500 B.P.) is more clearly distinguishable in the accumulation rates than is the humidity maximum (9000 - 7000 B.P.). The rate of dry matter accumulation was below average in most of the mires during the latter half of the Holocene, but exceeded the average values after 1400 B.P. In addition to the increased humidity of the climate, this was a result of changes in land use in the drainage basin.

In addition to peat, mineral matter eroded from the drainage basin also accumulates in river valley swamps. Layers of fines and sand and increases in the ash content of the peat indicate the location of ancient depositional areas. Thus the peat deposit in the present flood plain of Akanyaru is covered by fine mineral matter. Changes in land use since the mid-19th century have extended this flood plain and markedly increased the deposition of mineral matter on the swamp.

Key words (GeoRef Thesaurus, AGI): bogs, peat, stratigraphy, physical properties, chemical properties, deposition, sedimentation rates, absolute age, C-14, Quaternary, Rwanda, Burundi

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# INTRODUCTION

The majority of the world's mires are located in the former glaciated areas of the high latitude zones, where their maximum age is limited by deglaciation and shoreline displacement. In central Africa such absolute limiting factors are lacking, and thus quite different environmental factors have influenced the development of the mires.

The formation of the rift valleys, in which the Precambrian bedrock of the Lake Tanganyika basin sank as much as 700 m below sea level whereas that of the Ruwenzori area was elevated to more than 5000 m a.s.l., markedly altered the environment of the East African plateau. New lakes were formed, and the drainage basins and flow directions of many rivers were changed. The formation of a more pronounced relief also caused sharper differences in climate. The sequence of fairly rapid geological processes causing environmental changes is still going on.

The scientists of the early 20th century made observations on the glaciers of the highest mountains in East Africa and on the ancient shorelines surrounding the lakes (e.g., Nilsson 1931 and 1940) and efforts were made to describe the climatic changes by reference to glacier movements and water level fluctuations. One of their aims was to find a connection between the glaciations of northern and central Europe and the climatic changes documented in Africa. The failure to find true parallels was partly due to the lack of absolute dating methods and partly to the fact that the influence of non-climatic factors on the water levels of the lakes could not be evaluated (cf. Flint 1956). The matter was put aside for some time, but it has now become topical again in connection with the recent studies of global climate change (e.g. Bradley et al. 1995).

Regional climatic studies nevertheless continued, in spite of the difficulties in interhemispheric coupling. Lake-bottom sediments were studied, e.g. from Lake Kivu (Degens et al. 1973, Stoffers and Hecky 1978, Haberyan and Hecky 1987) and from Lake Tanganyika (Stockers and Hecky 1978, Haberyan and Hecky 1987, Gasse et al. 1989, Vincens 1989), and summaries of lake level fluctuations are numerous (e.g. by Livingstone 1975, Street and Grove 1976, 1979, Street-Perrott and Harrison 1985, Street-Perrott et al. 1989 and Street-Perrott and Perrott 1993). Pollen analysis has been used to deduce climatic changes in Kenya (van Zinderen Bakker 1964), Uganda (Morrison 1961, 1968, Morrison and Hamilton 1974, Hamilton et al. 1986, 1989, Taylor 1990, 1992, 1993), Rwanda (Hamilton 1982, Roche 1985, Roche and van Grunderbeek 1987) and Burundi (Bonnefille and Riollet 1988, Roche and Bikwemu 1989, Bonnefille et al. 1990, 1991, 1992).

The earliest studies of the vegetation and ecology of East-African mires were made in Uganda in the 1950's (Carter 1955, Lind 1956, Beadle and Lind 1960, Lind and Visser 1962), and the topic has later been discussed in a number of articles (e.g., van Zinderen Bakker 1965, Thompson 1973) and books (e.g., Lind and Morrison 1974, Rzoska 1976, Gore 1983, Denny 1985, Williams 1990, Finlayson and Moser 1991).

Thompson (1985) classifies the wetlands of Africa as follows:

- Freshwater herbaceous wetlands
  - Permanent
    - Reed swamps
    - Bog, fen and moorland
  - Seasonal
    - Black clays, pans and dambos
    - Floodplains and valley grasslands
    - Alkaline grasslands
- Freshwater swamp forests
  - Permanent
  - Seasonal
    - Floodplain forests
    - Riverine and gallery forests

The mires in the steep-sided river valleys of Rwanda and Burundi belong in the category of reed swamps, which typically have one distinctly dominant plant species, mostly *Phragmites, Typha, Cladium, Cyperus* (especially *C. papyrus*) or *Miscanthidium*. Thompson (1985) estimated the areal extent of the African reed swamps to be 70 000 - 80 000 km$^2$, of which approximately 940 km$^2$ is situated in Rwanda and Burundi (Shier 1985).

Although a considerable amount of work has been done on the vegetation and ecology of East and Central Africa, studies on the formation and properties of peat are scarce. The properties of tropical peat deposits have mainly been of interest in projects concerned with the cultivation of mires (Goossens 1960, Andriesse 1988, Radjagukguk 1992, etc.) and the use of peat as an energy source (Fig. 1). In the early 1980's a peat project was carried out in Burundi to promote the mining of a nickel ore deposit (Kalmari and Leino 1985), and information was also obtained in this connection on the history and ages of the mires (Pajunen 1981, 1984, 1985, 1990a and 1990b). A peat master plan survey was carried out in Rwanda in 1992 - 1993 (Ekono/BRGM 1993), including assessments of peat resources, hydrological conditions, environmental impacts, marketing and peat production. Some of the basic data for the present work were

Fig. 1. The structure, properties and history of peat deposits can be studied by geological surveys. Picture from the Buyongwe papyrus swamp in Burundi.

collected during these projects.

The purpose of this research is to describe the accumulation of both peat and mineral matter transported from the drainage basins in the mires of Rwanda and Burundi. It was known from dates obtained earlier (Pajunen 1984) that peat had been forming in the Akanyaru swamp complex for as much as 20 000 years, so that the deposits contain material from glacial as well as postglacial times. The terms 'glacial' and 'ice age' will be used here for the sake of the clarity of the time scale (cf. Gasse et al. 1989, Bonnefille et al. 1992), even though the area has not been glaciated at any time during the Quaternary. It is true, however, that the term 'cold stage', as used by Donner (1995), would be better for describing the history of the area than 'glacial'. The boundary between Pleistocene and Holocene is considered to be 10 000 B.P.

The rate of formation of peat deposits varies according to the mire basin and the time period concerned. Observations on the rates of thickness increment in peat deposits have been published by Tolonen (1973), Aaby and Tauber (1975), Zurek (1976, 1984) and Ikonen (1993) etc. for the boreal zone, and by Anderson (1964, 1983), Pajunen (1981), Sieffermann et al. (1988), Supardi et al. (1993) and others for the tropics.

The significance of information on peat accumulation rates for the study of climatic changes has increased (Gorham 1991, Maltby and Immirzi 1993, Franzén 1994, Tolonen et al. 1994), and in addition to thickness increment, information is also required on the dry matter and carbon accumulation rates and on the horizontal growth of mires. The research published so far regarding the rates of dry matter and carbon accumulation mainly concern mires in the boreal zone (e.g. Tolonen 1979, Tolonen et al. 1988, 1992a and 1992b, Ovenden 1990, Korhola 1992, Korhola et al. 1995, Ikonen 1995, Pajunen 1995), whereas observations concerning the tropics are largely limited to countries such as Burundi (Pajunen 1985), Indonesia (Diemont and Supardi 1987) and Rwanda (Pajunen and Karega in press). The study of horizontal growth requires the dating of numerous basal peat samples, a technique that has been used to assess the expansion of tropical mires in Jamaica (Digerfeldt and Enell 1985), although the majority of the work done again concerns mires in the boreal zone (e.g., Solem 1986, Foster and Jacobson 1990, Foster and Wright Jr. 1990, Korhola 1992, 1994, 1995).

## HISTORY OF THE AREA STUDIED

### Geological history

East Africa is mainly plateau with an altitude of more than 1000 m. It is broken by rift valleys and scattered volcanoes or chains of volcanoes (Fig. 2). The Great or Eastern rift valley extends from the Red Sea via Ethiopia and Kenya to the coast of Tanzania, while the Western rift valley extends from Uganda via the western parts of Rwanda and Burundi to the coast of Mozambique. Lake Edward, Lake Kivu and Lake Tanganyika are located in the Western rift valley and Lake Victoria in the area between the rift valleys.

The tectonic movements that led to the formation of Lake Tanganyika started in the area of the Western rift valley in the late Eocene and the early Oligocene. Deposition of sediments began on the bottom of Lake Tanganyika at least as early as the Miocene. On the basis of the thickness and sedimentation rate of the deposits, the age of the lowermost sediments has been estimated at approximately 20 million years (Tiercelin and Mondeguer

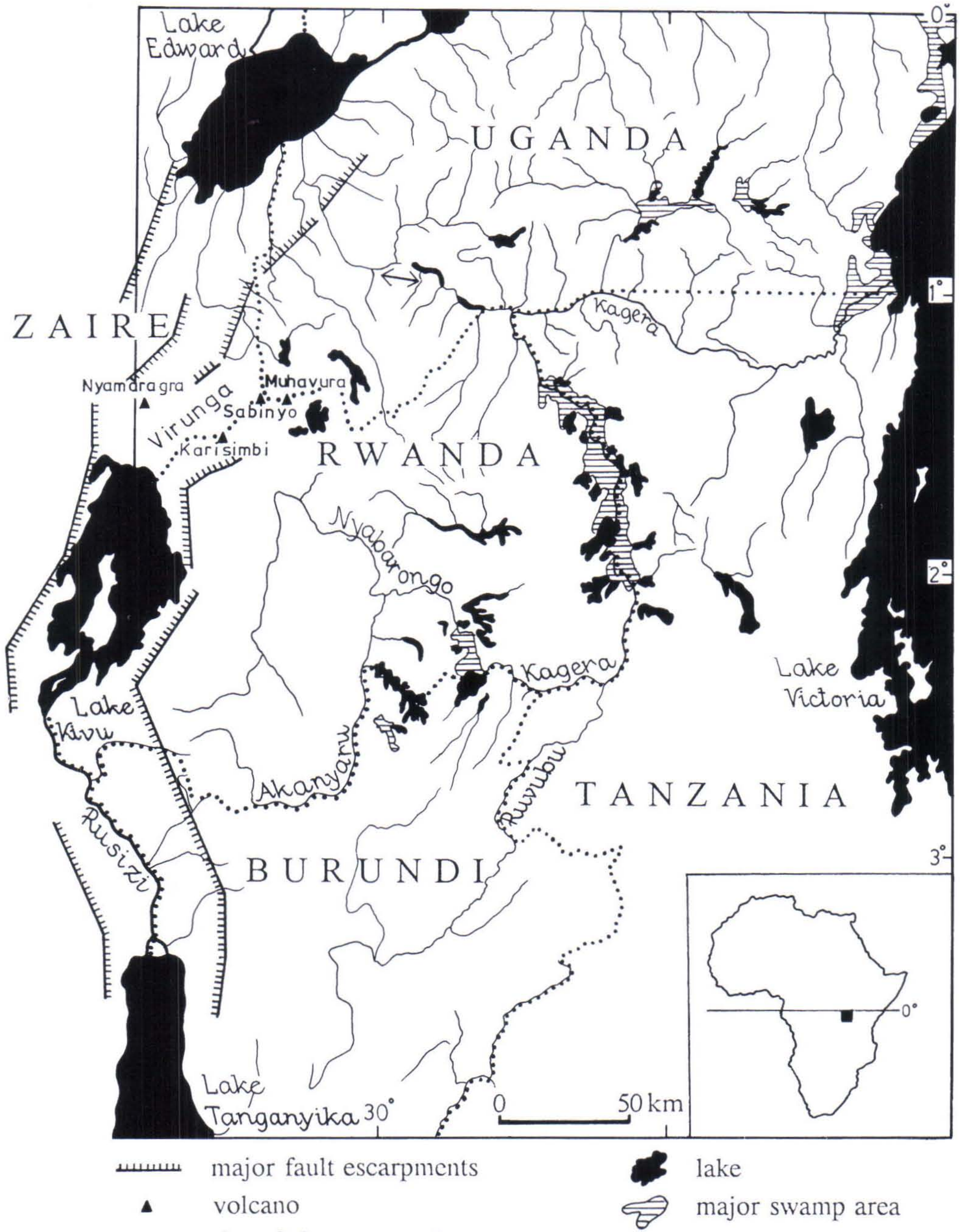


Fig. 2. Tectonic movements and volcanic activity related to the formation of the Western rift valley have influenced the history of the lakes and river systems of the area. Main fault lines according to Beadle (1981). Basic map: The Times Atlas of the World.

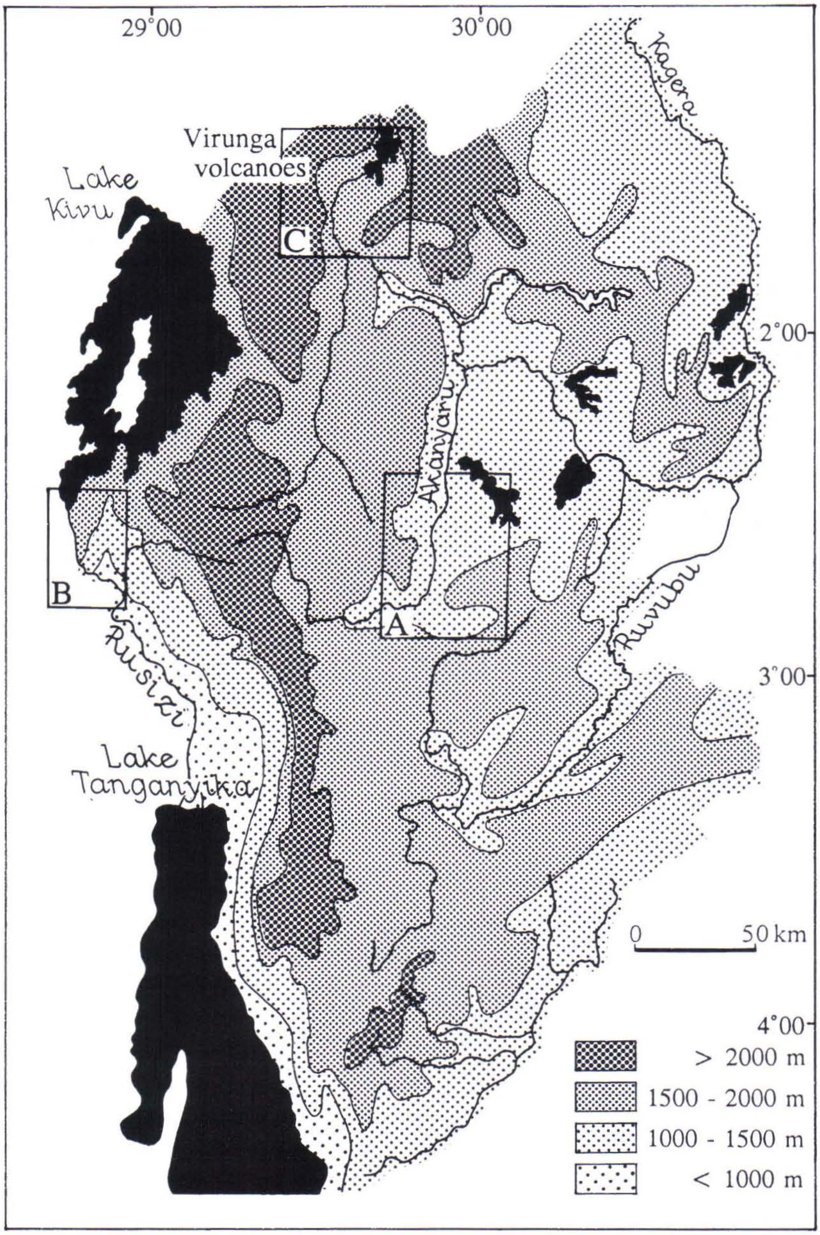


Fig. 3. The formation of the Western rift valley has influenced the relief of Rwanda and Burundi. The floor of the rift valley has sunk below the East African plateau and the rift flanks have risen above it. The locations of the mire basins studied are shown in Figures 10 (A), 12 (B) and 13 (C).

1991). Farther north the rift valley is younger. According to Ebinger (1989a) the northern Rusizi basin was formed 6 - 2 million years ago.

The flanks of the rift valley have risen 1 - 4 km above the surrounding plateau (Ebinger 1989b). The elevation has been strongest immediately outside the border-fault segment. At the same time as the flanks rose, the sinking basin became narrower. The sinking of the floor of the rift valley and the rising of the rim flanks has markedly affected the present relief of Rwanda and Burundi (Fig. 3). Today the flanks of the rift valley rise to an altitude of a little more than 2000 m a.s.l.

Towards the west the terrain slopes steeply, reaching an altitude of less than 1000 m in the vicinity of Lake Tanganyika and River Rusizi. East of the main drainage divide the terrain slopes more gently downward, reaching the 1300 m level near the border of Tanzania.

The northern end of the Tanganyika and the basin of Rusizi are still the most seismically active areas of the Western rift valley. However, in the Virunga area north of Lake Kivu the number of earthquakes is exceptionally small. According to Wohlenberg (1969) the magma reservoirs below the volcanoes prevent or slow down the building up of tension in the Earth's crust.

The volcanic activity of the Western rift valley is concentrated in four areas. These areas are: 1) Toro-Ankole NE of Lake Edward, 2) the Virunga area north of Lake Kivu, 3) the area of South Kivu and 4) the Rungwe area between the lakes Rukwa and Malawi. As concerns the development of the study area, the most significant areas are those of Virunga and South Kivu, which are partly on the Rwandan side of the border.

According to the summary presented by Tiercelin and Mondegeur (1991, p. 23-24) the volcanic activity started in the area of Lake Kivu approximately 20 million years ago. Especially active periods occurred 14 - 10 million and 8 - 5 million years ago. During those periods the greatest vertical tectonic movements also took place. The first walls in a north-south direction were formed in the areas of South Kivu and northern Rusizi during the latter period. A third active period began 2 million years ago, and it has continued until historical time.

Among the volcanoes of the Virunga area, Karisimbi, Bisoke, Sabyinyo, Gahinga and Muhabura are located on the northern border of Rwanda and surround the present drainage basin of Kagera. Nyiragongo and Nyamulagira, which are located entirely in Zaire, have been active until recent times (Battistini and Prioul 1981).

De Mulder and Pasteels (1986) distinguish three stages in the history of Karisimbi. According to K-Ar data the first stage occurred 140 000 ± 60 000 years ago and the second 90 000 ± 30 000 years ago. During the third stage remarkable eruptions occurred around 30 000 and 10 000 years ago. The eruptions of the first and second development stage of Karisimbi may have affected the history of the river systems and the eruptions of the third stage the history of the mires. $^{14}C$ dates from southwestern Uganda show that the yongest ash layers originate from 21 540 - 16 260 B.P. (Taylor 1992).

## History of the river systems

Tectonic changes and volcanism have affected the history of the river systems by changing the inclination of the ground surface and by damming river valleys. The development of the river systems at the upper courses of the Nile has been described by, e.g. Lind (1956), Beadle and Lind (1960), Bishop and Psnansky (1960), Rossi (1980) and Beadle (1981).

Before the uplift of the flanks of the rift valley, the main drainage divide of the Zaire/ the Nile was located east of the present Lake Victoria (Fig. 4). The present Kafu, Katonga and Kagera flowed to the west. As the flanks rose, the flow at the upper courses slowed down and finally lakes were formed there, the largest of which are Lake Victoria and Lake Kyoga. At first Lake Victoria was located farther west than today, and it may have discharged its water towards the west. The powerful land uplift near the rift valley continued, however. Finally Lake Victoria cut itself a new outlet and effluent, and so the main drainage divide shifted to the vicinity of the rift

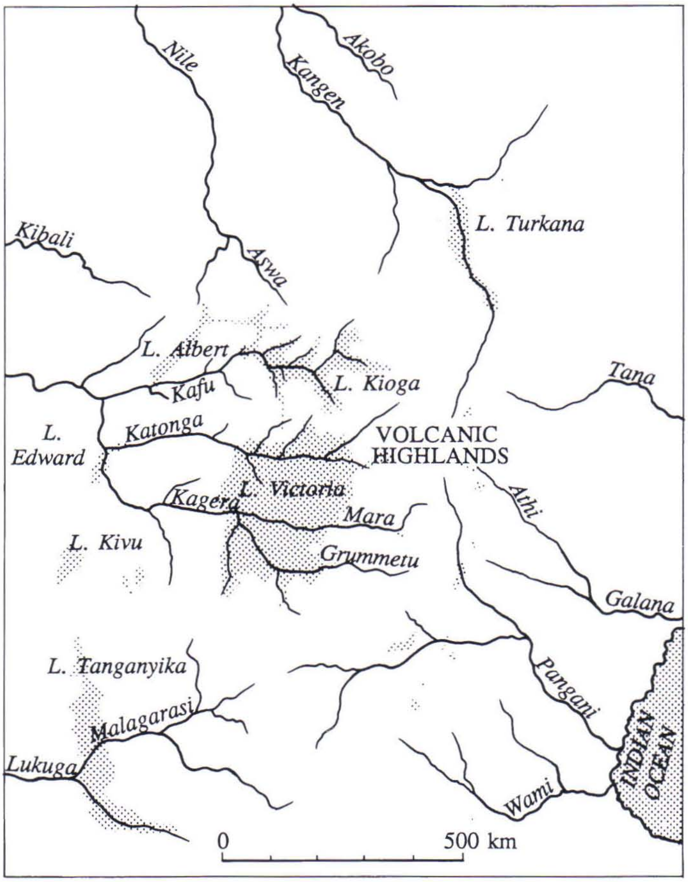


Fig. 4. The river system of East Africa before the formation of the rift valleys. The main drainage divide was located east of the present Lake Victoria. Redrawn according to Beadle (1981).

valley in western Uganda. East of the new drainage divide, the flow direction of the rivers changed.

The changes in drainage basins were caused not only by the inclination of the Earth's crust but also by volcanic activity. A lava flow, erupted from the Virunga area into the Western rift valley during the late Pleistocene dammed part of the upper courses of the Nile, joining them with the drainage basin of the Zaire. As a result of the eruption, Lake Kivu and its effluent, the Rusizi, were formed (Grove 1983). The eruptions of Virunga also dammed the Nyabarongo valley and may have changed the flow direction of the River Nyabarongo (Battistini and Prioul 1981).

If the formation of the Virunga volcanic chain caused the change in flow direction of Nyabarongo, it happened more than 100 000 years ago. If the flow direction was changed by tectonic uplift of the land, it may have occurred considerably earlier. Since most of the peat deposits are Holocene, there is a long time lag between the change in flow direction and the formation of the peat. In any case the time when the change in flow direction took place was favourable for the sedimentation of fines and also for paludification (Lind 1956). Although mire vegetation invaded the river valleys at some point of their development, it did not necessarily mean the beginning of peat accumulation.

## Climatic history

The most significant factors influencing the climate of the last glacial stage were the shift of the climatic zones, the shift of the oceanic currents and the increase in albedo of the Earth (e.g., CLIMAP 1976 and Manabe and Hahn 1977). The shift of the climatic zones was caused by the continental ice sheets extending from the polar regions towards the low latitudes. The oceanic currents were affected by shifts in wind zones and a lowering of the sea level. E.g., the Mozambique current, which influences the circulation in the Indian Ocean, did not exist 18 000 B.P. The increased albedo depended mainly on the increased amount of snow and ice and changes in vegetation. During the last ice age the deserts, steppes, grasslands and outwash plains had expanded at the expense of the forests (CLIMAP 1981).

During the maximum stage of the last ice age the temperature differences between the northern and southern hemisphere apparently decreased. The levelling down of temperature differences and air currents influenced the location of the meteorological equator (ITCZ). Today it is in the northern hemisphere during most of the year, whereas during the last ice age it was closer to the geographical equator (Nicholson and Flohn 1980). The location of the meteorological equator in East Africa affects especially the seasonal distribution of the precipitation.

According to the model of Manabe and Hahn (1977) the climate of the last ice age was drier than the present in tropical Africa. The amount of precipitation was smaller, and so was the average evaporation. During the ice age the precipitation decreased more than the evaporation, and so the discharge of the rivers was lesser than at present. The long-term fluctuation of the discharge has contributed to the formation of river valley mires.

Climatic changes easily affect the water level of closed lakes, whereas in lakes with effluents, the climatic stages dryer than today show in the form of water levels lower than the present. According to Street and Grove (1979), the fluctuations in water level of closed lakes are the best indicators of the paleoclimates of the continents during the late Quaternary. The lake sediments cover a fairly long period of time, they may be dated and the water levels of the lakes react faster to climatic changes than do the glaciers or the vegetation. On the basis of a sufficiently large material it is also possible to study the shift in climatic zones.

According to Street and Grove (1979) the lakes of tropical Africa had a fairly high water level before 21 000 B.P. The climate was somewhat cooler then and the evaporation possibly lesser. It is difficult to distinguish the effects of the precipitation and the temperature on the water level. 21 000 - 12 500 B.P. was an exceptionally dry stage in East Africa and many lakes dried completely. The drought was greatest at the end of that stage, 15 000 - 12 500 B.P. The first signs of a change towards a more humid climate may be observed 12 500 - 10 000 B.P. The water in the lakes began to rise rapidly 10 000 B.P. and the climate in tropical Africa was at its most humid 9000 - 7000 B.P. The water level of the lakes started to sink rapidly again 4500 $^{14}$C years ago, and many East African lakes have dried completely during the last few thousands of years.

The history of Lake Tanganyika and Lake Kivu fits the description by Street and Grove (1979) of the development of the lakes of tropical Africa. Lake Tanganyika was at its lowest 18 000 B.P. (Gasse et al. 1989) and Lake Kivu 16 000 - 14 000 B.P. (Haberyan and Hecky 1987). The water level of Lake Kivu rose after the climate had become more humid between 12 000 and 10 000 B.P., and Rusizi, the present effluent, cut through approximately 9400 B.P. Some 5000 $^{14}$C years ago the climate started turning drier, and 3500 B.P. Lake Kivu became a closed lake. Rusizi cut through again 1400 B.P. due to a climate somewhat more humid than today (Haberyan and Hecky 1987).

## MATERIAL AND METHODS

### Field studies

Most tropical mires differ significantly from those in higher latitudes. Methods of study developed for use in the northern regions must be adapted in order to suit the local conditions. For the purpose of this research, the methods used in Finland were used as a basis. They have been described by, e.g. Lappalainen et al. (1984). The line network method was used in the swamps of Buyongwe (Fig. 5), Ndurumu (Fig. 6) and Gishoma and the traverse site method in the other mires.

The samples were collected using a Hiller sampler, piston samplers, and Russian-type peat samplers of various sizes. In Burundi the

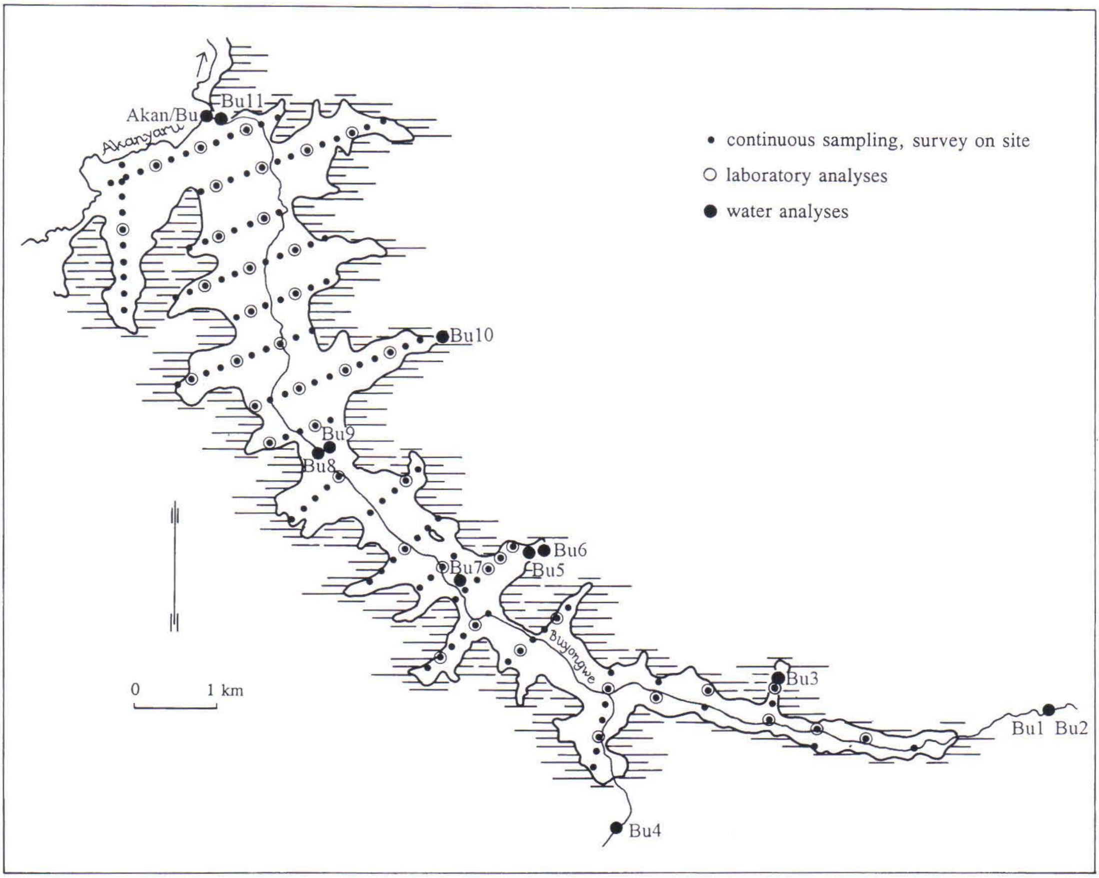


Fig. 5. Locations of survey sites on the Buyongwe swamp.

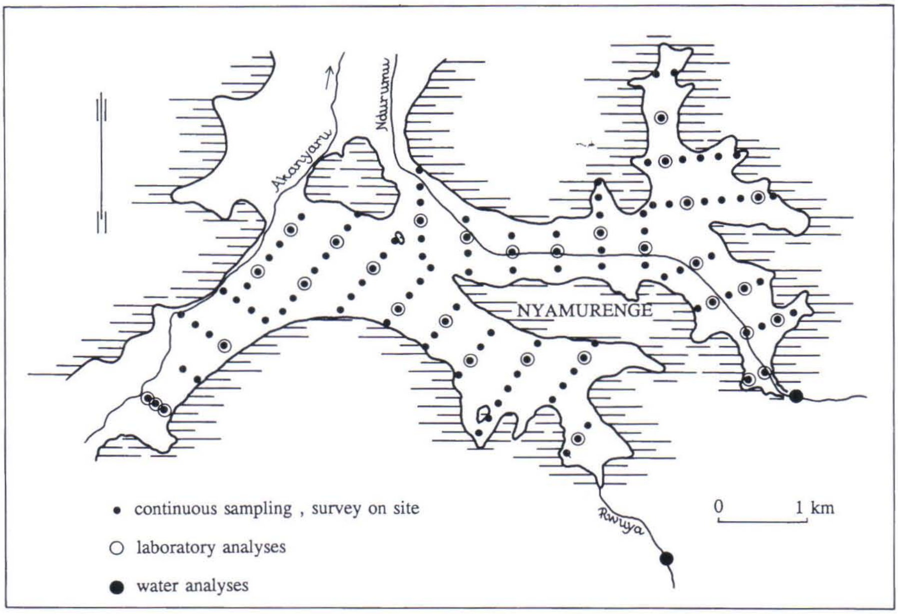


Fig. 6. Locations of survey sites on the Ndurumu swamp.

samples for field and laboratory determinations were collected by a Hiller sampler from a depth of more than 20 m. Laboratory samples from depths of less than 10 m were taken with a volumetric piston sampler (Fig. 7) and from depths of 10 - 20 m with a 50 mm piston sampler. In Rwanda the samples for field determination and part of the laboratory samples were collected with a Russian-type sampler (Fig. 8). The majority of the laboratory samples from the Gishoma swamp were taken with a volumetric piston sampler.

Since the difference in reliability is insignificant between the Russian-type sampler and the piston sampler (Tolonen and Iäs 1982), some of the volumetric laboratory samples from Rwanda were collected with a 50 mm Russian-type sampler. Factors favouring the Russian-type sampler are the speed of sampling, the vertically longer samples and a lesser need for extension rods.

The samples for dating were mainly collected at even intervals. The samples for dating from the Buyongwe swamp and the Ndurumu swamp were taken at two stages. The Buyongwe swamp was sampled 1980 and 1993. The sampling was continued from 20 m downwards, since the original survey site could no longer be found exactly. The basal peat sample from the Ndurumu swamp was taken in connection with the peat inventory in 1982 and the other samples for dating in 1993, when additional material was collected. Since the dry bulk density, net calorific value and carbon content were not known for the sites on the Buyongwe and Ndurumu swamps where the samples for dating were taken, the average values for the part of the swamp concerned were used in the calculations. The samples for dating from Rwanda were taken in 1992 and 1993 from sample series, on which the determinations necessary for calculation of the accumulation rates were carried out.

A pump sediment filtering apparatus developed at Uppsala University was used for filtration of water samples in the field. The water

Fig. 7. Samples for laboratory analyses were taken with a volumetric piston sampler. Volumetric samples are necessary for calculation of the dry bulk density and the rate of peat accumulation.

Fig. 8. Samples were taken with a Russian-type peat sampler for use in both field and laboratory determinations.

sampling was carried out during the spring rains, which had continued daily for weeks already. The volume of the samples was approximately one litre. The filter used was Whatman no. 4 filter paper. After filtration, the papers were dried and weighed in the laboratory.

The plant associations of the mires are generally described by site types. A site type classification developed for Finnish conditions (Cajander 1913) may not be used in the tropics, but the mire vegetation has to be described on the basis of indicator plants. In connection with the field work, efforts were made to find out the most common plant species of each survey site. In the determination of the plant species, the Flora of Rwanda (Troupin 1988) and literature describing mire vegetation was used (Deuse 1966, Lind and Morrison 1974, Thompson and Hamilton 1983).

The peat types are classified on the basis of plant species composition or structure. Kivinen (1948) divides the peat types on the basis of plant species composition into two main groups, *Sphagnum* peat and *Carex* peat. In some classifications *Hypnum* peat forms the third main group (e.g., Lappalainen et al. 1984). Mostly the peat consists of one or more main constituents (*Sphagnum*, *Carex* and *Hypnum*) and additional constituents, which may be, e.g. horsetail (*Equisetum*) and wood remains. According to the classifications for Finnish conditions, the peat types of Rwanda and Burundi would belong to one main group. The peat types may be distinguished only on the basis of additional constituents. In the present work the term '*Cyperus* peat' will be used instead of 'sedge peat', since the English term 'sedge peat' covers peat formed mainly from plants of the genus *Carex* (Eggelsmann et al. 1993).

The $\delta^{13}C$ values of the peat were used to describe the peat-forming vegetation. On the basis of the carbon metabolism the plants may be classified into the $C_3$ and $C_4$ types of plants. The photosynthesis of plants of type $C_4$ is more effective, in the range 50 - 90 mg $CO_2$ $dm^{-2}$ $h^{-1}$, while in the plants of type $C_3$ it remains below 40 mg $CO_2$ $dm^{-2}$ $h^{-1}$ (Bradbury and Grace 1983). As to their photosynthetic pathway, the majority of mire plants are of type $C_3$, including e.g., most trees, *Carex* and *Cladium*. Some species of *Cyperus* belong to type $C_3$, others to type $C_4$ (Hesla et al. 1982). Of the most common peat-forming plants in Rwanda and Burundi, *Cyperus papyrus*, *C. latifolius* and *Miscanthidium* are of type $C_4$.

The pathway of carbon metabolism also affects the carbon isotope fractionation (Troughton 1972). The average $\delta^{13}C$ value of the peat-forming plants of type $C_3$ is -25.5 ‰ and that of type $C_4$ -11.3 ‰ (Aucour et al. 1994). The $\delta^{13}C$ values of the peat reflect the distribution of the peat-forming vegetation into plants of types $C_3$ and $C_4$. The variation in $\delta^{13}C$ values has been used in the estimation of changes in the paleoenvironment (Krishnamurty and DeNiro 1982, Cerling et al. 1989, Hillaire-Marcel et al. 1989, Aucour et al. 1994).

The degree of decomposition was determined using the scale of one to ten introduced by von Post (1922). It is especially well suited to the determination of the decomposition degree of *Sphagnum* peat, but it is also generally applied to other types of peat.

## Laboratory analyses and calculations

The samples were sent to the laboratory packed in plastic bags. The wet samples were analysed for pH using a Knick pH Meter 761 Calimatic and an Ingold combined electrode. The water content was determined by drying the samples at a temperature of 105°C. The water content was calculated as weight-% of the wet weight. If the volume of the sample was known, the amount of total dry matter per volume unit (dry bulk density) was calculated.

The dried samples were pulverized. A part of the dry sample was used in the determinations of calorific value and of carbon, hydrogen and nitrogen content, and another part for the determination of ash content and for analyses of the ash. The calorific values were determined by a Leco AC 300 calorimeter (ISO 1928-1976) and reported in the form of net calorific values. The ash content was determined by ignition of the sample at a temperature of 815 ± 25°C and calculation of the ratio between ignition residue and dry weight of the sample. The concentrations of carbon, hydrogen and nitrogen were determined by a Leco CHN-600 analyser.

For determination of the chemical composition of the samples an ash sample of 0.150 g was dissolved in aqua regia, in which the volume ratio of nitric acid and hydrochloric acid is 1:3. The concentrations of 30 elements in the solution were determined by a Poly Scan 61 spectrometer. This inductively coupled plasma atomic emission spectrometric (ICP-AES) method is used in Finland for chemical analysis of till. Sulphides, carbonates and phosphates are almost totally dissolved in aqua regia, whereas silicates and some oxides are hard to dissolve (Koljonen et al. 1992).

The $^{14}C$ analyses were carried out at the radiocarbon laboratory of the Geological Survey of Finland (Su). The samples were dated on total organic matter after acid pretreatment. The measuring technique used was proportional counting of $CO_2$ (Äikää et al. 1992). The ages are conventional $^{14}C$ ages (years B.P., Before Present), i.e. they are based on the use of the 5568 yr half-life and are corrected for isotopic fractionation. The $^{14}C$ ages were converted to calendar years (Table 1, p. 24) for calculation of average thickness increment and total dry matter accumulation rates. The age calibration was done with a computer program (Stuiver and Reimer 1993) which integrates the calibration data published in the Calibration 1993 volume of Radiocarbon (Stuiver et al. 1993). The detailed calibration curve was smoothed to an extent commensurate with the estimated time-widths of the samples.

The average thickness increment of the peat deposit was obtained by dividing the vertical distance between the dated samples by the difference between the calibrated ages. The total dry matter accumulation rates were calculated using the following formula:

$A = r\,\rho$, where

$A$ = total dry matter accumulation rate ($g\ m^{-2}\ a^{-1}$)
$r$ = rate of thickness increment ($mm\ a^{-1}$)
$\rho$ = dry bulk density of the peat ($kg\ m^{-3}$)

The total dry matter was divided into organic matter and mineral matter on the basis of the ash content. The carbon accumulation rates were calculated from the total dry matter accumulation rates on the basis of the carbon content. Correspondingly the energy accumulation rates were calculated from that of total dry matter on the basis of the net calorific value. The results obtained are the long-term apparent accumulation rates.

## Amount and areal distribution of data

A total of 448 survey sites on 9 mires were studied. The data were collected partly during the peat inventory, partly during short expeditions. The peat inventories concentrated on the amount of peat and mainly on the study of properties essential in view of use for energy production. In connection with the additional studies, efforts were made to describe the history of the mires and the chemical properties of the peat, and so the number of sites varies greatly according to mire. In the field the properties of approximately 8350 samples were determined. Laboratory anlyses were carried out on a total of 1567 samples. The most numerous were the determinations of water and ash content. The ages of 45 samples were determined by the $^{14}C$ method.

There are numerous field observations and determinations of water and ash content from the Buyongwe and Ndurumu swamps. On the basis of the data obtained it is possible to examine the stratigraphy and variations in ash content of these peat deposits. As concerns the smaller mires, the main focus of the study was on the peat accumulation rates.

## DESCRIPTIONS OF THE MIRE BASINS, RESULTS AND INTERPRETATION

Five of the mire basins studied are situated within the Akanyaru swamp complex, two in the Western rift valley in the vicinity of Rusizi and two in the foreland of the Virunga volcanic chain. These areas differ from each other regarding both geology and climate.

Akanyaru is one of the upper tributaries of Kagera. It begins at the main drainage divide between the Nile and the Zaire at 2500 m a.s.l., and joins Nyabarongo at 1350 m a.s.l. (Fig. 9). The bedrock of the drainage basin is Precambrian (Carte géologique, Burundi 1981, Carte géologique du Rwanda 1991). The lower part of the Akanyaru valley has been paludified for a distance of approximately 90 km. The area covered by the swamp complex is approximately 25 900 ha, comprising the valley of the main river and the lower parts of the tributary valleys (Fig. 10).

The annual average temperature in the area of Akanyaru swamp complex is about 19°C. The precipitation amount varies according to the different parts of the area, being approximately 1200 mm $a^{-1}$ in the southern part and 800 mm $a^{-1}$ in the northern part (Atlas du Burundi 1979, Atlas du Rwanda 1981). The precipitation amount and its variations in the drainage basin control the hydrology of the rivers. Along with the local climatic conditions it thus has a marked effect on the development of the river valley swamps. The drainage basin of Akanyaru extends in the west to the drainage divide between the Nile and the Zaire. Towards the west the precipitation amount increases while the dry season becomes shorter.

The meteorological data collected in the Buyongwe swamp in the years 1983 and 1984 show an average temperature of 21°C. The daily temperature varied on an average 20°C, the average maximum being 32°C and the minimum 12°C. The daily variation is at its greatest during the dry season, when the minimum temperatures generally drop below 10°C. The precipitation amounts on the swamp correspond to the average values of the area, although the annual variations may be significant. During the years examined, it rained 1370 and 1030 mm. In 1983 the precipitation amount was only a little greater than the evaporation from open water (1340 mm). The evapotranspiration of natural mires is due to shading smaller than the evaporation from open water (e.g. Gaudet 1979). The difference between precipitation amount and evaporation reflects mainly the amount of water available for the vegetation of mineral soils. The vegetation of limnogenic river valley swamps, on the other hand, is dependent on the water flowing from the drainage basin.

The annual precipitation amount is divided into two rainy seasons and two dry seasons. The spring rains are more abundant than those of the autumn, and the dry season of the summer is longer and more pronounced than that of the winter. The periodical character of the rains is a significant factor in view of the hydrological conditions of the mires. Due to the two rainy seasons, the dry seasons of the study area are shorter and the water level fluctuations smaller than in the areas farther from

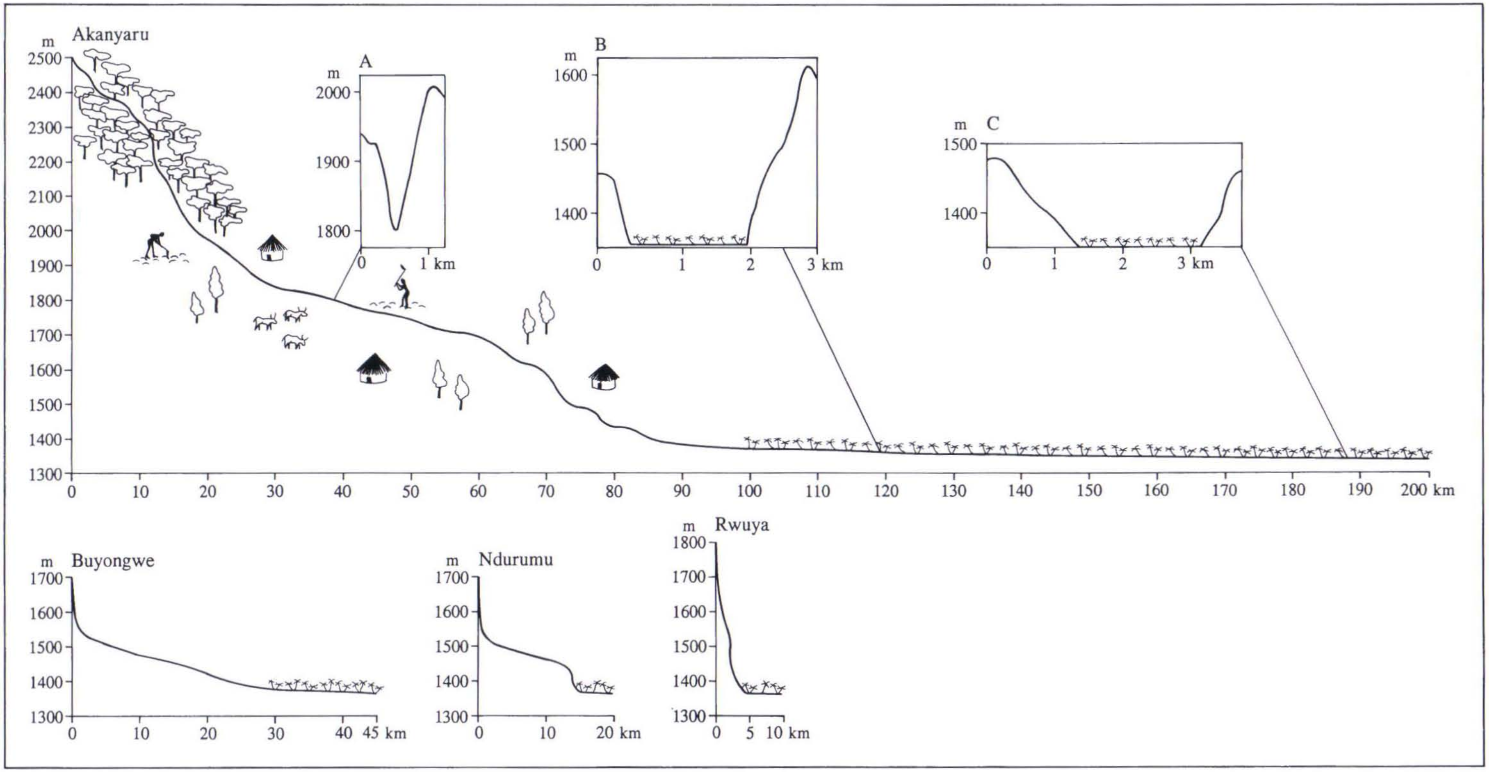


Fig. 9. Longitudinal sections of Akanyaru and its three tributaries. Differences in resistance to erosion in the bedrock cause steps in the longitudinal sections of Akanyaru and Ndurumu. The cross-sections of the Akanyaru valley are on a different scale.

the equator having only one rainy season. The data collected from the Buyongwe swamp show that the daily precipitation amount may be as much as 40 - 70 mm. The strong rains are especially erosive if they come after a dry period of several weeks. A study of erosion in the vicinity of Butare (Moeyersons 1989) showed that isolated rains of less than 2.5 mm do not cause notable erosion.

The average discharge of Akanyaru at the Butare - Ngozi road, about 15 km upstream of the swamp complex has been 21 $m^3$ $s^{-1}$ (Annuaire hydrologique 1971 - 1988). Its fluctuation follows, with a small delay, the seasonal fluctuation of the precipitation amount. The discharge is greatest in April (approximately

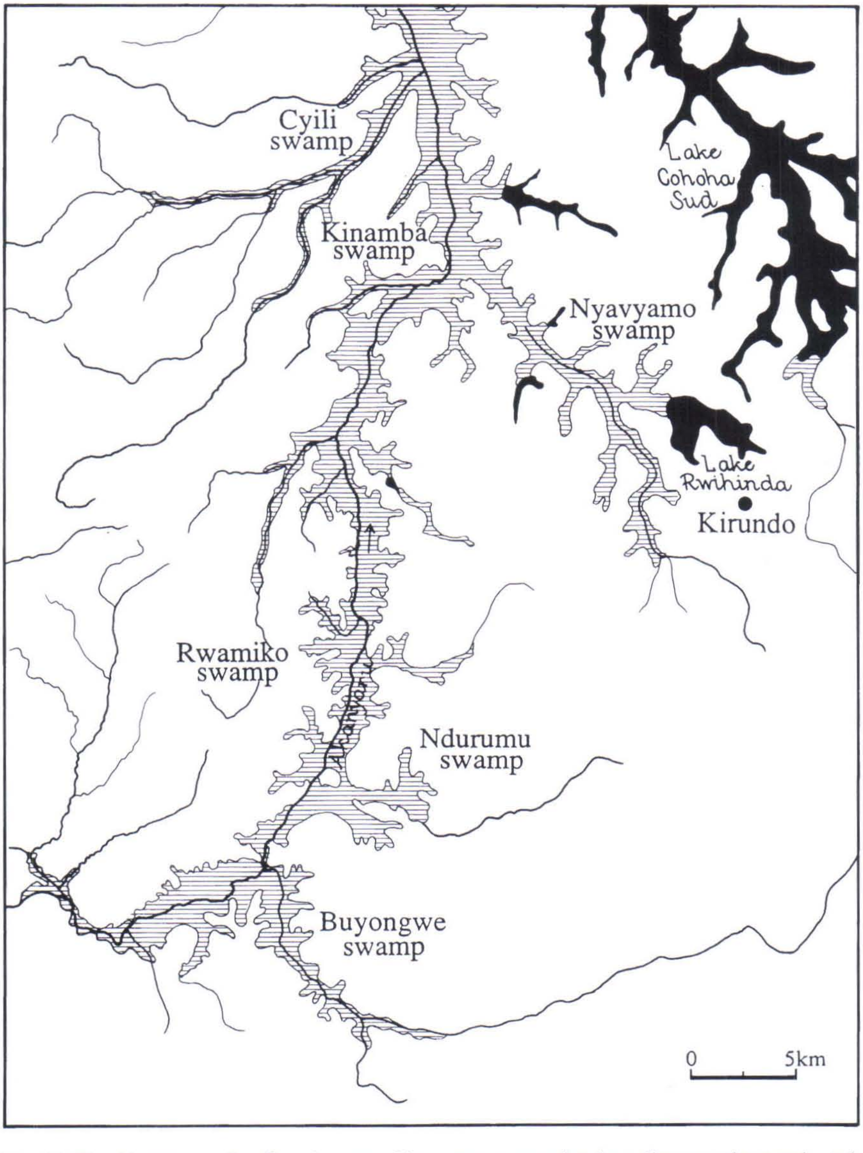


Fig. 10. The Akanyaru valley floor is covered by a swamp complex for a distance of approximately 90 km. In addition to the main river valley, the swamp covers the lower parts of the tributary valleys.

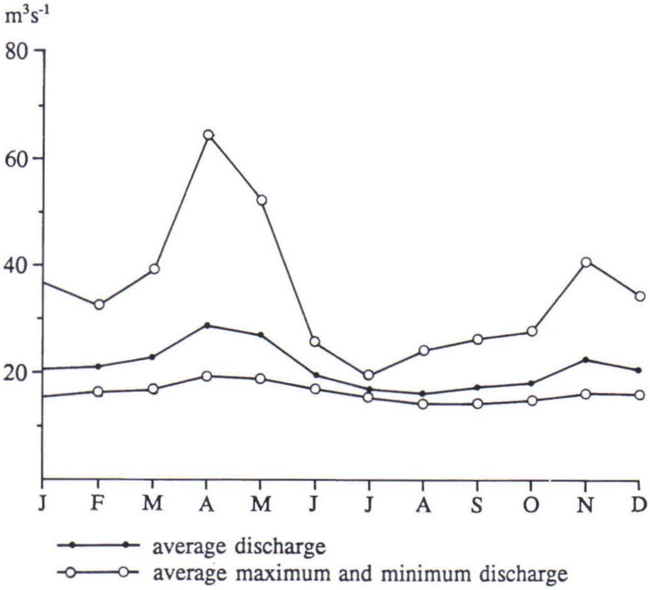


Fig. 11. Average annual fluctuations in the discharge of Akanyaru over 18 years (Annuaire hydrologique 1971-1988). The measuring point is situated upstream of the mire area. The fluctuation between rainy and dry seasons is especially reflected in the maximum discharge values.

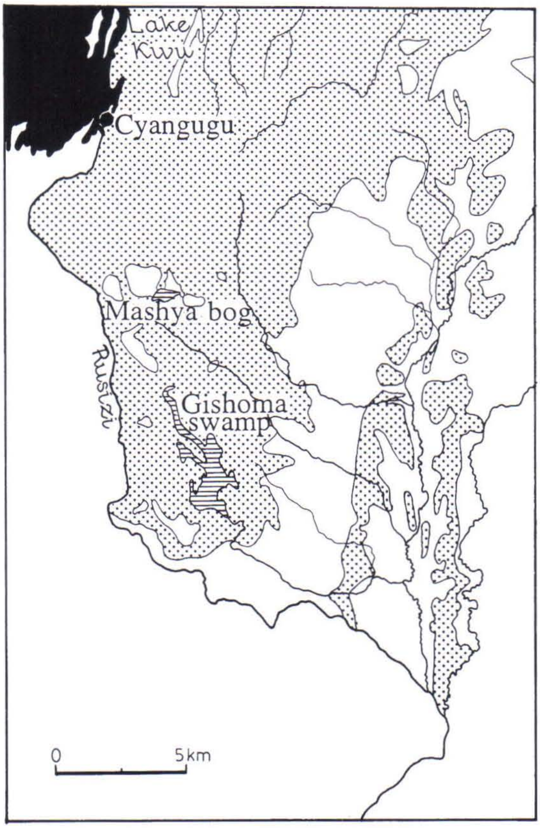


Fig. 12. The Gishoma and Mashya basins, representing the drainage basin of the Zaire, are situated in the Western rift valley. The stippling shows the distribution of Tertiary volcanites on the Rwandan side of the border (Carte Géologique du Rwanda 1991).

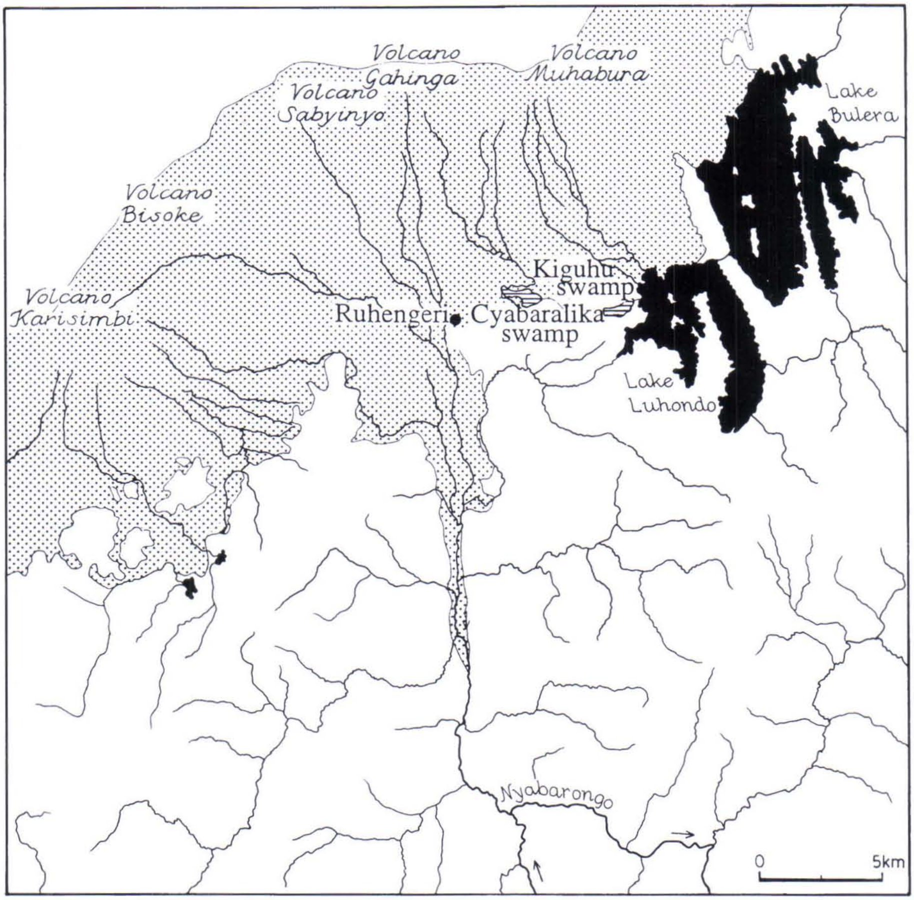


Fig. 13. Lava flows from the Quaternary volcanoes of Virunga (dot screen, Carte Géologique du Rwanda 1991) have dammed the valleys of the Precambrian area and formed basins for the swamps of Cyabaralika and Kiguhu.

29 $m^3 s^{-1}$), and smallest at the end of the dry season in August (approximately 16 $m^3 s^{-1}$, Fig. 11). On the basis of the long-term climatical changes it may be assumed that the discharge of Akanyaru increased during the early Holocene and decreased after the mid-Holocene. On the basis of the development of the Rusizi it may also be assumed that the discharge of Akanyaru increased around 1400 B.P. All changes in discharge were not, however, caused by changes in climate. The recent environmental changes caused by man have influenced both the discharge and its seasonal distribution.

The original vegetation in the western part of the drainage basin of Akanyaru was mountain rain forest. In the surroundings of the swamp area, however, the precipitation amount has been sufficient only for savannas. The original vegetation started to decrease after the beginning of the Iron Age, and today nearly all arable land is in use. The present population density around the swamp area exceeds 200 persons $km^{-2}$ (Bidou et al. 1991).

Tectonic changes and volcanism have significantly affeced the development of the landforms in the Rusizi area, west of the main drainage divide. The rock types are mainly

Tertiary volcanics (Fig. 12), aged approximately 5 - 7 million years (Pasteels et al. 1989). The Rusizi area is rainier than the Akanyaru area. The meteorological station of Kamembe is situated at a distance of 10 - 20 km from the mires studied. Its average precipitation amount is (1958 - 1989) 1430 mm $a^{-1}$ and temperature 19 - 20°C (Bulletin climatologique ... 1991). The annual precipitation amount is more evenly distributed in the Rusizi area than in the Akanyaru area. The dry season is also shorter and the autumn rain amounts significantly greater.

The swamps of Cyabaralika and Kiguhu are situated in the foreland of the Virunga volcanic chain in the drainage basin of the Nile (Fig. 13). The distance from the top of the nearest volcano to the swamps is 13 km. In the area of Precambrian bedrock the relief is strong with contrasts in elevation of 100 - 200 m. In the area of Quaternary volcanites the land slopes to the south. The average temperature of Ruhengeri is approximately 18°C and the precipitation amount about 1310 mm $a^{-1}$ (Sirven et al. 1974). Due to the greater altitude the temperatures are somewhat lower than in the areas of Akanyaru and Rusizi.

## Age determinations

The results of $^{14}C$ analyses are presented in Table 1 and discussed in connection with each mire. The description of the history is based on conventional $^{14}C$ ages. The ages range from 190 to 20 200 B.P. Most basal peat samples are from the turn of the Pleistocene and the Holocene or from the late Holocene (2500 - 1500 B.P.).

## The Buyongwe basin

The River Buyongwe is a tributary of the River Akanyaru, approximately 45 km long. It begins at an elevation of 1700 m, sloping fairly evenly to the swamp area in the lower part of the valley (Fig. 9, p.19). The swamp extends to a distance of 15 km from Akanyaru. The area of the drainage basin is approximately 370 $km^2$, some 14 $km^2$ of which is covered by swamp. No discharge information based on measurement data is available. On the basis of data concerning Akanyaru, the average discharge of Buyongwe may be estimated at approximately 5.5 $m^3 s^{-1}$.

The rock types of the drainage basin are mainly schists and phyllites, with quartzites at the northern edge (Fig. 14). Nearly flat-topped residual mountains are typical of the drainage basin. Their tops rise 200 - 300 m above the floor of the river valley. The soil consists of reddish-brown fine-grained weathering residue on the lower slopes and of coarse-grained weathering residue on the upper slopes.

During the time of study, vegetation of *Cyperus papyrus* covered most of the swamp (Fig. 15). At the most favourable sites the reeds were 4 - 5 m high, consisting almost completely of one plant species, which is typical of papyrus swamps. The biomass of papyrus swamps generally consists to more than 95 % of papyrus reed (Thompson 1976). The papyrus vegetation was especially luxuriant in the flood plain of Akanyaru, along the edges of the central channel of Buyongwe, and at the margins of the mineral soils. Beyond the papyrus zones the swamp vegetation consists mainly of smaller papyrus, other species of *Cyperus*, *Miscanthidium* grass and ferns. In some bays the dominant species of the swamps was *Cyperus latifolius*. The driest parts of the swamp were dominated by *Miscanthidium*, the basal layer of which consisted of *Sphagnum* mosses. These are the most acidic and most oligotrophic parts of the swamp (cf. Thompson 1985). The natural vegetation

Table 1. $^{14}C$ dating results. The calibrated age range is given with 1 σ (68 %) probability.

| Mire and sampling depth | Time-width* | Lab. no. | $\delta^{13}C$ | $^{14}C$ age | Cal. age range | Most prob. age |
|---|---|---|---|---|---|---|
| cm | yr | Su- | ‰ | yr B.P. | yr cal. B.P. | yr cal. B.P. |
| **Buyongwe swamp** | | | | | | |
| 500 | 60 | 948 | n. d. | 1430±150 | 1440-1200 | 1310 |
| 1000 | 80 | 949 | n. d. | 3070±150 | 3430-3050 | 3280 |
| 1500 | 140 | 950 | n. d. | 5700±160 | 6700-6330 | 6470 |
| 2000 | 160 | 951 | n. d. | 8650±120 | 9810-9490 | 9560 |
| 1970-2000 | 60 | 2375 | -28.6 | 9050±60 | 10040-9970 | 10000 |
| 2470-2500 | 100 | 2376 | -24.8 | 10120±80 | 11970-11270 | 11740 |
| 2770-2800 | 160 | 2377 | -23.1 | 11770±70 | 13820-13650 | 13730 |
| **Ndurumu swamp** | | | | | | |
| 480-500 | 40 | 2371 | -22.8 | 1410±50 | 1330-1280 | 1300 |
| 970-1000 | 60 | 2372 | -19.6 | 2060±50 | 2070-1940 | 2000 |
| 1470-1500 | 160 | 2373 | -27.9 | 4640±50 | 5400-5300 | 5350 |
| 1970-2000 | 160 | 2374 | -28.4 | 7380±50 | 8120-8090 | 8130 |
| 3250-3280 | | 1147 | n.d. | 20200±150 | ** | |
| **Rwamiko swamp** | | | | | | |
| 90-100 | 20 | 2575 | -14.3 | 230±40 | 300-270,<br>170-150 | 290 |
| 490-500 | 40 | 2576 | -24.0 | 1660±40 | 1570-1520 | 1540 |
| 1960-1980 | 100 | 2577 | -19.2 | 7720±60 | 8520-8400 | 8440 |
| **Kinamba swamp** | | | | | | |
| 480-500 | 100 | 2368 | -17.4 | 1730±50 | 1700-1560 | 1610 |
| 790-800 | 60 | 2573 | -15.8 | 5740±50 | 6630-6470 | 6510 |
| 980-1000 | 120 | 2369 | -20.4 | 6540±60 | 7440-7350 | 7400 |
| 1480-1500 | 80 | 2370 | -19.4 | 8270±60 | 9360-9190 | 9240 |
| 1665-1680 | 100 | 2574 | -17.7 | 10110±50 | 11880-11470 | 11710 |
| **Cyili swamp** | | | | | | |
| 200-210 | 40 | 2342 | -26.9 | 190±40 | 290-140 | 280,170 |
| 400-410 | 40 | 2343 | -26.8 | 950±50 | 930-780 | 910 |
| 600-615 | 40 | 2344 | -23.3 | 1370±45 | 1300-1270 | 1285 |
| 800-815 | 60 | 2345 | -18.0 | 2185±50 | 2310-2120 | 2150 |
| 900-915 | 40 | 2346 | -18.5 | 2495±50 | 2730-2460 | 2710,2610, |
| **Gishoma swamp** | | | | | | |
| Core A | | | | | | |
| 50-55 | 40 | 2281 | -21.0 | 285±55 | 430-290 | 300 |
| 150-155 | 20 | 2282 | -21.6 | 810±55 | 740-670 | 710 |
| 250-255 | 20 | 2283 | -19.6 | 1170±50 | 1160-990 | 1060 |
| 350-355 | 20 | 2284 | -16.3 | 1375±50 | 1310-1270 | 1290 |
| 417-420 | 20 | 2285 | -17.3 | 1600±50 | 1540-1410 | 1510 |
| Core B | | | | | | |
| 440-445 | 20 | 2286 | -16.4 | 1440±50 | 1350-1290 | 1320 |
| Core C | | | | | | |
| 770-774 | 20 | 2287 | -18.5 | 2000±40 | 1990-1880 | 1940 |

(Table 1 cont.)

| Mire and sampling depth | Time-width* | Lab. no. | $^{13}C$ | $^{14}C$ age | Cal. age range | Most prob. age |
|---|---|---|---|---|---|---|
| cm | yr | Su- | ‰ | yr B.P. | yr cal. B.P. | yr cal. B.P. |
| **Mashya bog** | | | | | | |
| 90-100 | 40 | 2338 | -26.0 | 510±40 | 540-510 | 530 |
| 190-200 | 40 | 2339 | -28.3 | 980±45 | 940-830 | 920 |
| 290-300 | 40 | 2340 | -27.2 | 1305±40 | 1280-1180 | 1260 |
| 400-410 | 40 | 2341 | -29.0 | 1855±40 | 1840-1720 | 1800 |
| **Cyabaralika swamp** | | | | | | |
| 90-100 | 160 | 2347 | -18.1 | 2940±40 | 3140-3020 | 3080 |
| 190-200 | 200 | 2348 | -17.5 | 4500±40 | 5240-5040 | 5110 |
| 290-300 | 160 | 2349 | -23.4 | 7150±65 | 8000-7880 | 7950 |
| 390-400 | 140 | 2350 | -20.8 | 8340±70 | 9420-9250 | 9360 |
| 520-530 | 160 | 2351 | -22.4 | 10470±70 | 12460-12280 | 12370 |
| **Kiguhu swamp** | | | | | | |
| 90-100 | 200 | 2352 | -25.4 | 9520±60 | 10580-10470 | 10510 |
| 190-200 | 100 | 2353 | -27.1 | 11680±60 | 13710-13550 | 13630 |
| 290-300 | 80 | 2354 | -26.7 | 12300±60 | 14480-14270 | 14370 |
| 390-400 | 120 | 2355 | -24.2 | 13490±70 | 16250-16050 | 16150 |

* estimates used for smoothing the calibration curve
** beyond the range of calibration dataset

has decreased markedly during the last decade, and the cultivated land now extends to Akanyaru.

## Solids and nutrients in the water

Samples Bu1 and Bu2 were collected on subsequent days from a point, where the river flows into the swamp area (Fig. 5, p.13; Table 2). The amount of suspended matter was approximately 50 mg $l^{-1}$ and the amount of dissolved matter twice that much, i.e. about 100 mg $l^{-1}$. The daily fluctuations are great especially in the amount of suspended matter due to the distribution of the rains. The occasional rains of the dry season affect the quality of the water considerably more. The concentrations of dissolved main nutrients vary only slightly.

Gisuma is the largest tributary of Buyongwe. Its drainage basin is very steep-sided. In this river the amount of suspended matter (sample Bu4) was considerably greater than in the main channel, and the amount of dissolved matter nearly as great. The concentrations of main nutrients were of the same order of magnitude.

The samples Bu3, Bu5, Bu6 and Bu10 are from small brooks descending from the sides of the valley to the swamp. Their drainage basins are small and a significant part of the water is groundwater discharging at the foot of the slopes. The amount of suspended matter was in all samples less than 50 mg $l^{-1}$.

Sample Bu7 is from the upper end of a canal dug in the central part of the swamp. The amount of suspended matter is there half the amount occurring at the same time in the main channel, which flows into the swamp (Bu1). The concentrations of calcium, magnesium and sulphur, on the other hand, are slightly higher. At the lower end of the canal (sample Bu8) the amounts of both suspended and dissolved matter are somewhat higher than at the upper end. The canal has increased the flow velocity of Buyongwe and the river has started eroding the river sediments buried in peat deposits. The turbidity of the water increases in the canal toward the lower course.

Sample Bu9 is from an old natural channel, which flows through the papyrus swamp parallel to the canal. The most marked difference between the natural channel and the canal is in the amount of suspended matter. In the natural channel the amount of suspended matter was only 1 mg $l^{-1}$, whereas in the canal it was 32 mg $l^{-1}$. The concentrations of main nutrients are, except for sulphur, higher in the natural channel than in the canal. Sample Bu11, which is from Buyongwe approximately 100 m before the river joins Akanyaru, contains only half of the amount of suspended matter compared with the lower part of the canal.

The water of Akanyaru differs from the water of Buyongwe as regards colour and concentrations of suspended and dissolved matter. The water of Akanyaru is yellowish-brown whereas in the lower part of Buyongwe it is almost clear. The sample Akan/Bu is from Akanyaru immediately upstream of the point where it is joined by Buyongwe. The content of suspended matter in Akanyaru is 18 times that of the lower part of Buyongwe. The difference regarding dissolved matter is one and a half times.

Pätilä (1985) has published data concerning the oxygen content of the water of Buyongwe. The samples are from the years 1981 and 1982, and the sites are the same as those used in this research. The oxygen content of the water of Buyongwe upstream of the swamp area (site Bu1, Fig. 5, p.13) was approximately 76 %, in the central part of the swamp area (site Bu8) 4 % and upstream of Akanyaru (site Bu11) 2 %. The oxygen content of the water

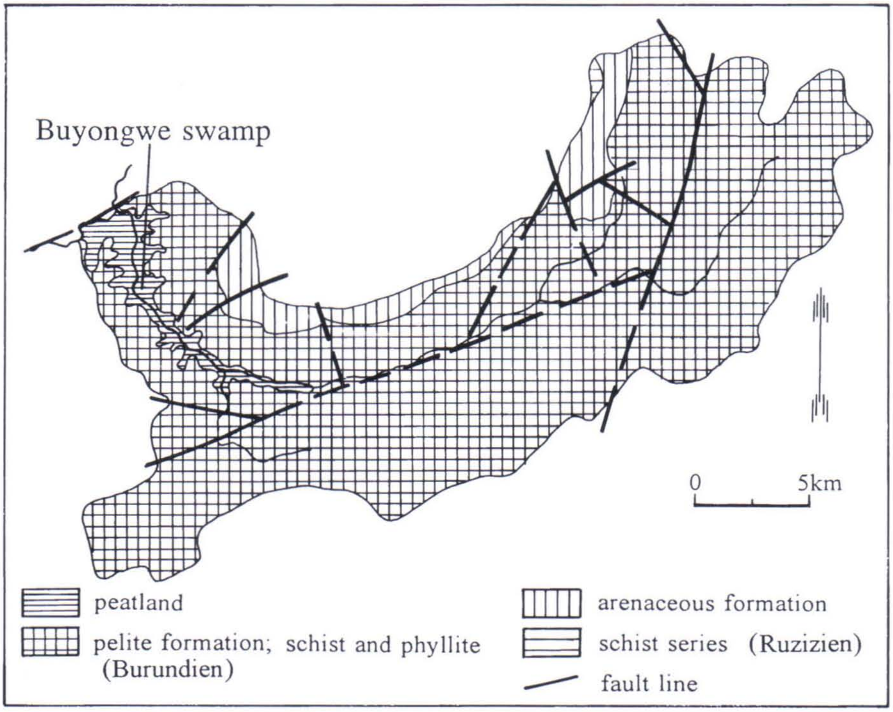


Fig. 14. Bedrock and fault lines of the Buyongwe drainage basin (Carte Géologique du Burundi 1981). The swamp covers approximately 4 % of the drainage basin.

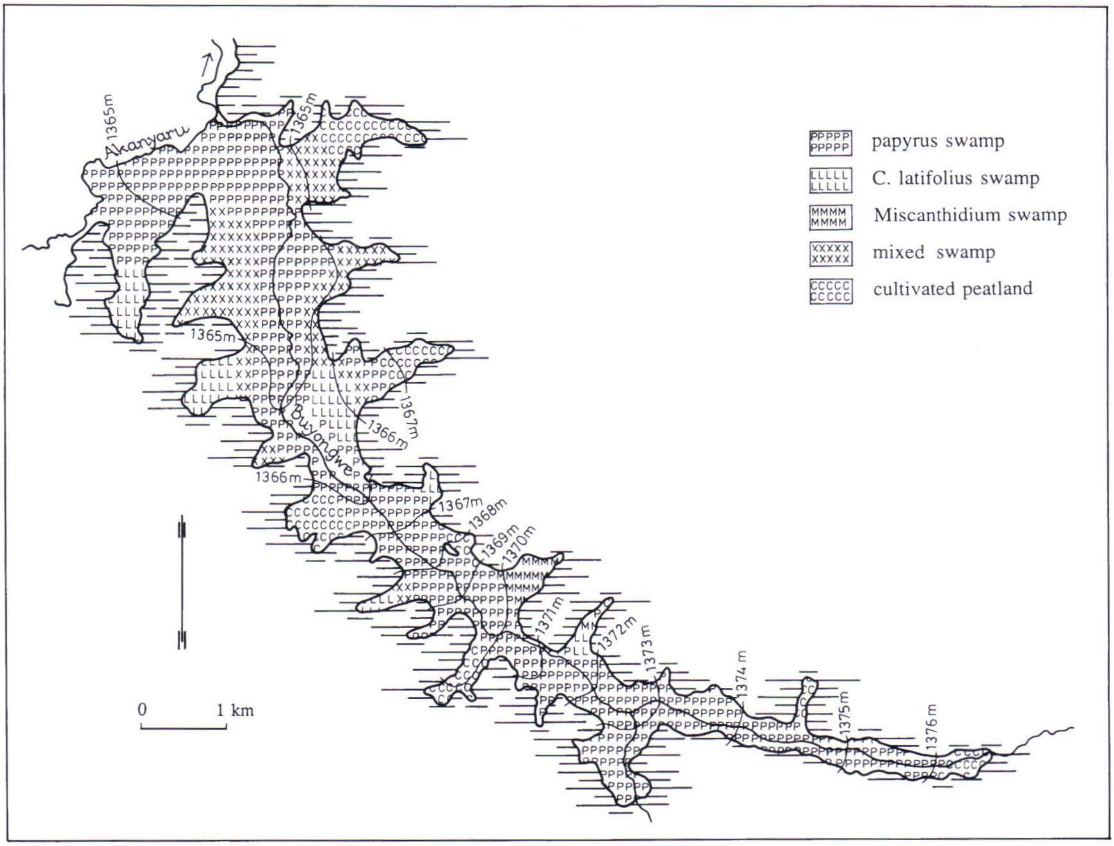


Fig. 15. Surface relief and vegetation of the Buyongwe swamp. *Cyperus papyrus*, *Cyperus latifolius* and *Miscanthidium violaceum* are the dominant plant species. The papyrus swamps are concentrated on the flood plains of the rivers and peatland cultivation in the drier bays.

of Akanyaru upstream of the point where the river is joined by Buyongwe (site Akan/Bu) was approximately 53 % and downstream of this point 40 %. The nearly oxygen-free water of Buyongwe decreases the oxygen content of the water of Akanyaru.

## Stratigraphy

The studies of the Buyongwe swamp extended to Akanyaru. Both rivers have influenced the history of the northern part of the study area (Fig. 16). The present Akanyaru deposits sand on the bottom and banks of the channel and fines farther away on the flood plain. Peat is accumulated beyond the flood plain. Akanyaru follows a winding course in the main river valley and its channel shifts gradually due to the uneven erosion of the banks. At the same time, the deposition areas of the fluvial and alluvial sediments and the areas of peat formation also shift. After the shift of the channel, peat has started to form overlying the sand and fines. Correspondingly, sand and fines has started to deposit overlying the peat along the new course of the channel. Sand beds between the peat layers show the location of ancient river channels.

The present flood plain of Akanyaru is covered by a layer of yellowish-brown fines, extending over one kilometre from the river and thinning out evenly with growing dis-

Table 2. Suspended and dissolved matter in the River Akanyaru and its tributaries.

| Sample | Date | Suspended matter | Dissolved matter | Ca | K | Mg | Na | P | S |
|---|---|---|---|---|---|---|---|---|---|
| | | mg l$^{-1}$ | mg l$^{-1}$ | mg l$^{-1}$ | mg l$^{-1}$ | mg l$^{-1}$ | mg l$^{-1}$ | mg l$^{-1}$ | mg l$^{-1}$ |
| Akan/Bu | 2.5.93 | 286 | 157 | 3.9 | <2 | 2.0 | 3.1 | 0.07 | 1.66 |
| Akan/Rw | 23.4.93 | 192 | 188 | 4.4 | 4 | 2.2 | 4.1 | 0.06 | 2.11 |
| Bu1 | 2.5.93 | 62 | 95 | 3.4 | 2 | 1.6 | 2.2 | <0.05 | 1.45 |
| Bu2 | 3.5.93 | 43 | 104 | 3.6 | <2 | 1.8 | 2.1 | <0.05 | 1.36 |
| Bu3 | 2.5.93 | 37 | | | | | | | |
| Bu4 | 3.5.93 | 108 | 84 | 2.2 | <2 | 1.5 | 1.7 | <0.05 | 1.67 |
| Bu5 | 2.5.93 | 43 | 78 | 2.3 | <2 | 0.9 | 1.4 | <0.05 | 0.98 |
| Bu6 | 2.5.93 | 8 | | | | | | | |
| Bu7 | 2.5.93 | 29 | 90 | 4.0 | <2 | 2.0 | 2.2 | <0.05 | 2.29 |
| Bu8 | 2.5.93 | 32 | 120 | 4.4 | <2 | 2.3 | 2.6 | <0.05 | 2.08 |
| Bu9 | 2.5.93 | 1 | 109 | 5.4 | 3 | 2.7 | 2.8 | 0.09 | 0.39 |
| Bu10 | 2.5.93 | 10 | | | | | | | |
| Bu11 | 2.5.93 | 16 | 94 | 4.8 | 3 | 2.5 | 2.6 | <0.05 | 1.77 |
| Rwuya | 30.4.93 | 62 | 53 | 0.9 | <2 | 0.4 | 0.7 | <0.05 | 0.33 |
| Ndurumu | 30.4.93 | 43 | 145 | 4.7 | <2 | 1.8 | 2.1 | <0.05 | 3.52 |
| Rwamiko | 23.4.93 | 51 | 168 | 3.9 | <2 | 1.3 | 8.4 | <0.05 | 0.28 |
| Kinamba | 23.4.93 | 14 | 614 | 53.8 | <2 | 17.5 | 51.8 | 0.13 | 26.0 |
| Cyili | 23.4.93 | 9 | 250 | 14.6 | 3 | 7.1 | 15.6 | 0.13 | 6.35 |

tance. Site C is located in the present flood plain of Akanyaru (Fig. 17). The floods have several times earlier reached this point, as shown by the interbedding of fines and well decomposed papyrus peat. Sections A and B represent peat deposits accumulated in a small drainage basin. The amounts of water flowing from the drainage basin have been so small that no river channel has formed on the swamp. The mineral matter eroded from the drainage basin has been deposited in a narrow rim zone. On the other hand the floods of Akanyaru have not reached the bay. For this reason the beds of fines and sand typical of the main river valley are lacking in this deposit.

At site D fluvial sediments are present from the base up to a depth of 20 m. In the upstream direction the fluvial sediments reach higher and higher in the deposit, and the continuous peat layer thins out correspondingly, as shown by sections D - G and H - h (Fig. 18). The lower part of the profiles consists of interbedded layers of sand, fines, clayey peat and peat. The location of the river channel has determined the character of the material to be deposited at any given time. In the Buyongwe valley the bays extending to the sides form small drainage basins, the history and stratigraphy of which resemble those of sites A and B.

According to classifications compiled for Finnish conditions, nearly all the peat types of the Buyongwe swamp belong in the group of sedge (*Cyperus*) peat. Wood may be an additional constituent. Under certain conditions papyrus peat, grass peat and fern peat may be identified macroscopically. Judging from the vegetation remains the vegetation zones have generally been stationary. The distribution of the vegetation on the swamp is mainly determined by the location of rivers and mineral soils. Papyrus peat has been deposited on the banks of rivers and at the margins of mineral soil areas, and other *Cyperus* and grass peat in small bays.

The most significant changes in vegetation concern the tree species. Swamp forests earlier covered nearly all bays and the more sloping central part of the swamp. The average content of bog wood at a depth of 0 - 5 m is 0.7 % and at a depth of 5 - 10 m 1.0 %. The swamp forests have disappeared from the vicinity of the channel earlier than from the margins and bays of the swamp. The decrease in wood content of the upper part of the deposit is also visible in the peat samples of the *Miscanthidium - Sphagnum* area (Table 3). In these the wood content is one fourth at a depth of 5 - 10 m, but only less than one tenth at a depth of 0 - 5 m. The peat has been formed mainly by grasses. Although *Sphagnum* moss occurs on the surface of the swamp, it does not form peat under these conditions. The 15 m long series of samples studied by Hillaire-Marcelin et al. (1989) was collected in the same area. It shows a distinct minimum of $C_4$ plants at a depth of 5 - 10 m. The scarcity of $C_4$ plants reflects indirectly the abundance of

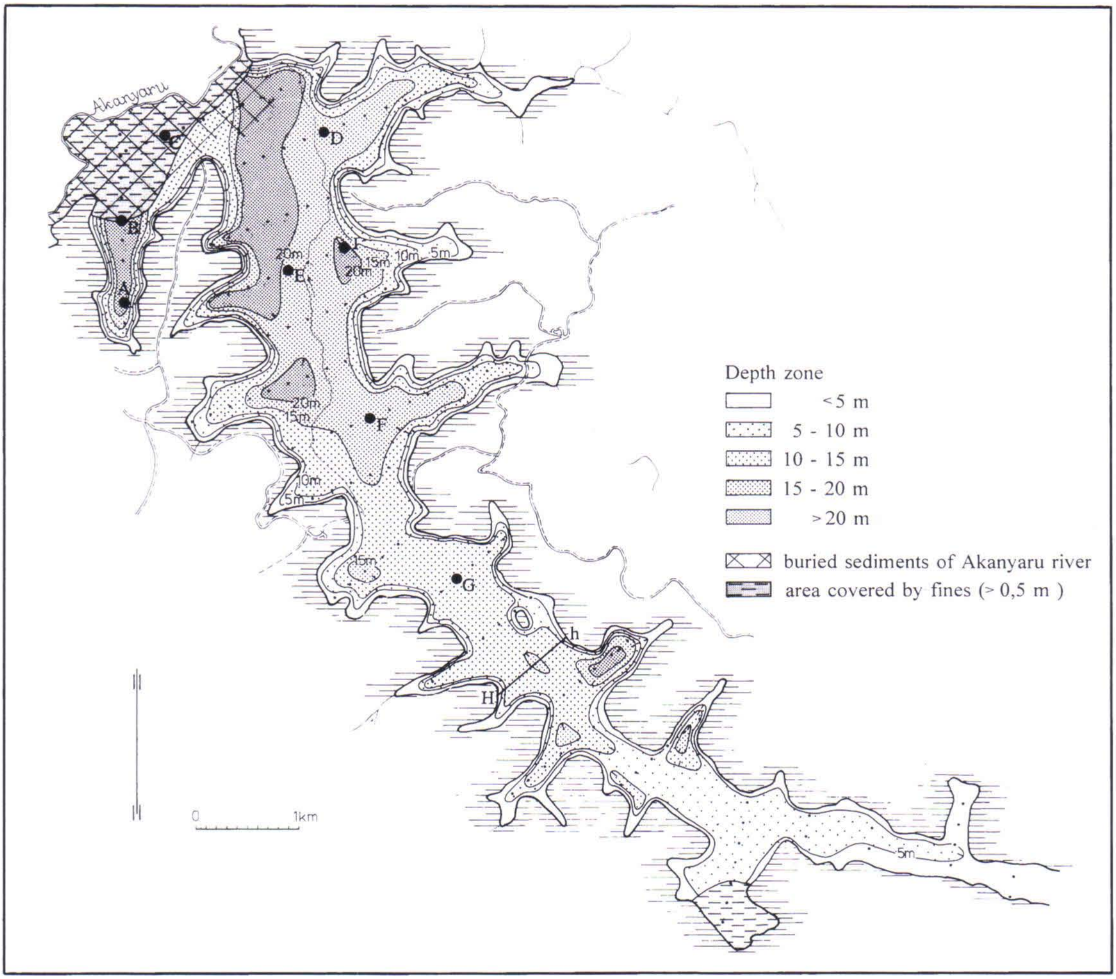


Fig. 16. Thickness of the peat layer in the Buyongwe valley. A layer of fines covers the peat on the Akanyaru flood plain in the NW corner of the area. The stratigraphic sequence of sites A - G is shown in Figure 17 and that of the line H - h in Figure 18. The samples for dating are from site I.

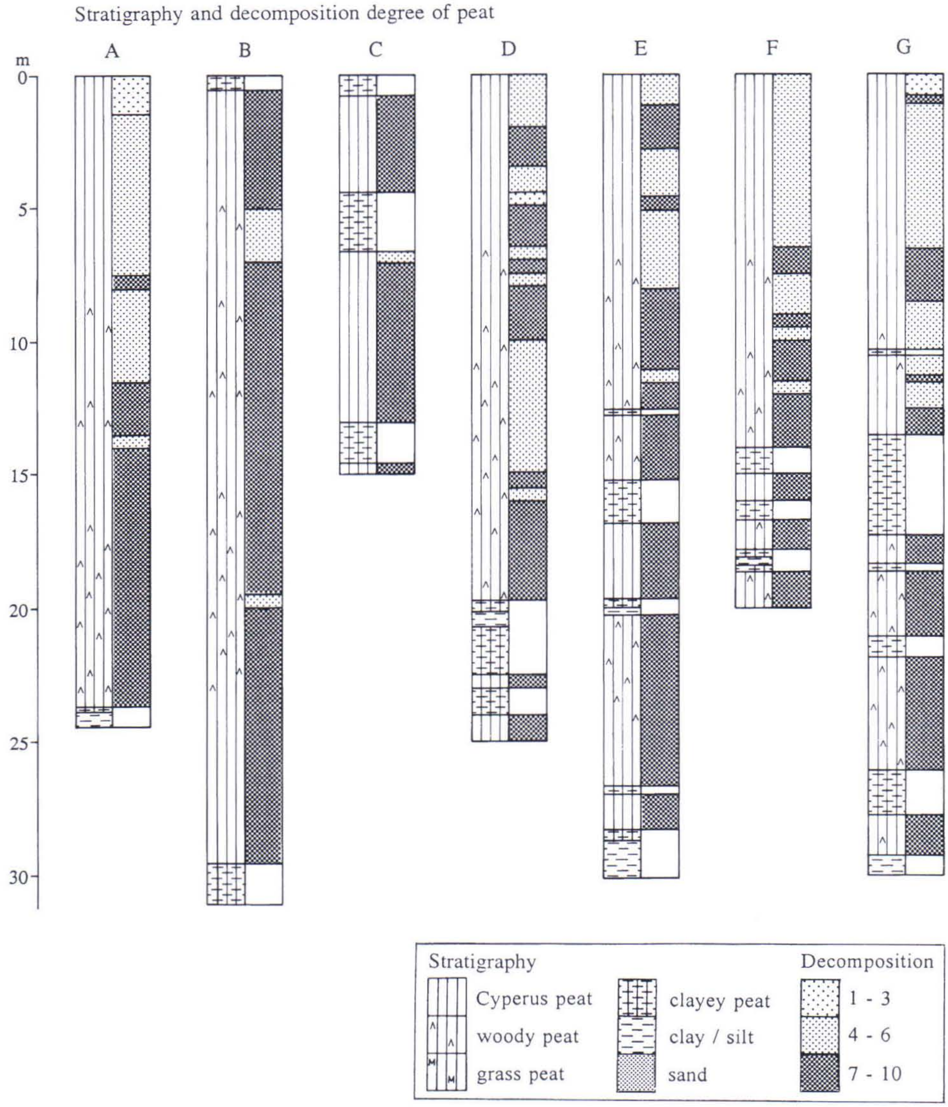


Fig. 17. Along with peat, mineral matter transported by the rivers has also been deposited on the Buyongwe swamp. The left half of the bar shows the stratigraphic sequence of the peat and mineral soils and the right half the degree of decomposition of the peat on the von Post scale. The sites are shown in Figure 16.

wood remains in the part of the deposit concerned. Woody peat beds of corresponding age have been observed in the mires of southwestern Uganda, too. Taylor (1993) stated that the *Syzygium*-dominated swamp forests rapidly became more widespread approximately 3100 B.P. and started to decrease about 1300 B.P. The bed with abundant wood at a depth of 5 - 10 m in the Buyongwe swamp accumulated 3070 - 1430 B.P., and thus the swampy forests prevailed on both mires during the same time.

The degree of decomposition of the peat increases with depth. Near the surface it is approximately 5, near the base about 8, averaging 6.7. Regional differences are most clearly distinguishable in the uppermost (0 - 5 m) layer. Its decomposition degree is 7 - 8 along Akanyaru and 4 - 5 in the small bays of the central part.

Section C (Fig. 17) represents a highly decomposed peat bed on the banks of Akanyaru. Site B is situated at the rim of the present flood plain and site A completely beyond it. The decomposition degree of the peat bed decreases with increasing distance from Akanyaru. The average decomposition degree (0 - 20 m) is 7.2 at site B and 5.9 at site A. The water level fluctuation along Akanyaru is stronger than in the small bays, promoting the

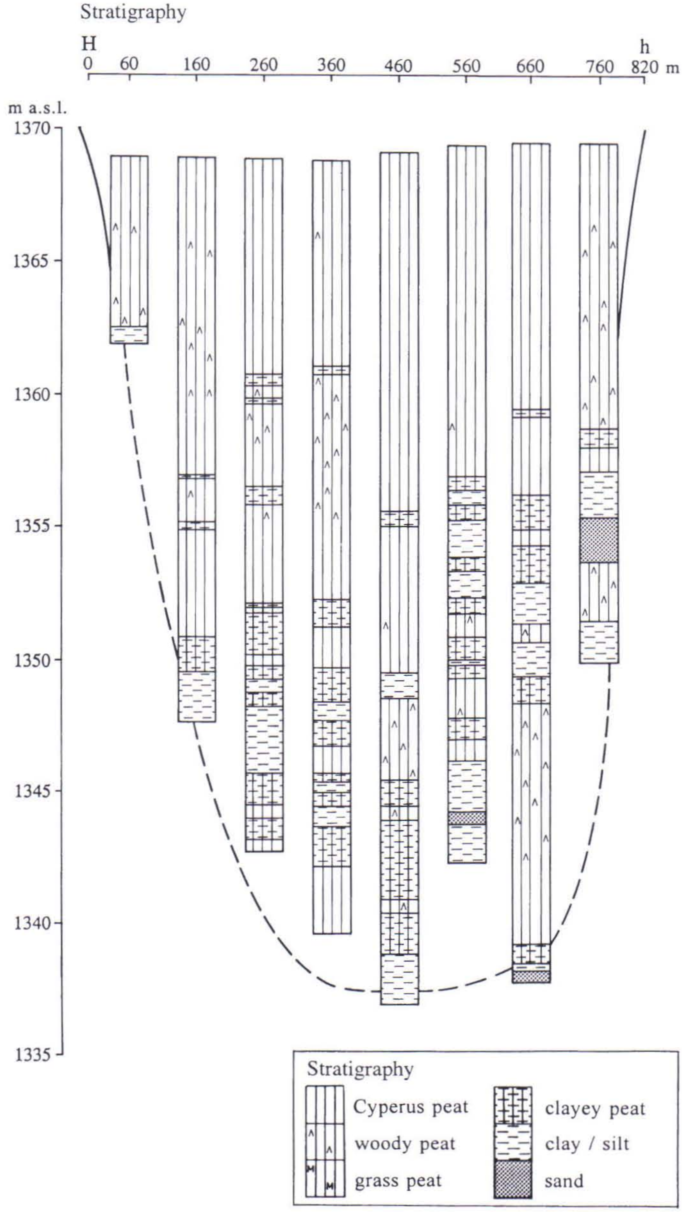


Fig. 18. Cross-section of the central part of the Buyongwe swamp showing the distribution of peat and mineral soils. The location of the section is shown in Figure 16.

Table 3. Botanical composition of peat samples collected in an area dominated by *Miscanthidium-Sphagnum* on the Buyongwe swamp.

| Depth<br>m | *Sphagnum*<br>% | *Cyperaceae*<br>% | *Graminae*<br>% | Wood<br>% |
|---|---|---|---|---|
| 2 | 1 | 13 | 81 | 5 |
| 4 |  | 5 | 87 | 8 |
| 6 | 1 | 8 | 67 | 24 |
| 8 |  | 4 | 71 | 25 |

decomposition of the peat and contributing to the differences in decomposition observed.

## Ash content of the peat

The ash content of the peat varies both vertically and horizontally, with high concentrations in the southeastern part, near the base throughout the area, and also near the surface along Akanyaru. In the northern part the lowest concentrations were found at a depth of 5 - 10 m. The average ash content of peat beds containing less than 30 % ash was 11.4 %.

Sites B and C (Fig. 19) are located on the flood plain of Akanyaru, 200 - 300 m from the channel, and sites A, D and E at the margin of the present flood plain. At all sites the ash content of the uppermost sample is extremely high. At sites D and E, high figures are obtained only at the surface and near the base, which shows that the floods of Akanyaru have not previously reached these sites. At sites A, B and C a peat layer with abundant ash occurs at a depth of approximately 3 m. Probably the river flowed temporarily near these sites at the time when this layer was formed. In the deposits at sites B and C, alluvial sediments and peat low in ash alternate.

The floods of Akanyaru have not reached sites F and G. The raised ash content in the surficial part is due to increased erosion in the drainage basin of Buyongwe. Site F is located by the channel of Buyongwe. The ash content of the peat accumulated during the early development of the swamp is high. The swamp was then considerably shorter than today and the river transported mineral matter all the way to the lower part of the valley. Great variations occur in the ash content at a depth of 12 - 18 m. In the uppermost bed to a depth of 11 m the ash content is low. At this stage the mire has spread so far towards the upper courses that almost all the mineral matter transported by the river was deposited before site F. At sites E and G the peat low in ash extends deeper than at site F. During the early history of the swamp, the River Buyongwe flowed in the central part of the valley near site F, and sites E and G were then beyond the flood plain of the river.

Sites H, I and J are located at a distance of approximately 3 km from Akanyaru. Site I is by the central channel and sites H and J at the lower end of small bays extending towards the sides (Fig. 19). The upper part (0 - 10 m) of the deposit at site I is low in ash, corresponding to that of site F. The ash content of the middle and lower parts shows strong variations due to the occasional floods of Buyongwe reaching site I. The small bays have been beyond the flood plain of Buyongwe, so that in them (sites H and J) the peat low in ash reaches deeper than in the central part of the valley (site I). The ash content of the uppermost samples in the deposit is higher in the bays than in the middle of the valley. The reason for this is the recent increase of the erosion. The mineral matter transported from the slopes of the valley is deposited mainly along the edges of the swamp.

Site K is located in the centre of the swamp at a distance of about 7 km from Akanyaru. This point is in the middle of the valley. The ash content is fairly high and greatly varied. The upper part of the deposit does not contain a layer low in ash corresponding to that of the sites downstream. The river has deposited mineral matter in the middle of the swamp up to the present day.

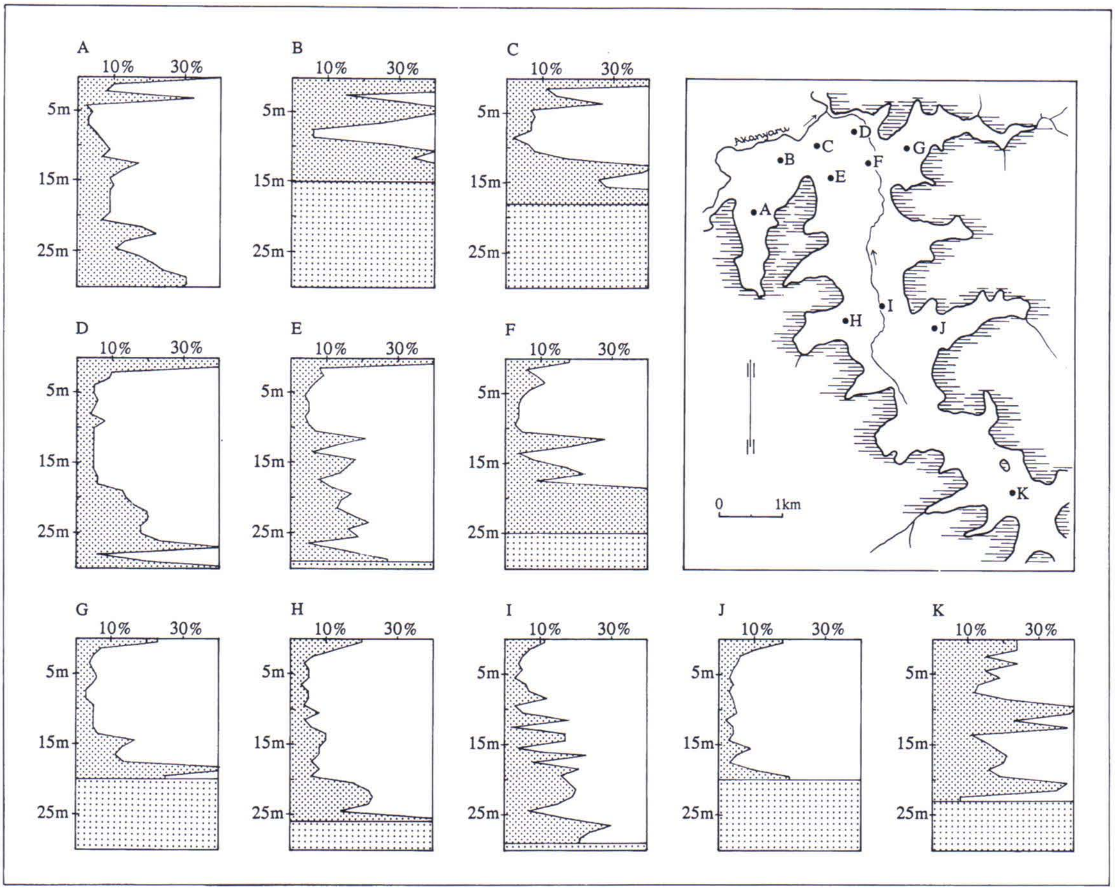


Fig. 19. Ash content of the peat in the Buyongwe swamp. The locations of the sites in relation to the river channel affect their ash content.

## Other physical and chemical properties

The average water content in the Buyongwe swamp is 90 - 92 % in the surficial part of the peat layer, decreasing with depth, so that it is 85 - 86 % at a depth of more than 20 m. The water content varies locally, too. The most waterlogged layers are those near the surface along the central channel. The average for the entire swamp is 89.9 %. The dry bulk density of the upper part of the deposit (0 - 10 m) averages 81 kg m$^{-3}$. The average net calorific value for the peat of the Buyongwe swamp is on an average 19.2 MJ kg$^{-1}$. The variation in net calorific value is inversely proportional to the variation in ash content.

In connection with the peat inventory of the Buyongwe swamp a chemical analysis was carried out on the combined samples from the northern and central parts. The results were as follows (Ekono 1983):

| | northern part | central part |
|---|---|---|
| carbon | 54.5 % | 50.2 % |
| hydrogen | 4.6 % | 4.6 % |
| oxygen | 27.4 % | 29.2 % |
| nitrogen | 1.9 % | 2.0 % |
| sulphur | 0.8 % | 1.0 % |
| ash | 10.8 % | 13.0 % |

The carbon content was higher in the northern part than in the central part due to the higher degree of decomposition and slightly lower ash content of the peat.

In order to study the vertical variation, a 16 m long series of samples was analysed from site I in the northern part of the swamp during the additional studies. The average carbon content is 57.0 %, with the highest concentrations at a depth of 4 - 13 m. The nitrogen concentration in the two uppermost samples is over 2 %, in the others 1.4 - 1.9 %. The sulphur concentration is less than 0.3 % in the uppermost layer of 5 m, and increases with depth, being 0.3 - 0.5 % at a depth of 5 - 10 m and 0.5 - 1.0 % at a depth of more than 10 m. In comparison with the results from the combined sample (Ekono 1983), the carbon content of the sample series from the northern part of the swamp is higher and the sulphur content lower.

In the sample series from site I the ash content is at its lowest at a depth of 5 m. The minimum concentrations of most of the elements also occur at the same depth (Fig. 20). The maximum concentrations of most of the main elements occur in the uppermost samples of the series. Otherwise the concentrations vary only a little with depth. The heavy metal concentrations are low in the upper part of the deposit (0 - 10 m). High concentrations occur at the depths of 11 m and 14 - 15 m, where the concentrations of copper and zinc are the most increased. In woody peat the concentrations of these metals are generally higher than in other types of peat (Kurki 1975), and so the higher concentrations in the basal part of the sample series may also reflect the increased wood content.

### Accumulation of peat

The accumulation of peat in the northern part of the swamp (site I) started approximately 12 000 B.P., and has continued since then. If it is assumed that the rate of accumulation has been even and that no decay of organic matter occurs in the anaerobic catotelm of the peat layer, the mass versus age curve becomes linear. If the rate of accumulation remains even, the decay of the organic matter in the catotelm makes the curve concave (e.g., Warner et al. 1993). An increasing accumulation rate has the same effect. A decreasing accumulation rate makes the curve convex, provided that no decay of organic matter occurs in the catotelm. In the mass versus age curve for the Buyongwe swamp (Fig. 21) there is a slightly convex section during the early Holocene and a slightly concave section after the middle of the Holocene, indicating changes in accumulation rate due to hydrological changes.

On an average, the total dry matter accumulation rate has been 201 g $m^{-2}$ $a^{-1}$ and that of carbon 104 g $m^{-2}$ $a^{-1}$ (Table 4). The rates of total dry matter and energy accumulation have been at their maximum during the early Holocene, 10 000 - 9000 B.P. In the uppermost part of the deposit, formed after 1400 B.P., the rate of total dry matter accumulation is almost as great and the organic matter and carbon accumulation rates slightly greater than in the part of the deposit formed during the early Holocene. The location in different parts of the peat deposit of the accumulation maxima of total dry matter and energy, and on the other hand of organic matter and carbon, is due to the difference between the layers in ash content, carbon content and net calorific value. The smallest accumulation rates occur in the part of the deposit formed after the mid-Holocene.

### Interpretation

Most of the mineral matter that is carried in suspension is deposited in the swamp area, and thus the content of suspended matter in the water decreases evenly except for the canal. This decrease reflects the capability of natural mires to retain mineral matter, and

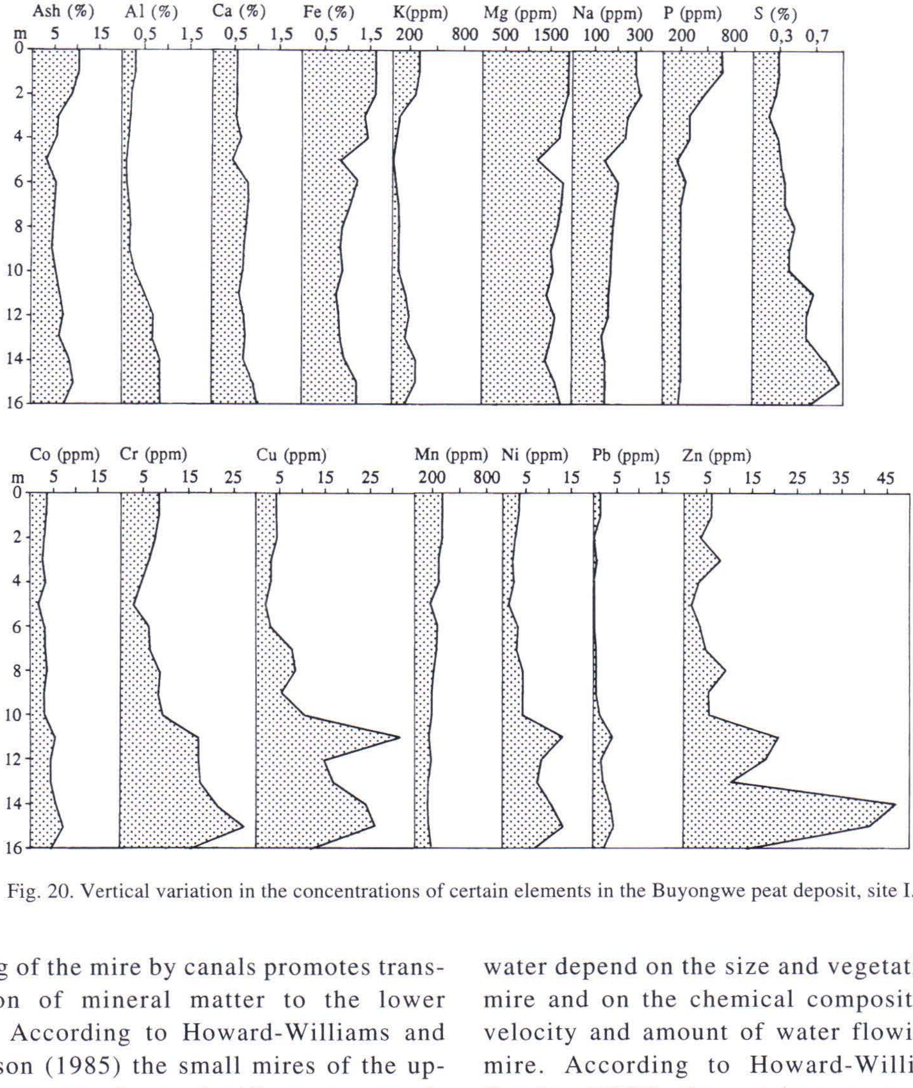


Fig. 20. Vertical variation in the concentrations of certain elements in the Buyongwe peat deposit, site I.

draining of the mire by canals promotes transportation of mineral matter to the lower course. According to Howard-Williams and Thompson (1985) the small mires of the upper courses may be as significant as regards the prevention of erosion as are the the extensive mires located at the lower courses. An effective retention of mineral matter requires that the mire be preserved in its natural state.

In general the concentrations of dissolved matter vary less from area to area than do those of suspended matter (Gregory and Walling 1973), which is also true for the Buyongwe swamp. The nutrient content of the water rises somewhat as the river flows through the swamp area. According to Thompson (1976) the changes in chemical composition of the water depend on the size and vegetation of the mire and on the chemical composition, flow velocity and amount of water flowing to the mire. According to Howard-Williams and Gaudet (1985) the nutrient content of the water flowing through the mire may rise due to the pump effect especially during periods of abundant discharge.

Due to differences in the drainage basins the water of the River Buyongwe differs from that of the River Akanyaru. The content of suspended matter in the water flowing into the Buyongwe swamp is only one fifth of the corresponding content in Akanyaru. The deposition occurring on the Buyongwe swamp causes considerably greater differences in the concentrations of suspended matter at the junction of the two rivers. Akanyaru carries the mineral matter mainly in suspension and Buyongwe in solution.

Before the initiation of peat formation, fluvial and alluvial sediments have been deposited in the lower parts of the valleys of Akanyaru and Buyongwe. Due to the continuous deposition the valley floor has risen both in the Akanyaru valley and in the lower part of the Buyongwe valley. Sand has deposited on the floor of the ancient channel, fines in the flood plain and peat beyond the flood plain. As the deposits grew thicker, the swamp area expanded both laterally and towards the upper course. The lateral extension of the mire expanded the area of peat formation, while the extension of the mire towards the upper course shifted the deposition areas of mineral matter in the same direction. Gradually these areas shifted so far that fluvial sediments were no longer transported to the lower part of the valley. From that time on, peat has been forming all over the lower part of the valley. The continuous peat deposit has reached a thickness of nearly 30 m, the thickest parts located in the northern part of the swamp and at the mouth of the small tributary bays (Fig. 16).

The peat stratigraphy shows a decrease of the swamp forests during the last one and a half millenia, which may be due to a change in climate toward greater humidity or to changes in the land use of the drainage basin. In this area the shift to the Iron Age occurred approximately 2000 B.P. (Van Grunderbeek et

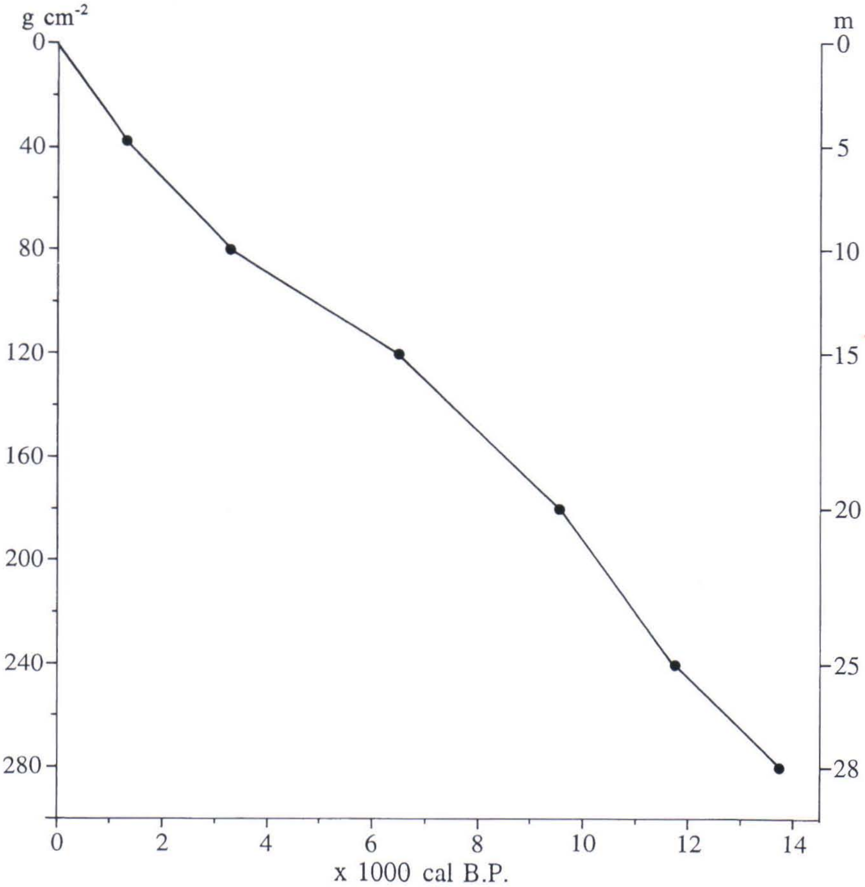


Fig. 21. Cumulative mass of total dry matter below the surface in relation to calibrated ages of the peat in the Buyongwe swamp.

Table 4. Accumulation of dry matter, carbon and energy in the Buyongwe swamp.

| Period | Thickness increment | Accumulation rates | | | | |
|---|---|---|---|---|---|---|
| | | Total dry matter | Organic matter | Mineral matter | Carbon | Energy |
| $^{14}$C yr B.P. | mm a$^{-1}$ | g m$^{-2}$ a$^{-1}$ | g m$^{-2}$ a$^{-1}$ | g m$^{-2}$ a$^{-1}$ | g m$^{-2}$ a$^{-1}$ | MJ m$^{-2}$ a$^{-1}$ |
| 1430 - 0 | 3.82 | 298 | 272 | 26 | 166 | 5.5 |
| 3070 - 1430 | 2.54 | 208 | 198 | 10 | 121 | 4.0 |
| 5700 - 3070 | 1.57 | 127 | 113 | 14 | 69 | 2.8 |
| 8650 - 5700 | 1.62 | 189 | 147 | 42 | 90 | 3.8 |
| 10120 - 9050 | 2.87 | 359 | 267 | 92 | 163 | 6.3 |
| 11770 - 10120 | 1.51 | 189 | 154 | 35 | 94 | 3.3 |
| 11770 - 0 | 2.03 | 201 | 171 | 30 | 104 | 3.9 |

al. 1983), whereafter the influence of man on the environment increased. According to Taylor (1993) the felling of the forests in the drainage basin is especially clearly distinguishable after 800 B.P. It may be related to the spreading of the nomad culture brought to the area by the Tutsis (Hamilton et al. 1989). The decrease of natural vegetation in the drainage basin has increased the discharge and the wateriness of the mires. Because of the varied soil types the settlement is concentrated on the lower slopes near the swamp. Bays have been taken into agricultural use and the trees growing at the edges of the swamp have been cut for firewood.

The present flood plain of Akanyaru is covered by a yellowish-brown layer of fines. Corresponding extensive layers are not present deeper in the deposit, and thus its formation reflects exceptional conditions in the drainage basin of the river. The decrease in mountain rain forests and the spreading of the agricultural areas are the most significant environmental changes of the last few centuries in the drainage basin of Akanyaru. The decrease in forests has been found to increase both discharges and deposition of sediments (Gregory and Walling 1973).

The accumulation maximum of peat occurred approximately 10 000 - 9000 B.P. During that period the climate became more humid and the water levels of the lakes rose rapidly. The increasing discharge of Akanyaru and Buyongwe expanded the flood plains and created ideal conditions for the accumulation of peat. The production of biomass was abundant, since due to the small size of the swamp the rim effect reached all the way to the site.

The rates of accumulation of peat were at their minimum directly after the middle of the Holocene, increasing again after 3000 B.P. The accumulation maximum and minimum of the Buyongwe swamp correlate well with the climatic changes in the area during the Holocene. The increasing accumulation values of the uppermost peat layer may be influenced by both climatical and non-climatical factors. The accumulation of peat may have been promoted both by the increased wateriness of the swamp and by the expansion of papyrus swamps into former swamp forest areas.

Gorham (1991) has obtained an average accumulation of 13.3 g cm$^{-2}$ for carbon in the peat deposits of the high latitudes. The corresponding accumulation for the northern part of the Buyongwe swamp is more than ten times that figure.

## The Ndurumu basin

The drainage basin of Ndurumu occupies an area of approximately 160 km$^2$, about 11 km$^2$ of which is covered by swamp. The rock types of the drainage basin are mainly schists and granites. The area upstream of the swamp is surrounded by quartzite mountains (Fig. 22). The surrounding mountains rise 200 - 300 m above the valley floor, while the relative altitudinal differences in the central part of the basin are approximately 100 m.

The River Ndurumu begins at an altitude of approximately 1700 m on the drainage divide toward Buyongwe. The channel descends regularly to 1440 m (Fig. 9, p.19). During the next kilometre it penetrates a quartzite ridge and falls to the swamp area at the 1370 m level. The river flows in the swamp area for about 7 km before joining Akanyaru. The average discharge of Ndurumu into the swamp area is about 2 m$^3$ s$^{-1}$.

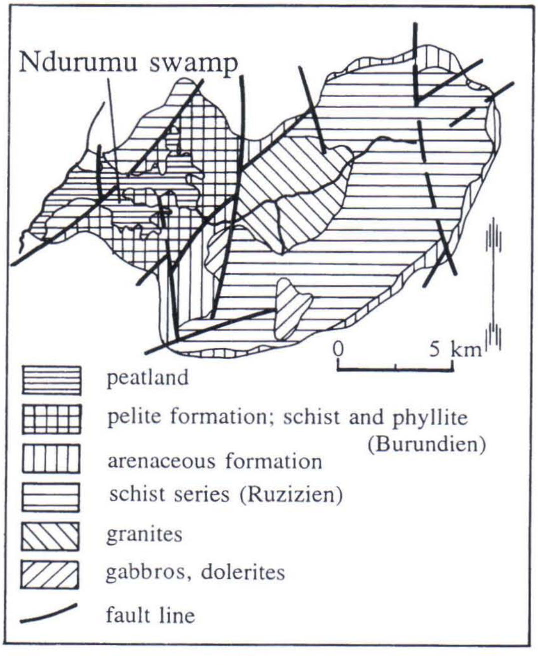


Fig. 22. Lithology and fault lines of the Ndurumu drainage basin (Carte Géologique du Burundi 1981). The swamp covers approximately 7 % of the drainage basin.

The ridge of Nyamurenge divides the swamp area in two hydrologically separate areas. The waters of Ndurumu flow through the northern one. Several brooks discharge into the southern area, the biggest one of them the steeply sloping Rwuya, which begins on the slopes of Nyamugari (Fig. 9, p. 19). Its drainage basin is small and the rock types mainly quartzite. The nutrient content of Rwuya is considerably lower than that of the water of Ndurumu (Table 2, p. 28).

During the time of study, the *C. papyrus* vegetation was dominant along Ndurumu (Fig. 23). Fern swamps were encountered beyond the papyrus zone. The most sloping area was covered by swamp forests. Swamps formed by *Cyperus* species, *Miscanthidium* grass and ferns occur on the gently sloping areas in the southern and northeastern parts. The Akanyaru valley was dominated by a thick vegetation of papyrus.

### Stratigraphy

The Ndurumu swamp may be divided stratigraphically into three parts of different character, which are the northern basin, the southern basin and the western basin, which is bordered by Akanyaru (Fig. 24). These differ from each other regarding the thickness and structure of the peat deposit.

The development of the northern part has been influenced by Ndurumu, which flows through the swamp area. The lowermost beds consist of fluvial and alluvial sediments, alternating with peat beds. Upward the proportion of river sediments decreases while the proportion of peat increases. Survey sites A, B, C and D (Fig. 25) represent the middle and upper part of the deposit. Sites A, B and D are located in the central part of the valley. From these toward the lower courses the thickness of the peat increases. Site C is located beyond the flood plain of Ndurumu. Its stratigraphy reflects a peat bed formed in a small drainage basin. The proportion of fluvial sediments is smaller and the decomposition degree of the peat is lower than by the channel.

Rwuya, the biggest brook that discharges into the southern basin, does not form a channel in the swamp area, and so the material eroded from the mineral soils is deposited in a narrow rim zone. Fluvial sediments between peat beds occur only near the base and in the upper part of the valley. The continuous peat deposit is at its maximum more than 30 m thick (survey sites G and H, Fig. 25). In the southeastern part of the valley there is a less than a metre thick layer of clay and clayey peat at a depth of approximately 17 - 18 m (I, Fig. 25).

Akanyaru has influenced the development of the western part of the swamp. The stratigraphy of the deposit is similar to that of northwestern Buyongwe. The thickness of the continuous peat bed is varied, from a few metres to nearly 30 m. The present flood plain of Akanyaru is also in the area of Ndurumu covered by a yellowish-brown layer of fines, which thins out with growing distance from the river (Fig. 26). At present the flood plain of Akanyaru extends to approximately 450 m from the channel, but earlier it was considerably narrower. At site 445 m a thick sand bed, indicating the location of an ancient channel, has been found. At adjacent sites peat has been forming at the same time, and thus the flood plain at that time extended less than 200 m from the channel.

Papyrus peat has formed in areas within the

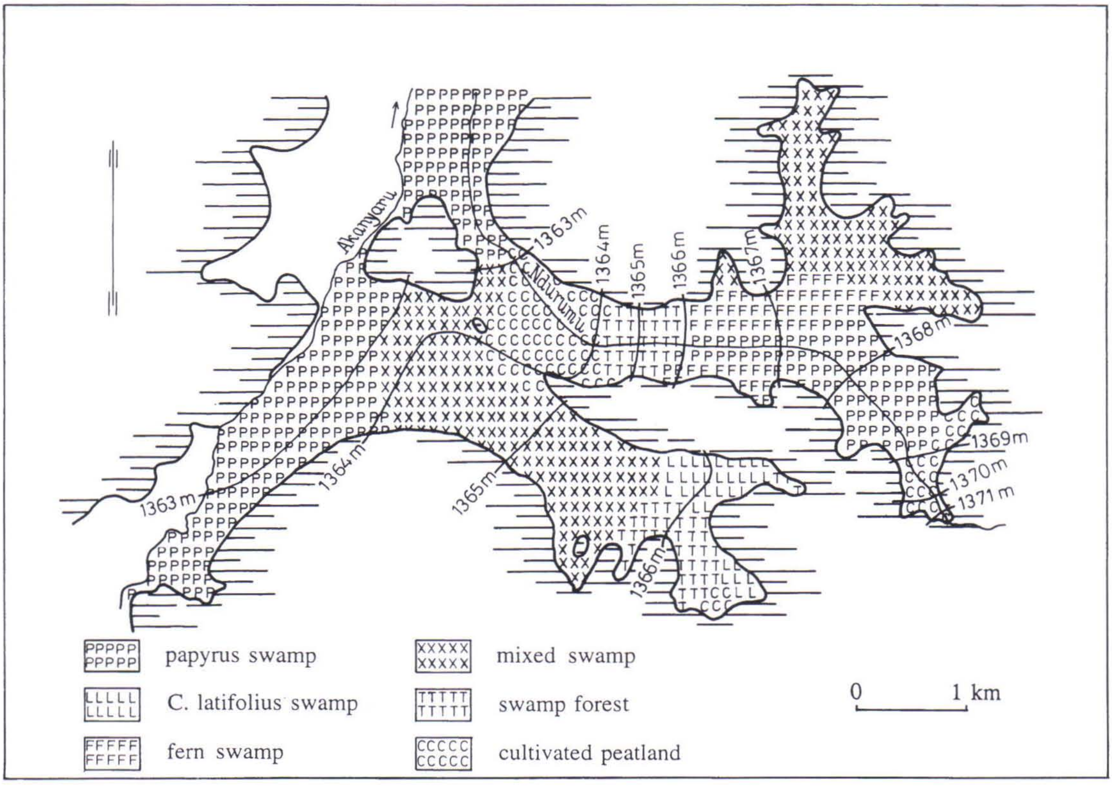


Fig. 23. Surface relief and vegetation of the Ndurumu swamp. Papyrus grows mainly on the flooded areas by the rivers. *C. latifolius* swamps and mixed swamps occur in the flattest areas, and swamp forests in more sloping areas.

range of influence of the rivers, and grass peat, fern peat and peat containing several constituents beyond them. The most significant changes have occurred in the distribution of swamp forests. During the time of study, forest was growing only in the steepest areas of the northern part. Drilled samples show that trees have been growing over nearly the whole swamp at some stage. On the basis of the number of observations it is, however, difficult to conclude whether single trees or swamp forests proper have been growing in this area.

The peat bed north of Nyamurenge (B, Fig. 25), contains remains of wood from the base up to the surface. In the eastern part of the basin the woody peat is overlain by a little less than 10 m of *Cyperus* peat (C and D, Fig. 25). The middle of the southern basin is occupied mainly by *Cyperus* peat and grass peat (F, G and H, Fig. 25). At a depth of 15 - 25 m woody peat occurs, again overlain by *Cyperus* peat and grass peat. The uppermost bed of *Cyperus* and grass peat thins out towards the margins of the basin. At the margins remains of wood occur nearly throughout, from the base to the surface. The lowest $\delta^{13}C$ values (approx. -28 ‰) of the samples for dating from the southern basin were obtained from the depths of 15 and 20 m. They support the drilling observations and show that the peat was formed from $C_3$ plants, mainly from trees. In the western part, which borders on Akanyaru, remains of trees occur especially at the margins of mineral soils.

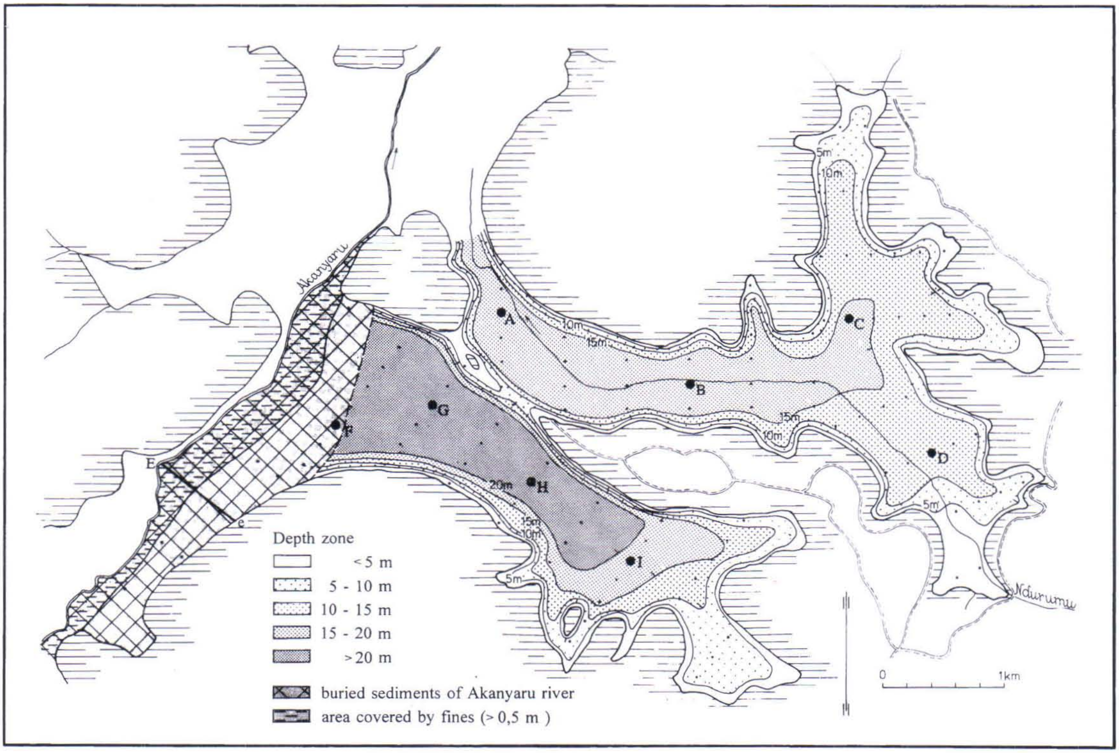


Fig. 24. Thickness of the peat deposit in the Ndurumu swamp. The development of the northern basin was affected by the River Ndurumu and that of the western basin by the River Akanyaru. The southern basin was beyond the direct influence of the rivers. The northern and the southern basins were separated by a central isthmus until approximately 2000 B.P. The stratigraphic sequence of sites A - I is shown in Figure 25 and that of the line E - e in Figure 26.

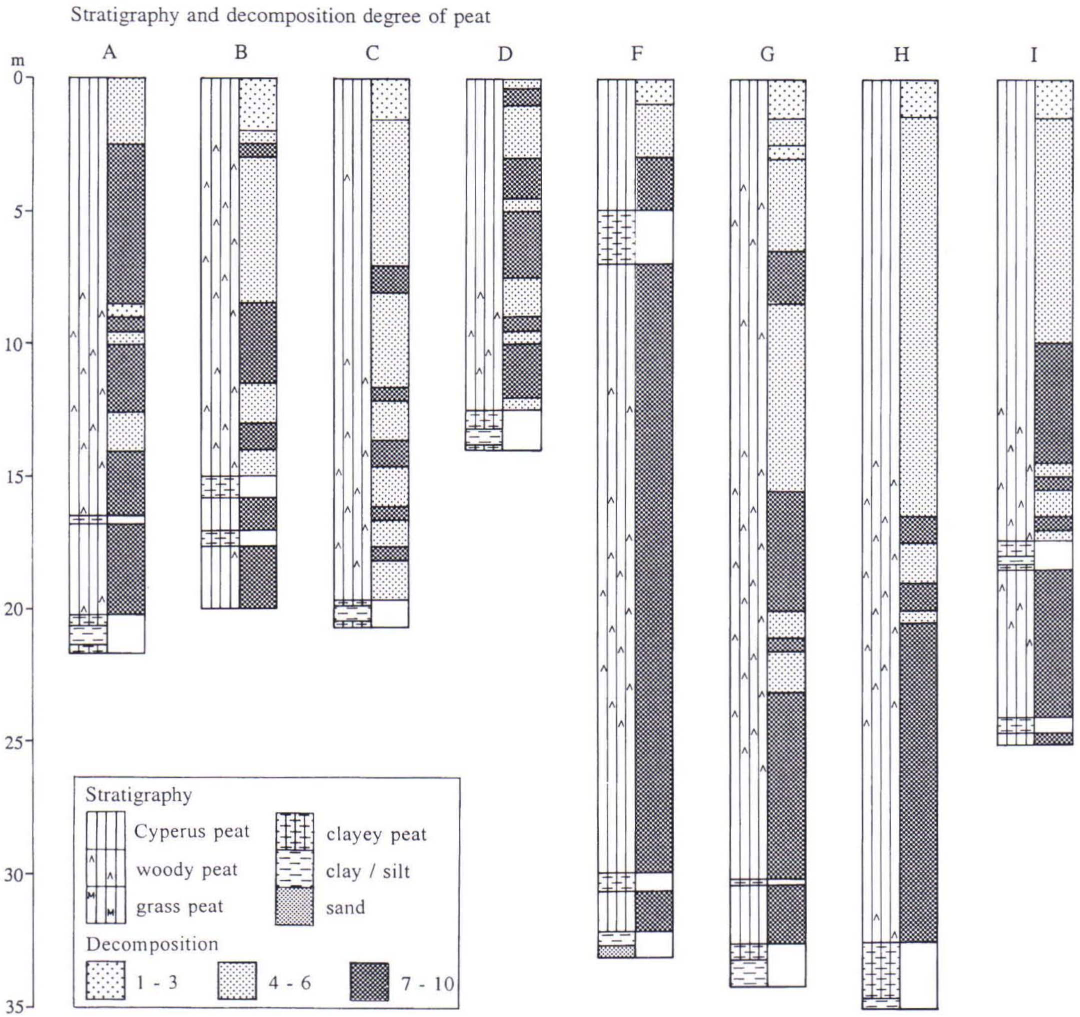


Fig. 25. Distinct stratigraphic differences exist between the various parts of the Ndurumu swamp. Sites A, B, C and D represent the northern part, F the western part and G, H and I the southern part. Their locations are shown in Figure 24.

The average decomposition degree of the peat is 6.2. It increases with depth, so that near the surface (0 - 5 m) it is 5.2 and near the base (25 - 30 m) 8.0. The decomposition does not, however, increase evenly, but well decomposed beds (7 - 10) alternate with moderately decomposed beds (4 - 6) (Fig. 25). Weakly decomposed peat (1 - 3) is generally found only at the surface. Decomposition horizons extending into vast areas have not been found. Since the sites (Fig. 6, p.14) are located at a distance of 200 m apart, the continuity of the various beds could not be verified.

The degree of decomposition increases in the northern basin towards the lower course (A - C, Fig. 25). The upper part of the swamp area (D) also contains well decomposed peat. In the southern basin (G, H) the moderately decomposed peat extends to a depth of approximately 15 m. The peat of the basal part is well decomposed. Within the range of influence of Akanyaru (F, Fig. 25 and E-e, Fig. 26) the well decomposed peat extends from the surface down to the base.

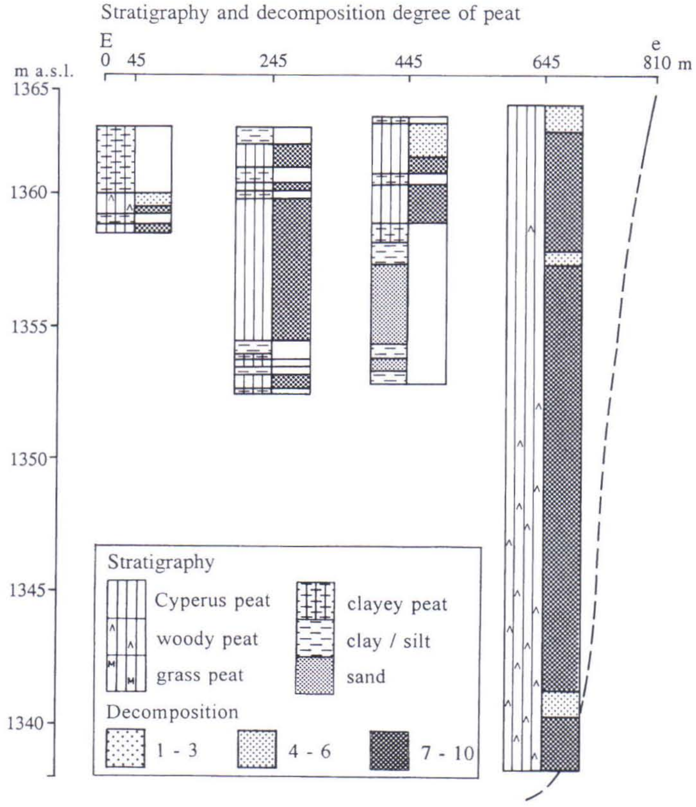


Fig. 26. The River Akanyaru has affected the development of the western part of the Ndurumu swamp. The proportion of peat in the deposit increases with distance from the river. The site at 645 m has always been beyond the area of deposition of river sediments, and no mineral matter from the slopes has been washed that far. The location of the line E - e is shown in Figure 24.

## Ash content of the peat

The ash content of the peat bed containing less than 30 % ash is 11.3 %, i.e. the same order of magnitude as in the Buyongwe swamp. The differences between samples are great. The location in relation to the rivers causes local variations, so that the ash content equals the average of the swamp in the northern basin, is below average in the southern basin and higher than average in the western part.

The mineral matter deposited by Ndurumu has raised the ash content of the northern basin during the early stages of the history of the swamp (Fig. 27, A - E). Sites A, B and C are in the middle of the basin. The effect of the floods of Ndurumu is distinguishable at site A to a depth of 10 m. The ash content in the basal part is fairly high and strongly varied, whereas the content in the upper part is low except for the uppermost sample. The decay of organic matter, accelerated by agriculture, has increased the ash content of the surficial layer. The increasing effect of Ndurumu on the ash content has ceased earlier at sites B and C, although they are located upstream of site A. The flood plain of Ndurumu has been narrow and sites B and C have been located farther from the ancient channel than site A. Site D is located at the mouth of a bay towards the northeast beyond the range of influence of Ndurumu, and site E in the Ndurumu valley towards the east. The effect of material transported from mineral soil areas is observable at site D up to a depth of 15 m and at site E up to the surface.

Site F is located in the Akanyaru valley close to the Burundian edge of the swamp. The present Akanyaru flows near the opposite side of the swamp. The effect of the floods of Akanyaru is most pronounced in the uppermost sample, which has the maximum ash

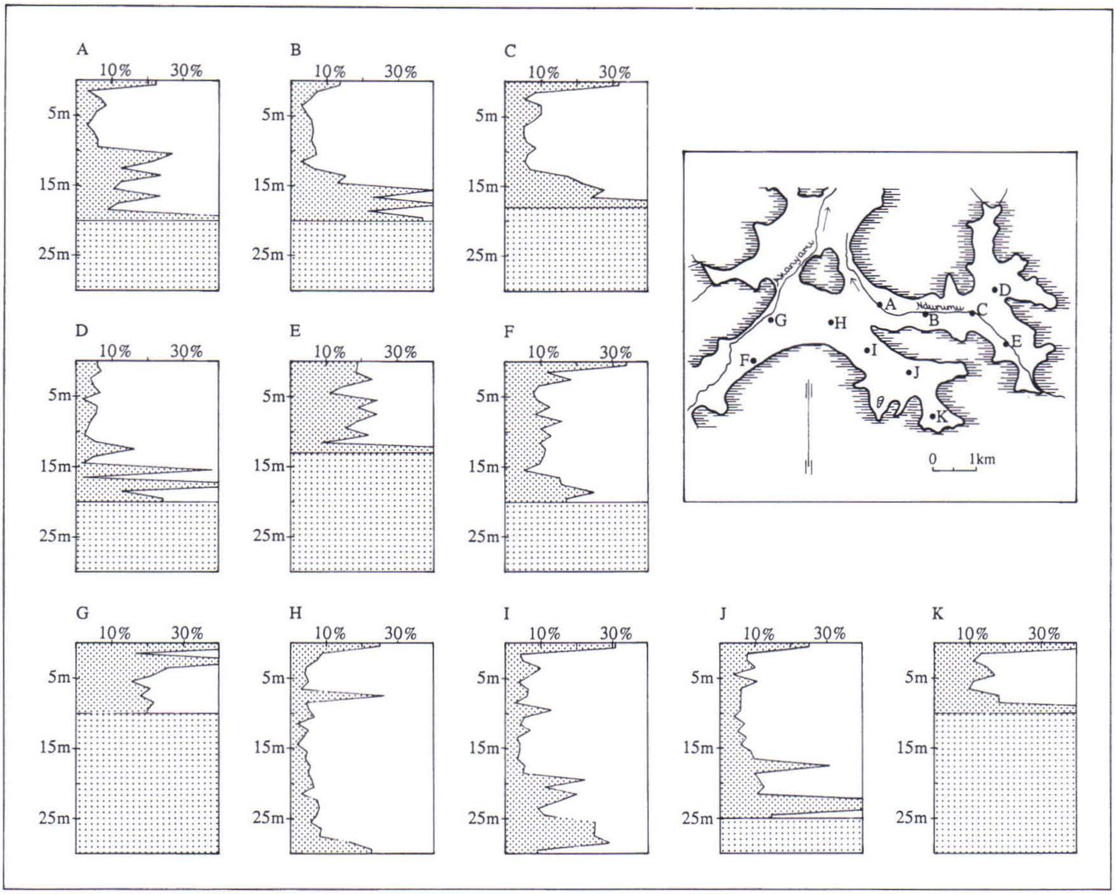


Fig. 27. Ash content in the Ndurumu swamp. The figures are higher in the northern basin due to the mineral matter deposited by the River Ndurumu.

content of the 20 m deep sample series. The river can never have been farther away, and thus the rapid deposition of mineral matter during recent times is unique in the history of the swamp.

The ash content of the surficial part is exceptionally high at site G, which is located approximately 150 m from Akanyaru. At a depth of 5 - 10 m the ash content is about 20 %, and from greater depths results are lacking due to layers of sand and fines.

Sites H, I and J are located in the southern basin beyond reach of the floods of Akanyaru. In the main part of the deposit the ash content is about 5 %. The high content in the surficial samples is probably caused by the increased erosion within the drainage basin. In the field determinations the clay layer found at site J increases the ash content of the sample taken from a depth of 17 - 18 m. Thin bands of clay were encountered somewhat deeper (19 - 20 m) at site I, and they are probably part of the same flood deposit. The ash content figures of site K indicate the increase of erosion during recent times in the drainage basin. The figures are low considering the location of this site. Rwuya, which discharges into the same bay, transports considerably less mineral matter to the swamp than does Ndurumu.

## Other physical properties of the peat

The water content of the Ndurumu peat deposit is fairly high, and the average of the whole swamp is 92.0 %. The water content is somewhat lower than average in the northern basin, in the southern basin higher than average and in the western part near average. The differences between samples are great. The average water content decreases gradually with depth.

The watery peat extends to the base in the middle of the southern basin, and although the water content decreases with depth, it is still 91 - 92 % at a depth of 25 - 30 m. The basal part has not been compacted to such a degree as in the northern basin, in the western part of the swamp or in the Buyongwe swamp. The most significant difference between the southern basin and the other areas is the small amount of fluvial and alluvial sediments. The river sediments interlayered with the peat probably increase the compaction of the basal part.

The average net calorific value is 19.2 MJ kg$^{-1}$. The ash content influences the variation of the calorific value both horizontally and vertically. The highest net calorific values were obtained for the deposits at a depth of 10 - 15 m in the southern basin.

## Accumulation of peat

Peat has been accumulating in the southern basin of Ndurumu for 20 000 years. Judging from the peat stratigraphy the accumulation has been uninterrupted. The curve depicting the mass versus age of the dry matter is nearly straight to 2000 cal. (calibrated age) B.P. (Fig. 28). Concluding from this the accumulation has been regular and either the decay of organic matter in the catotelm has been nearly

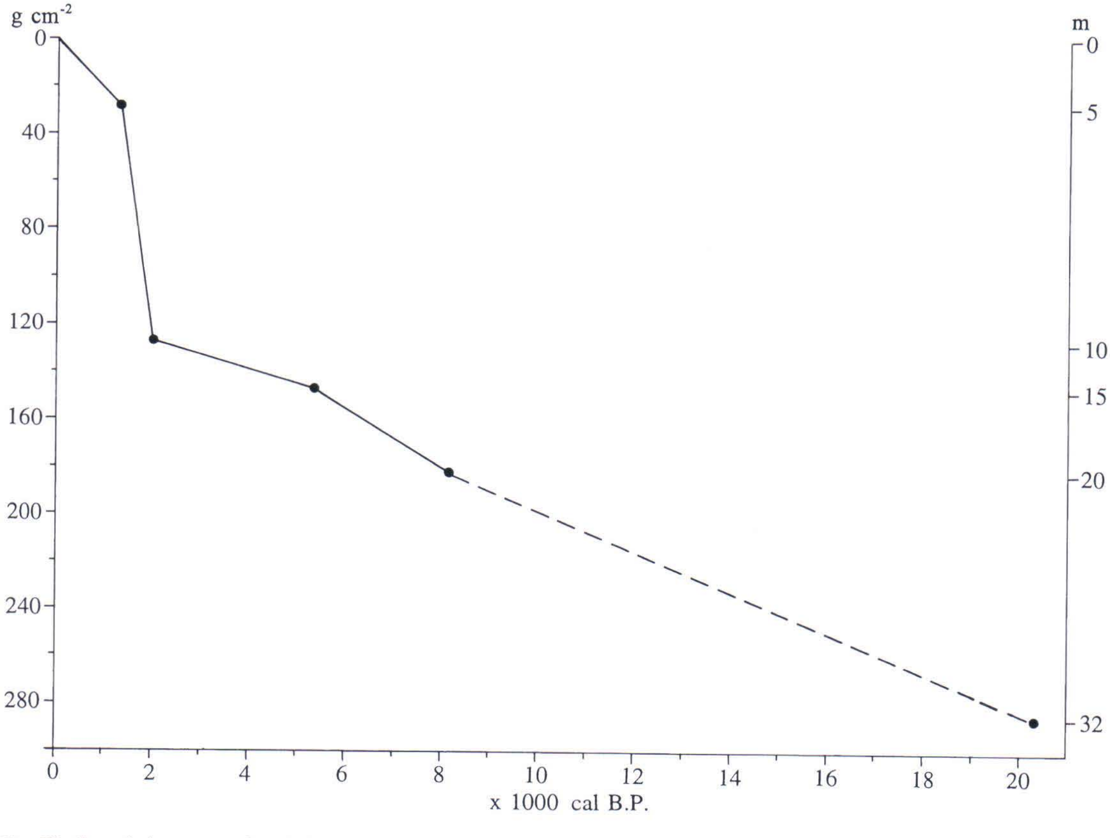


Fig. 28. Cumulative mass of total dry matter below the surface in relation to calibrated ages at site G on the Ndurumu swamp. The lowermost sample was beyond the range of calibration.

Table 5. Accumulation of dry matter, carbon and energy in the Ndurumu swamp.

| Period | Thickness increment | Accumulation rates | | | | |
|---|---|---|---|---|---|---|
| | | Total dry matter | Organic matter | Mineral matter | Carbon | Energy |
| $^{14}$C yr B.P. | mm a$^{-1}$ | g m$^{-2}$ a$^{-1}$ | g m$^{-2}$ a$^{-1}$ | g m$^{-2}$ a$^{-1}$ | g m$^{-2}$ a$^{-1}$ | MJ m$^{-2}$ a$^{-1}$ |
| 1410 - 0 | 3.77 | 219 | 197 | 22 | 113 | 4.1 |
| 2060 - 1410 | 7.07 | 502 | 458 | 44 | 259 | 10.0 |
| 4640 - 2060 | 1.49 | 58 | 56 | 2 | 30 | 1.3 |
| 7380 - 4640 | 1.80 | 128 | 122 | 6 | 66 | 2.8 |
| 20200 - 7380 | 1.06* | 85* | 75* | 10* | 44* | 1.7* |
| 7380 - 0 | 2.53 | 152 | 142 | 10 | 78 | 3.2 |
| 20200 - 0 | 1.62* | 108* | 99* | 9* | 56* | 2.2* |

* lower end not calibrated

negligible or the increasing accumulation rate has compensated for the cumulative decay in the catotelm. The mass versus age curve grows steeper after 2000 cal. B.P. due to the marked increase in accumulation rate. As a whole the mass versus age curve is concave. However, the change that occurred 2000 cal. B.P. is so abrupt that decay in the catotelm cannot be the only cause of the shape of the curve. The hydrological conditions of the swamp have become more favourable for the accumulation of peat after 2000 cal. B.P.

On the average, the total dry matter accumulation rate has been 108 g m$^{-2}$ a$^{-1}$, that of carbon 56 g m$^{-2}$ a$^{-1}$ and that of energy 2.2 MJ m$^{-2}$ a$^{-1}$ (Table 5). Since the lowermost sample could not be calibrated, the figures obtained for the lowermost layer are not completely comparable with those of the other layers. In any case the accumulation rates of layers formed during different time periods are considerably varied. At their maximum the differences are nearly tenfold.

## Interpretation

The different stratigraphies in the three ba-

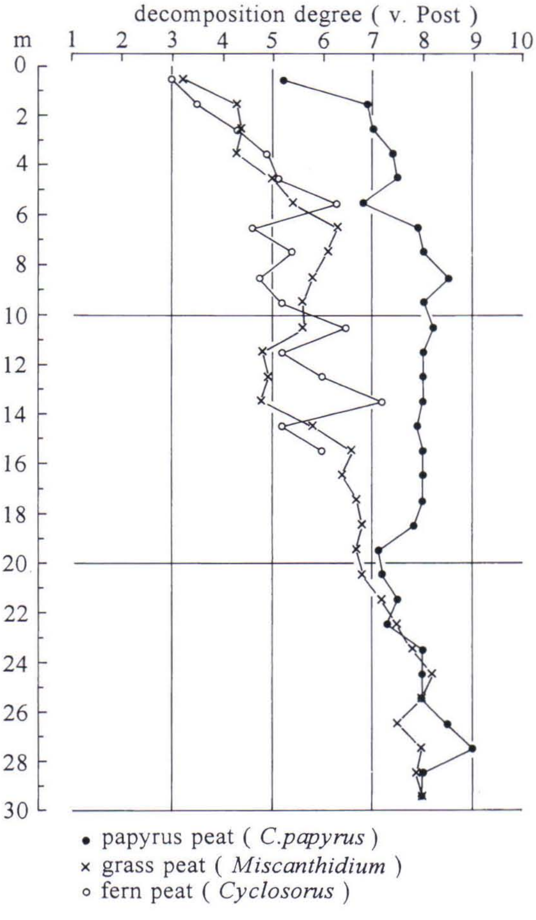


Fig. 29. Since papyrus grows in areas where the decay of plant matter is fastest, the degree of decomposition of papyrus peat is higher than that of grass peat or fern peat. This difference is distinguishable to a depth of 20 m.

sins of Ndurumu depends mainly on the different capability of the rivers to carry mineral matter and on differences in nutrient content of the water. The latter largely determines the dominant vegetation, while the nutrient content and the water level fluctuations together influence the decomposition of the peat. The papyrus peat forming in the flood plains of the rivers is considerably better decomposed than is the grass or fern peat forming beyond the flood plains (Fig. 29). The differences in decomposition degree are distinguishable to a depth of 20 m. The areas favourable to papyrus growth are also favourable to decay organisms.

The long intervals between samples in the basal part make it difficult to study the history of the peat accumulation. The lowermost bed of 12 m comprises the main part of the history of the swamp, including the dryness maximum during the last glacial stage 15 000 - 12 500 B.P. as well as the postglacial humidity maximum 9000 - 7000 B.P. (Street and Grove 1979). It is very probable that the lowermost bed in the Ndurumu swamp contains considerable variations in accumulation rate. If it is assumed that the rate of accumulation also increased in the Ndurumu swamp approximately 10 000 years ago, the accumulation during the last glacial stage must have been very small. The peat accumulation rate is at its minimum in the part accumulated 4600 - 2100 B.P., corresponding to the driest climatic stage of the Holocene, whereas the accumulation maximum of the Ndurumu swamp cannot be explained by changes in the macroclimate.

Factors independent of the climate may have contributed to the variations in accumulation rates. Between the southern basin and the Akanyaru valley there is a tectonic fault line (Fig. 22). Since the land uplift is strongest close to the rift valley, the Akanyaru valley may have risen in relation to the southern basin. This in turn may have caused the beginning of peat accumulation as early as during the maximum stage of the last ice age. Another factor influencing the hydrology of the southern basin was the mergence of the southern basin with the northern one as a result of the thickness growth of the peat. This happened about 2000 years ago, i.e. at the same time as the accumulation rates in the southern basin accelerated. If the surface of the southern basin was lower, the mergence of the surfaces of the two swamps raised the water level in the southern basin, temporarily favouring the accumulation of peat.

## The Rwamiko basin

At Rwamiko the River Akanyaru flows close to the eastern edge of the swamp complex. The swamp forms four 1 - 2 km long bays at the western edge. The samples are from two adjacent bays and from the main river valley (Fig. 30). The area of the drainage basin situated to the north is 8 km$^2$ and that of the southern one 4.3 km$^2$. The proportion of the swamp (21 %) is the same in both drainage basins.

The contrasts in altitude are great. The highest points of the drainage basins is approximately 250 m above the surface of the swamp. The gradient of the slopes is at its steepest more than 50 % and at the lower slopes 20 - 30 %. The highest hills of the area consist of quartzite, which is very resistant to weathering. The soil on the slopes is fairly coarse-grained weathering residue.

The original vegetation on the swamp is varied, from the dense papyrus swamp by Akanyaru to the *C. papyrus - Miscanthidium* swamp of the bays. The gradual change in vegetation from the bank of the main river towards the margins of the swamp reflects the decrease in water level fluctuations, the decrease in nutrient content and the increase in acidity. The bays are entirely beyond the range of influence of the floods of Akanyaru. The water flowing into the bays from the drainage basin (Rwamiko, Table 2, p. 28) is poorer in nutrients than the water of Akanyaru in the vicinity of Rwamiko (Akan/Rw). Rice is cultivated in the southern bay and in front of it.

## Stratigraphy

The present flood plain of Akanyaru is covered by a layer of fines, which thins out with growing distance from the river. At a distance of 40 m from the channel it is 2.6 m thick and decreases to 1.1 m at a distance of 80 m, then staying in the range 0.3 - 0.5 m as the distance grows from 100 to 1400 m. Judging from the thickness of the layer of fines the flood plain of Akanyaru extended to a little less than a hundred metres from the channel before the recent increase in erosion, and has grown rapidly since then.

Judging from the samples for sieve analysis collected from the bottom of the channel of Akanyaru the sand transported along the bottom is somewhat finer in the vicinity of Rwamiko (average 0.10 mm) than in the vicinity of Buyongwe (average 0.20 mm). Some of the coarser material is deposited between Buyongwe and Rwamiko. The sedimentation of mineral matter carried by the river is also reflected by the decrease in the content of matter carried in suspension between Buyongwe and Rwamiko (Table 2, p. 28). On the other hand the concentrations of dissolved matter and those of most main nutrients are higher in the vicinity of Rwamiko than in the vicinity of Buyongwe.

Papyrus reed has been the main peat-forming plant in the central part of the valley. Towards the bays the swamp grows poorer in nutrients and the content of wood and *Miscanthidium* grass increases in the peat deposit (Fig. 31). The influence of the waters flowing from the drainage basin is limited to a narrow rim zone. Swamp forests have covered the valley repeated times. At several sites woody peat occurred at a depth of more than 15 m and at a depth of approximately 5 m. The thickness of the layers of woody peat varies at the various sites, showing that the forests

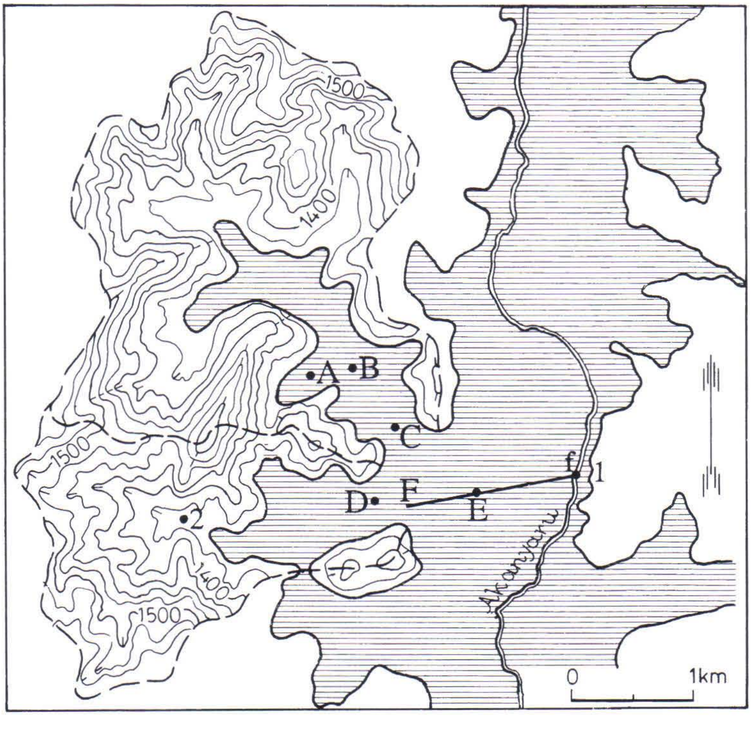


Fig. 30. The Akanyaru swamp complex forms bays in the two small drainage basins of Rwamiko west of the main river Akanyaru which are not reached by its flood waters. The water samples are from a brook discharging into the southern bay (2) and from Akanyaru (1). Points A - E show the locations of the survey sites. The line F - f in the Akanyaru flood plain shows the location of the sections in Figure 32.

at times expanded to the valley of the main river, at times again withdrew to the bays. In the middle of the main valley the uppermost bog wood layer was found at a depth of 5 m.

## Physical properties of the peat

The peat deposit in the northern bay is very watery. Its water content is at site B (Fig. 30) 93 - 95 % from the surface to a depth of 14 m, and in the basal part it is approximately 92 %. The water content is one percentage unit lower at site D. In the central part of the Akanyaru valley (site E) the water content of the surficial part is about 91 % and that of the basal part approximately 90 %.

The bays have continuously been out of reach of the floods of Akanyaru, which is evident from the low ash content, which averages approximately 6 % at site B, 7 % at site D and 15 % at site E. Layers with abundant ash are lacking at sites B and D, whereas site E shows a high content at the surface, at a depth of 8 - 9 m and near the base. The ash content of the uppermost samples (0 - 0.5 m) increases from the margin of the swamp towards Akanyaru (Fig. 32). The ash content and degree of decomposition influence the calorific value of the peat. The average net calorific value is approximately 20 MJ $kg^{-1}$.

## Chemical properties of the peat in the Akanyaru flood plain

The floods have raised the concentrations of aluminium and iron in the surficial samples collected from the flood plain of Akanyaru (Fig. 32). The concentrations decrease and the layer containing the high ratios thins out with growing distance from the river. The aluminium concentrations follow the variations in ash content.

The calcium content is 0.2 - 1.2 %. The concentrations of the uppermost layers with abundant ash are lower than those of layers from greater depth, whereas the proximity of the river does not influence the calcium concentrations.

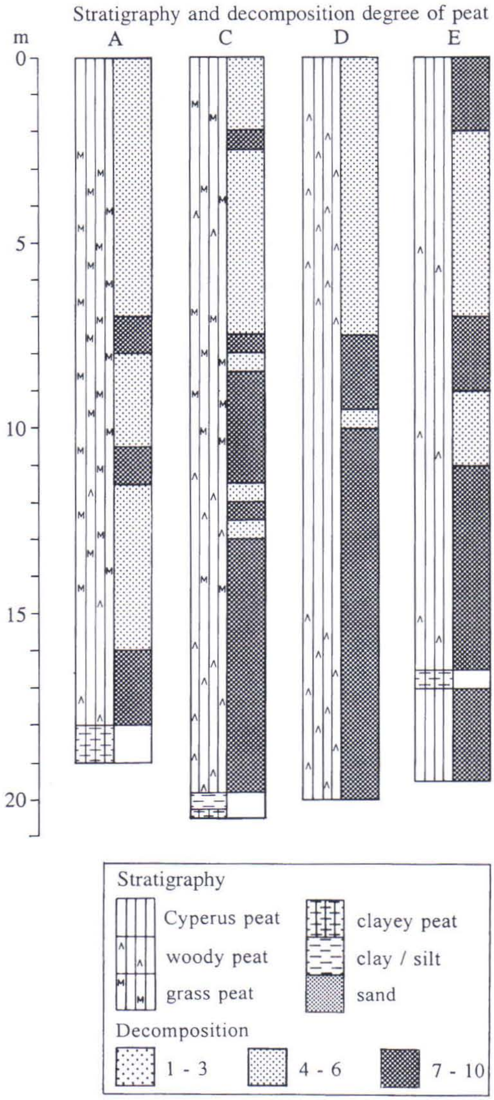


Fig. 31. *Miscanthidium* grass forms a significant part of the present vegetation of the bays of Rwamiko, and its macrofossils are abundant in the peat. Swamp forests have dominated the area at several stages in its history.

Near the river channel the sulphur concentrations are higher than at the margins of the flood plain, increasing with depth. Due to washing the concentrations of the surficial samples are low in the vicinity of the channel, too. The sulphur concentrations of the water of Akanyaru are nearly tenfold compared with those of the water flowing from the drainage basin to the bays (Table 2, p. 28), which partly explains the local variations in sulphur concentration of the peat.

The highest concentrations of potassium, sodium and phosphorus were found in the uppermost samples. Due to the mineral matter deposited by Akanyaru the potassium concentrations are slightly higher in the vicinity of the channel, whereas the proximity of the channel does not affect the sodium and phosphorus ratios. The magnesium and manganese concentrations do not show any distinct vertical or horizontal differences, but their concentrations are of the same order of magnitude along the channel and at the margins of the flood plain.

The concentrations of cobalt in the peat are slightly higher near the river than at the margins of the flood plain. The floods of Akanyaru have strongly increased the ratios of chromium, copper, nickel, lead and zinc in the surficial layer. This layer thins out and the concentrations decrease with increasing distance from the river.

### Accumulation of peat

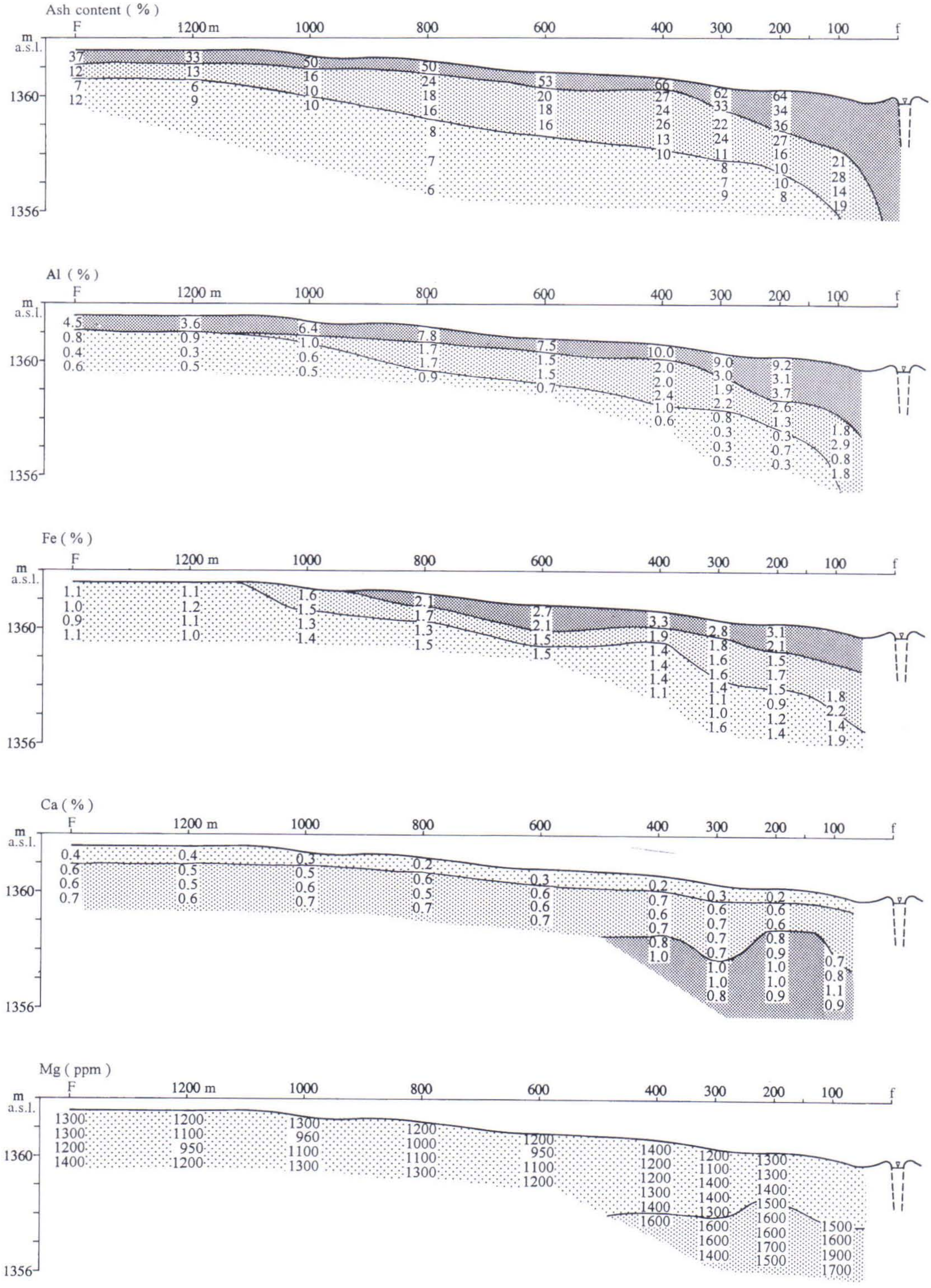
The average rate of thickness increment of the peat deposit has been 2.33 mm $a^{-1}$. The total dry matter accumulation rate is 217 g $m^{-2}$ $a^{-1}$ and that of carbon 112 g $m^{-2}$ $a^{-1}$ on an average (Table 6). In the uppermost five metres (1660 - 0 B.P.) both the rate of thickness increment and the dry matter accumulation rate were greater than average. On the surface of the swamp abundant alluvial sediments have accumulated, affecting the accumulation rates for organic matter, mineral matter and carbon. The bulk of the deposit (5 - 19 m) probably includes considerable variations in accumulation rates.

### Interpretation

In the Akanyaru valley the peat deposit is underlain by gyttja layers. The $^{14}C$ age of a sample taken from the contact between peat and gyttja indicates that peat began to accumulate in the central part of the swamp (site E) approximately 7700 B.P. Swamp forests have been more common in the bays than in the main river valley, where the forests have not expanded since about 1600 B.P. The decrease of the forests after this time may, like regarding the Buyongwe swamp, be due to either a change in climate or changes in the land use of the drainage basin.

The contact between the alluvial layer and the peat in the surficial part of the deposit is too recent to be dated by the $^{14}C$ method. If the rate of thickness increment is assumed to have remained constant, the age obtained for the contact between the alluvial deposit and the peat is approximately 100 B.P. on the basis of the $^{14}C$ age of the uppermost dated sample, and about 120 B.P. on the basis of the most probable calibrated date. It is, however, very probable that the alluvial sediments deposited on the surface of the swamp have compacted the underlying peat to some degree, so that the contact between fines and peat has sunk lower than the original surface. Thus the age of the contact calculated on the basis of constant rate of thickness increment has to be considered mainly as the maximum age.

The expansion of the flood plain of Akanyaru increased the deposition of mineral matter and the supply of nutrients in the main valley. The increased deposition of mineral matter also influenced the chemical stratigraphy of the peat to some degree. The concentrations of most of the main elements decrease with depth. Corresponding results were obtained from a certain soligenous valley mire in Great Britain (Naucke et al. 1993). No decrease in the magnesium concentration with depth can, however, be detected in the flood plain of Akanyaru. The expansion of the flood plain is most clearly distinguishable in the distribution of trace element concentrations.


Ash content ( % )
Al ( % )
Fe ( % )
Ca ( % )
Mg ( ppm )
F
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1000
800
600
400
300
200
100
f
m a.s.l.
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1356
37
12
7
12
33
13
6
9
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Fig. 32

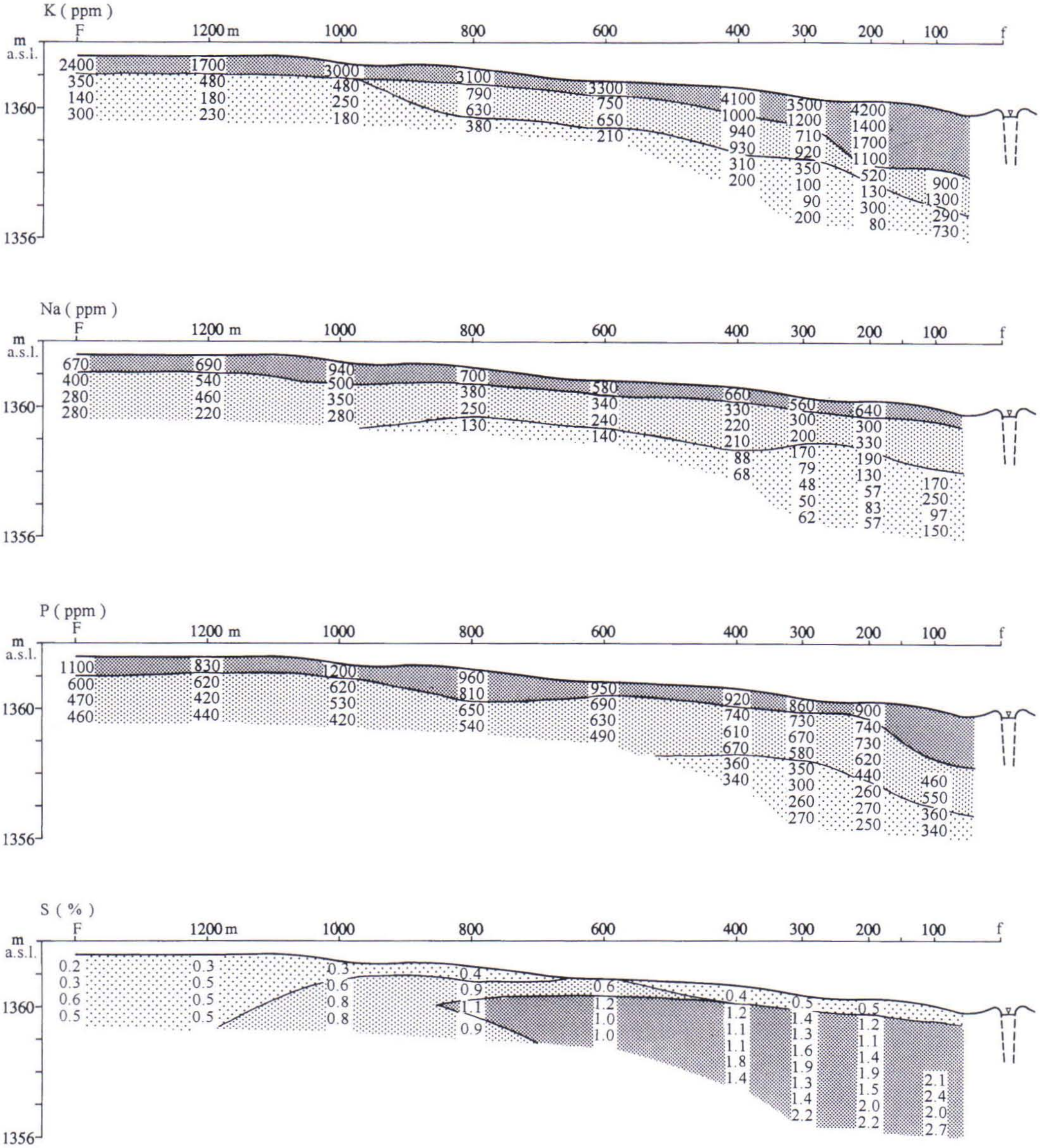

Fig. 32. Variations in ash content and concentrations of certain elements in the 2 - 4 m thick surficial part of the peat deposit of the Akanyaru flood plain at Rwamiko. The total thickness of the peat deposit is approximately 20 m.

Table 6. Accumulation of dry matter, carbon and energy in the Rwamiko swamp.

| Period | Thickness increment | Accumulation rates | | | | |
|---|---|---|---|---|---|---|
| | | Total dry matter | Organic matter | Mineral matter | Carbon | Energy |
| $^{14}$C yr B.P. | mm a$^{-1}$ | g m$^{-2}$ a$^{-1}$ | g m$^{-2}$ a$^{-1}$ | g m$^{-2}$ a$^{-1}$ | g m$^{-2}$ a$^{-1}$ | MJ m$^{-2}$ a$^{-1}$ |
| 230 - 0 | 3.28 | 243 | 153 | 90 | 83 | 2.9 |
| 1660 - 230 | 3.20 | 275 | 249 | 26 | 148 | 5.3 |
| 7720 - 1660 | 2.14 | 205 | 180 | 25 | 107 | 3.9 |
| 7720 - 0 | 2.33 | 217 | 189 | 28 | 112 | 4.1 |

## The Kinamba basin

Kinamba is a 2.5 km long and approximately 300 m wide bay in the Akanyaru swamp complex. The drainage basin occupies an area of 9 km$^2$, 0.75 km$^2$ or 8 % of which is covered by swamp. The hills surrounding the drainage basin rise in southeast 50 - 75 m and in northwest 200 m above the surface of the peatland (Fig. 33). Two small brooks discharge into the swamp from the southwestern end. Their discharge is so small that no channels have formed in the swamp area.

The soil consists mainly of fine-grained weathering residue. Coarse-grained weathering residue is found on the steeper slopes. Judging from samples for sieving from the northwestern slope the soil there consists of clay. Due to washing the clay content of the tilled layer is about 5 percentage units lower than deeper in the soil.

The swamp is covered by a dense, 3 - 4 m high growth of *C. papyrus*. Scattered deciduous trees occur among the papyrus. At the margins, ferns and *Typha* also occur.

The water sample from the brook discharging into the Kinamba swamp contained 14 mg l$^{-1}$ of suspended matter and 614 mg l$^{-1}$ of dissolved matter (Table 2, p. 28). The content of suspended matter is lower than in most of the other brooks discharging into the Akanyaru swamp complex. The content of dissolved matter is, on the contrary, higher than in any other sample. The calcium, magnesium, sodium, sulphur and manganese concentrations of the water flowing to the Kinamba bay are among the highest in the material.

### Stratigraphy

The thickness of the peat deposit is a little less than 20 m at site A in the lower part of the valley. At the base of the deposit there is greenish gyttja clay, which is overlain by clayey peat. Judging from the *Cyperus* peat in the basal part, the development of the swamp started as treeless swamp (Fig. 34). The upper part of the deposit consists of alternating beds containing *Miscanthidium* grass and wood remains. Apparently papyrus reed, *Miscanthidium* grass and deciduous trees have been alternating as the dominating vegetation of the lower part of the valley. This is also indicated by the $\delta^{13}$C values, which are in the range -17.4 - -20.4 ‰. The peat deposit of the central part of the swamp (site B) is about 12 m thick. The woody peat extends from the base up to a depth of 10 m. It is overlain by *Cyperus* peat. A thin clayey alluvial layer occurs at a depth of 6.5 m.

### Physical and chemical properties of the peat

The average water content of the peat of

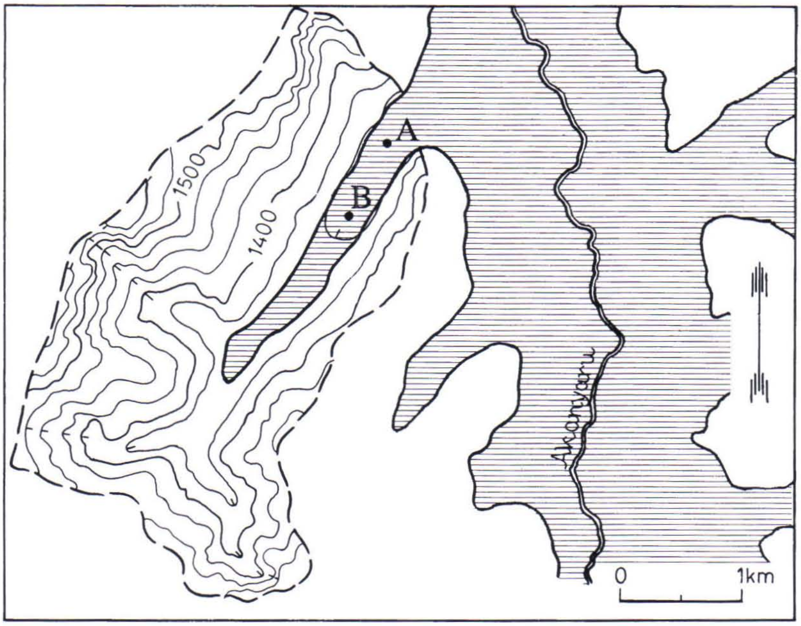

Fig. 33. The Kinamba swamp covers approximately 8 % of the drainage basin. Points A and B show the locations of the sites.

Kinamba is 91 % and the dry bulk density 87 kg $m^{-3}$. The water content decreases and the dry bulk density increases slowly with depth. However, the contrasts between individual samples are considerable. The peat deposit in the Kinamba valley to the west is drier than that in the Nyavyamo valley to the southeast which was surveyed in connection with the peat inventory project (Ekono 1983).

In the bulk of the deposit the ash content of the peat is 5 - 10 %. The vertical variation is nearly identical in the lower part and in the central part of the valley (Fig. 35). The ash content of the uppermost sample (0 - 1 m) is about 14 %. Slightly increased figures occur at depths of 3 - 4 m and 6 - 7 m, and in the lower part of the valley also at a depth of 12 - 15 m. The average net calorific value of the samples from the lower part of the valley is 18.7 MJ $kg^{-1}$. The net calorific value of the samples containing less than 10 % ash is in the range 19 - 20 MJ $kg^{-1}$.

The samples from site A contain an average of 54.9 % carbon, 4.6 % hydrogen, 27.7 % oxygen and 1.6 % nitrogen. The carbon con-

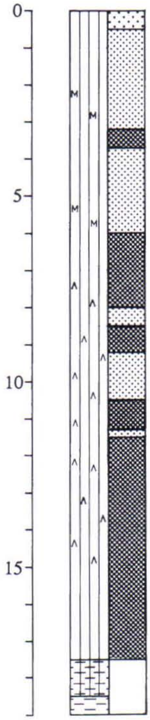

Fig. 34. Swamp forests, papyrus swamps and *Miscanthidium* swamps have prevailed at survey site A on the Kinamba swamp. For key to the symbols, see Figure 31.

tent varies from 49 to 59 %, with the highest figures obtained from samples from the central part of the deposit, low in ash. The highest concentration of nitrogen (2.0 %) was found in the uppermost sample. The magnesium and sodium concentrations of the peat deposit are very high (Fig. 36). The sodium concentrations are especially high in the surficial part of the deposit. The concentrations of calcium and potassium are higher than, e.g. in the Buyongwe swamp. The vertical variation of the aluminum concentration correlates with the variation in ash content. The alluvial layer found at a depth of 6 - 7 m is reflected in the concentrations of most of the main elements and trace elements. The layer at a depth of 13 - 14 m, containing abundant ash, is reflected as increased concentrations of aluminium, potassium, chromium, copper, nickel, lead and zinc. The concentrations of iron, potassium, sodium and heavy metals in the gyttja deposits at base are high, whereas those of calcium and manganese are low. The concentrations of water-soluble chloride are 800 - 1000 ppm in the surficial part (0 - 6 m) and 100 - 200 ppm in the basal part (8 - 17 m).

## Accumulation of peat

On an average, the total dry matter accumulation rate has been 124 g $m^{-2}$ $a^{-1}$ and that of carbon 68 g $m^{-2}$ $a^{-1}$ (Table 7). The accumulation rates vary from layer to layer. In the cumulative mass versus age curve (Fig. 37) there are two periods of gentle, fairly slow accumulation and two periods of steep, fairly rapid accumulation. During the two millenia following the mire formation the accumulation rates were considerably smaller than average. The greatest accumulation rates were found in the part of the deposit formed 8300 - 6500 B.P., after which the accumulation continued for 800 more years at nearly the same rate. The smallest accumulation rates were found in the part of the deposit formed 5700 - 1700 B.P. The accumulation rates in the uppermost layer, formed after 1700 B.P., are again considerably greater than average.

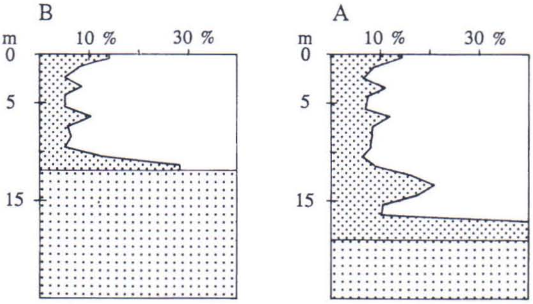

Fig. 35. Ash content in the Kinamba swamp. The figures vary in the same way at both sites.

## Interpretation

Although the discharge of the brooks into the swamp is small, the influence of the water flowing from the drainage basin is distinguishable in the chemical composition of the peat in the lower part of the valley. The magnesium and sodium concentrations are high in the surficial part.

The ancient lake in the Akanyaru valley extended to the lower part of the Kinamba valley. On the basis of the lowermost $^{14}C$ age, this part of the valley was terrestrialised approximately 10 000 years ago. The mire formation in the Kinamba valley was synchronous with the rapid rise of the water levels of the East-African lakes. The rise in the level of the swamp in the Akanyaru valley influenced the variations in accumulation rates in the Kinamba swamp. The accumulation maximum is synchronous with the humidity maximum of the Holocene. The slowing accumulation rates reflect the change toward a drier climate approximately 5000 years ago. The increasing accumulation rates may be due to either a change toward a more humid climate approximately 1400 years ago or the changes in land use within the drainage basin of Akanyaru. Both factors may have increased the wateriness of the swamp and thus increased the ac-

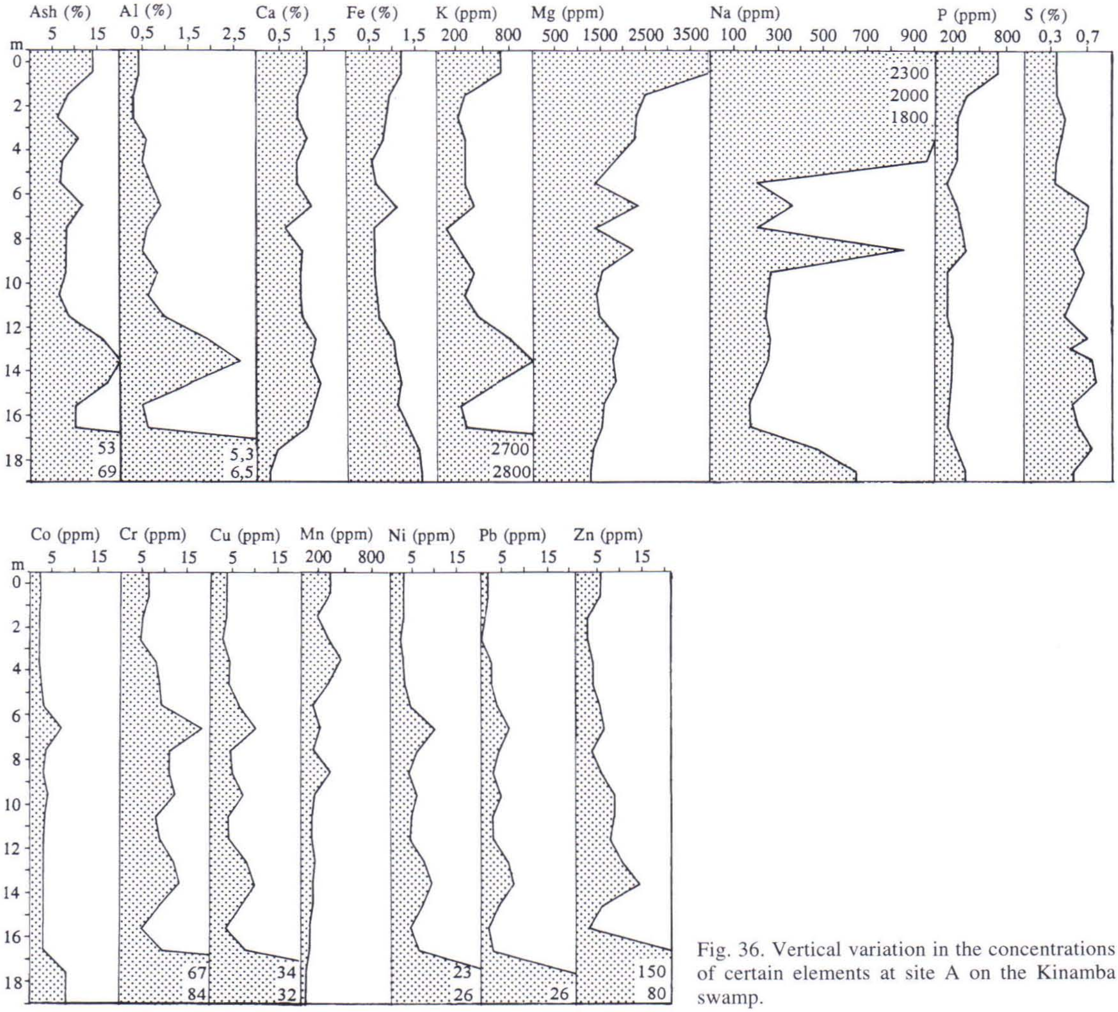

Fig. 36. Vertical variation in the concentrations of certain elements at site A on the Kinamba swamp.

Table 7. Accumulation of dry matter, carbon and energy in the Kinamba swamp.

| Period | Thickness increment | Accumulation rates | | | | |
|---|---|---|---|---|---|---|
| | | Total dry matter | Organic matter | Mineral matter | Carbon | Energy |
| $^{14}$C yr B.P. | mm a$^{-1}$ | g m$^{-2}$ a$^{-1}$ | g m$^{-2}$ a$^{-1}$ | g m$^{-2}$ a$^{-1}$ | g m$^{-2}$ a$^{-1}$ | MJ m$^{-2}$ a$^{-1}$ |
| 1730 - 0 | 3.04 | 195 | 177 | 18 | 106 | 3.7 |
| 5740 - 1730 | 0.61 | 51 | 46 | 5 | 29 | 1.0 |
| 6540 - 5740 | 2.25 | 209 | 192 | 17 | 123 | 4.2 |
| 8270 - 6540 | 2.72 | 272 | 235 | 37 | 145 | 4.8 |
| 10110 - 8270 | 0.74 | 72 | 65 | 7 | 40 | 1.3 |
| 10110 - 0 | 1.43 | 124 | 111 | 13 | 68 | 2.3 |

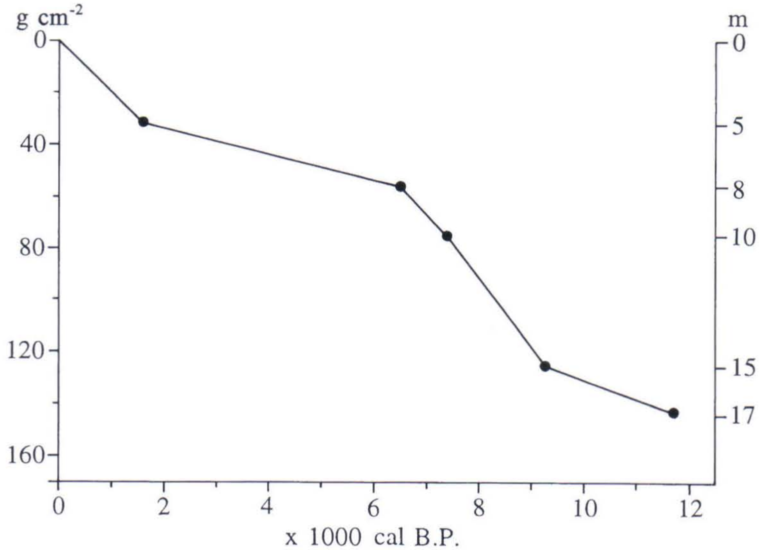

Fig. 37. Cumulative mass of total dry matter below the surface in relation to calibrated ages at site A on the Kinamba swamp.

cumulation of peat. The changes in climate fit in well with the variations in accumulation rates in the Kinamba swamp. The humid climatic periods corresponded to the periods of rapid accumulation and the dry ones those of slow accumulation.

## The Cyili basin

Cyili, one of the largest tributaries of Akanyaru, has several branches without a distinct main river (Fig. 38). Its longest branches extend approximately 35 km, to the vicinity of Butare. The drainage basin occupies about 282 km$^2$ and the swamp approximately 6.1 km$^2$, corresponding to 2 % of the drainage basin. The swamp extends to approximately 8 km from the valley of Akanyaru.

The vegetation of the Cyili swamp differs from those described earlier. The part in natural condition is covered with a dense growth of 2 - 3 m high *Cladium mariscus*. At the margins there is a narrow zone of papyrus. The upper part of the swamp is covered by extensive rice fields.

The water samples from Cyili were taken from Nyiramageni, the southernmost main branch. The concentration of suspended matter was 9 mg l$^{-1}$ and that of dissolved matter 250 mg l$^{-1}$ (Table 2, p. 28). The amount of suspended matter was small in comparison with the other tributaries of Akanyaru. Extensive rice fields on the valley floors retain the mineral matter eroded from the slopes of the drainage basin. The concentrations of dissolved matter as well as those of most main nutrients are greater than those in Akanyaru, but smaller than in the water flowing to the Kinamba swamp.

### Stratigraphy

The peat deposit in the lower part of the Cyili valley is approximately 10 m thick. It is underlain by clayey peat and clay. The peat deposit is considerably thinner than that of the tributary valleys farther south. The area has been covered by alternating *Cladium* swamps, other reed swamps and swamp forests. Woody peat occurs at a depth of 5 - 6 m in the lower part of the valley. The $\delta^{13}C$ values are approximately -18 ‰ in the basal part of the deposit and -27 ‰ in the surficial part. This indicates that the vegetation was formed by both $C_3$ and $C_4$ plants during the early stages of the history of the swamp. Later the $C_3$ plants (*Cladium mariscus*) totally replaced the $C_4$ plants. The decomposition degree of the peat deposit is fairly low, 3 - 6 in the surficial part and 6 - 9 near the base.

### Physical and chemical properties of the peat

The water content of the peat deposit of Cyili is very high, approximately 94 - 96 % in the uppermost two metres. Volumetric samples of the surficial part could not be obtained due to the low degree of decomposition and the wateriness. The water content decreases with depth and is in the samples from the basal part less than 90 %. The ash content varies locally, being 13 - 29 % in the central part of the swamp and 8 - 16 % in the lower part. The ash content starts increasing strongly at a depth of more than 8 m due to clayey layers. The net calorific value rises slowly to a depth of 8 m, averaging 18.5 MJ kg$^{-1}$.

The pH of the peat is here the highest of the study, averaging 6.2. In the uppermost two metres thick bed it is near neutral (6.4 - 7.2). The carbon content averages 54 %, that of hydrogen 5.1 % and that of nitrogen 1.8 %. The sulphur contents are high, ranging 0.8 - 4.7 %. The site averages for two sites are 1.7 % and 2.4 %. Besides sulphur, the concentrations of calcium, magnesium and sodium are

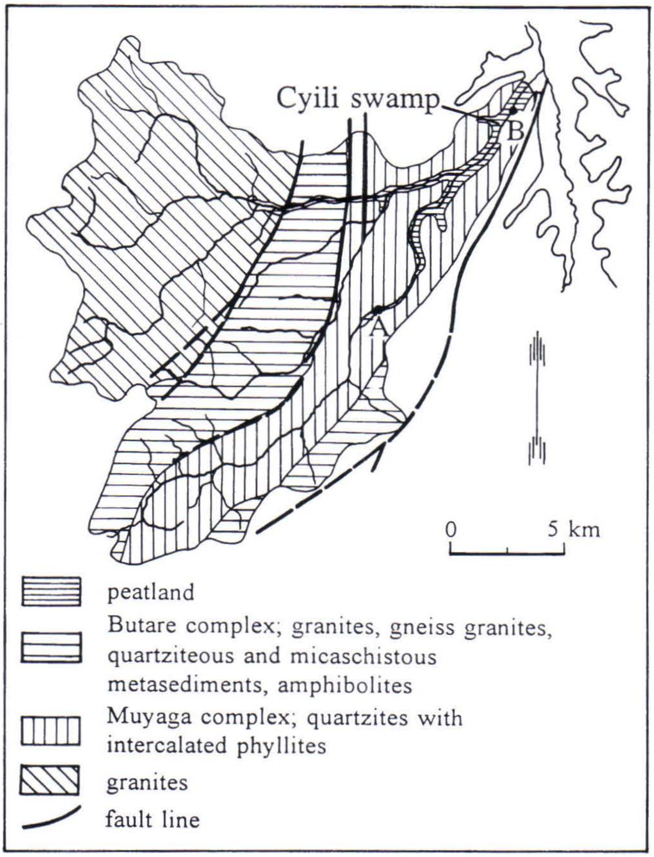

Fig. 38. Lithology and fault lines of the Cyili drainage basin (Carte Géologique du Rwanda 1991). The area of the swamp is 6.1 km$^2$, covering only 2 % of the drainage basin. The water samples are from site A and the samples for dating from site B.

also high (Fig. 39). The concentrations of potassium, phosphorus and manganese are high in the uppermost samples, whereas the heavy metal concentrations are low.

## Accumulation of peat

The initiation of peat formation in the Cyili valley occurred approximately 2500 years ago. Since then the peat deposit has grown by an average of 3.48 mm $a^{-1}$. The surficial part is very watery, and so the uppermost sample for $^{14}C$ dating has probably sunk lower than the original swamp surface (Fig. 40). No volumetric samples were collected from the surficial layer, and thus no accumulation rates were calculated for it. The average total dry matter accumulation rate during the period 2495 - 190 B.P. was 209 g $m^{-2}$ $a^{-1}$, that of carbon 113 g $m^{-2}$ $a^{-1}$ and that of energy 4.1 MJ $m^{-2}$ $a^{-1}$ (Table 8). The accumulation rates are greatest in the part of the deposit formed 1400 - 1000 B.P.

## Interpretation

The fairly high nutrient content of the water flowing to the swamp influences the vegetation and the chemical composition of the peat layer. As a contrast to the other areas studied in the Akanyaru swamp complex, the prevailing vegetation is here that of a *Cladium* swamp (Fig. 41). According to Thompson (1985), *Cladium* favours calcium and occurs only in exceptionally nutrient-rich environments. The average calcium concentration of the peat is 1.83 %, which is considerably higher than that of the Kinamba swamp (0.98 %) or that of the Buyongwe swamp (0.70 %). Peuraniemi and Pihlaja (1988) have obtained

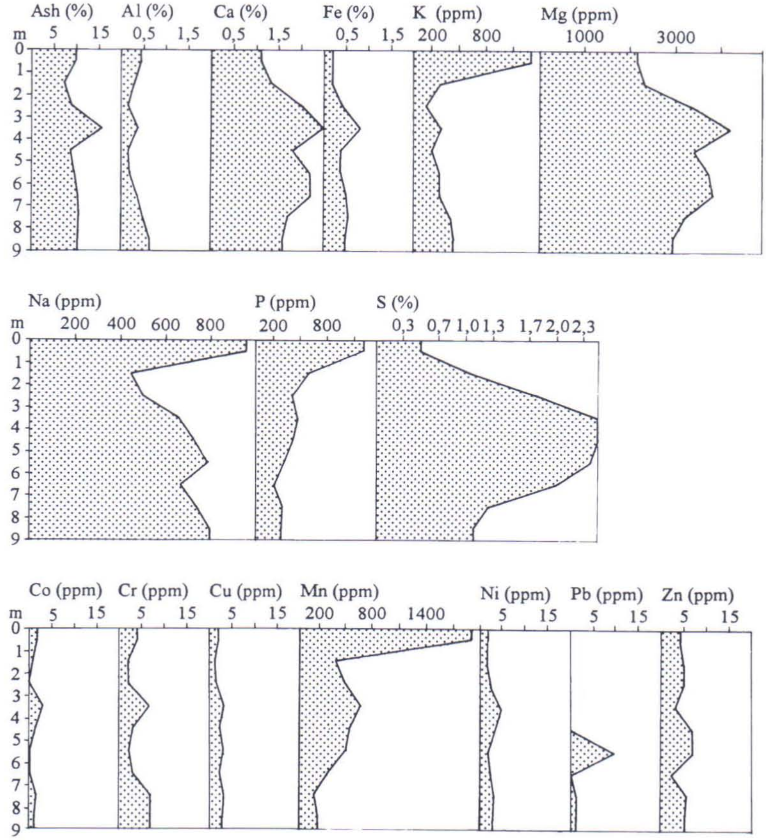

Fig. 39. Vertical variation in the concentrations of certain elements at site B on the Cyili swamp.

0.41 % as the average calcium concentration of 861 peat samples collected in Finland. The bedrock of Finland, like that of the drainage basin of Akanyaru, is poor in calcium. Virtanen (1993) has obtained a calcium concentration of 1.5 % for a Finnish peat layer bordering on calcareous schist, about the same value as that of the peat layer of Cyili. Considerably higher concentrations have been obtained for mires in tropical limestone areas, such as the Black River Morass in Jamaica, where the average calcium concentration of *Cladium* peat is as high as 7.1 % (Digerfeldt and Enell 1984).

The Cyili swamp also shows the highest concentrations of magnesium and sulphur in the study. The average sulphur concentrations of peat are in Finland on an average about 0.2 %. The sulphur concentrations of minerotrophic peats are considerably higher in the tropics than in the temperate zone. Especially high concentrations (1.6 - 10 %) have been found in coastal mires (Blackwood and Robinson 1985, Ekono Oy 1985 and Chateauneuf et al. 1986).

The initiation of mire formation occurred in the lower part of the valley approximately 2500 B.P. during a fairly dry climatic stage. The paludification of mineral soil generally

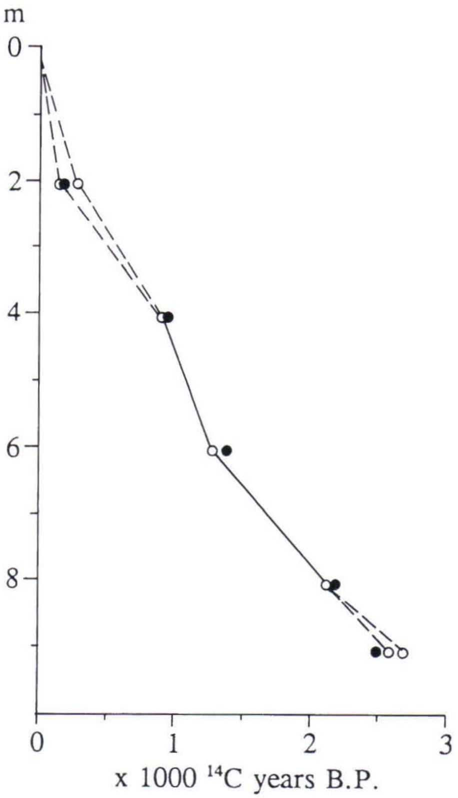

Fig. 40. The $^{14}$C ages of samples from site B on the Cyili swamp (black dots) and the calibrated ages (circles) in relation to the sampling depth.

Table 8. Accumulation of dry matter, carbon and energy in the Cyili swamp.

| Period | Thickness increment | Accumulation rates | | | | |
|---|---|---|---|---|---|---|
| | | Total dry matter | Organic matter | Mineral matter | Carbon | Energy |
| $^{14}$C yr B.P. | mm a$^{-1}$ | g m$^{-2}$ a$^{-1}$ | g m$^{-2}$ a$^{-1}$ | g m$^{-2}$ a$^{-1}$ | g m$^{-2}$ a$^{-1}$ | MJ m$^{-2}$ a$^{-1}$ |
| 190 - 0 | 7.32* | - | - | - | - | - |
| 950 - 190 | 3.17* | 161* | 141* | 20* | 87* | 3.0* |
| 1370 - 950 | 5.40 | 337 | 306 | 31 | 187 | 6.9 |
| 2185 - 1370 | 2.31 | 225 | 201 | 24 | 124 | 4.4 |
| 2495 - 2185 | 2.17* | 162* | 146* | 16* | 91* | 3.3* |
| 2495 - 190 | 3.48* | 209* | 188* | 21* | 113* | 4.1* |

* several probable cal. ages for upper or lower end

Fig. 41. The Cyili swamp is covered by *Cladium mariscus*, except for a narrow papyrus zone at the edge.

requires increased humidity. Since the climate during the paludification was fairly dry, the paludification of the Cyili valley is related to the history of the Akanyaru valley. The continued accumulation of peat in the Akanyaru valley caused an increase of the wateriness in the lower parts of the Cyili valley. On the other hand the amount of mineral matter transported to the lower parts of the valley has been smaller during the dry climatic period. The accumulation of peat has continued fairly regularly throughout this dry period. The accumulation maximum dates to approximately 1400 - 1000 B.P. The wateriness of the swamp has increased due to climatic reasons or changes in land use within the drainage basin.

The peat deposit of Cyili is considerably younger than the others of corresponding thickness in the Akanyaru area. The age of the peat at a depth of 8 m is about 2200 years in the Cyili swamp, but 5700 years in the Kinamba swamp at a distance of less than 4 km. This age difference cannot be explained by the compaction of the peat deposits, since the peat deposit of Kinamba is twice as thick as that of Cyili, and thus the compaction of the Kinamba swamp would be expected to be greater than that of the Cyili swamp. A fault line (Fig. 38) between the two basins indicates that tectonic changes may have influenced their vertical position.

## The Gishoma basin

The Gishoma basin was formed as a result of tectonic movements at the upper courses of the Gishoma river. The waters flow via Gishoma to Rusizi and on to Lake Tanganyika. The drainage basin of the swamp covers 16.5 km$^2$, 25 % or 4.1 km$^2$ of which is occupied by the swamp (Fig. 42). The surface altitude of the peatland is 1610 - 1650 m. The highest hills in the drainage basin rise approximately 100 m above the peatland.

After the Second World War fuel peat has been produced from the Gishoma swamp. The peat was used for heating at the Katana cement factory on the Zairese side of the border. The production area was about 50 ha. At present the peatland is almost entirely cultivated. Swamp plants proper still occur in the vegetation of the rainy season. Some small *Syzygium* forests have occurred on the swamp, but they have been cleared for the purpose of agriculture.

### Stratigraphy

The thickness of the peat deposit in the main basin exceeds 5 m and in the bay towards the west 7 m (Fig. 43). The peat layer surrounding the former peat mining area has been compacted. The bottom of the basin is covered by grey clay (Fig. 44), overlain by thin alternating layers of gyttja, peat and clay. Layers of clayey gyttja and gyttja are approximately 0.5 m thick and were found at nearly all sites of the main basin.

The peat consists mainly of sedges and grasses. Although *Syzygium* forest once covered part of the swamp, the content of wood remains in the peat is low. The areas probably became forested quite late, so that stumps occur only in the surficial layer. $\delta^{13}$C determinations show that the peat-forming vegetation included both $C_3$ and $C_4$ species. The most significant peat-forming $C_4$ plant was *C. latifolius*. Judging from the $\delta^{13}$C values, which decrease towards the surface, the ratio of $C_4$ plants has decreased.

The average decomposition degree of the peat is 5.1. In the southern part and at the margins of the main basin the peat is better decomposed than average. The decomposition degree generally increases with depth, although not regularly (Fig. 44).

### Physical and chemical properties of the peat

The average water content of the peat is 93.8 % and the dry bulk density 59 kg m$^{-3}$. In the main basin the water content is varied, ranging 91 - 95 % and the dry bulk density 39 - 80 kg m$^{-3}$. The highest water content values were found in the bay extending towards the west (site C, Fig. 43) and the lowest ones in the bay extending towards the northwest (D).

The ash content of the peat samples is in the range 3 - 30 %, averaging 9.2 %. The ash content of most samples from the southern and central parts of the main basin is 4 - 7 % and in those from the northern part 6 - 10 %. The lowest figures were found at site C and the highest ones in the bay towards the northwest (D). The calorific values are 20 - 22 MJ kg$^{-1}$ in the southern and central part of the main basin and at site C, somewhat lower in the northern part of the main basin and at site D.

The average pH of the peat is 4.9. In the main basin the individual results are 4.4 - 5.3. The values show a slight decrease in pH towards the south, downstream, whereas the contrasts are small in the vertical direction with no distinct difference between surface and base.

In most samples the concentration of carbon is 53 - 57 %, that of hydrogen 5.3 - 5.7 % and that of nitrogen 1.7 - 2.1 %. No observable differences exist between the various parts of the swamp. The nitrogen concentration decreases with depth at all sites. The sulphur concentration of the dry matter averages 0.17 %, ranging 0.15 - 0.19 % in most of the sam-

Fig. 42. The Gishoma swamp covers approximately 25 % of the drainage basin. Possible fault lines were deduced from maps and aerial photos (Pajunen and Karega in press). Arrows show the locations of landslides.

ples from the main basin. At site C the values are slightly lower and at site D slightly higher than in the main basin. The vertical variations are irregular.

In the analysed series of samples from the southern part of the main basin (site A) the concentrations of iron, cobalt and nickel are somewhat higher but those of calcium and potassium slightly lower than the average for the Akanyaru area (Fig. 45). The highest concentrations of potassium, sodium and phosphorus were found in the uppermost samples. Otherwise the vertical variation was slight.

### Accumulation of peat

The dating results are from the sample series of site A in the main basin and from the basal peat samples of sites B and C. The time of peat initiation for site A is approximately 1600 B.P. The mass versus age curve for the

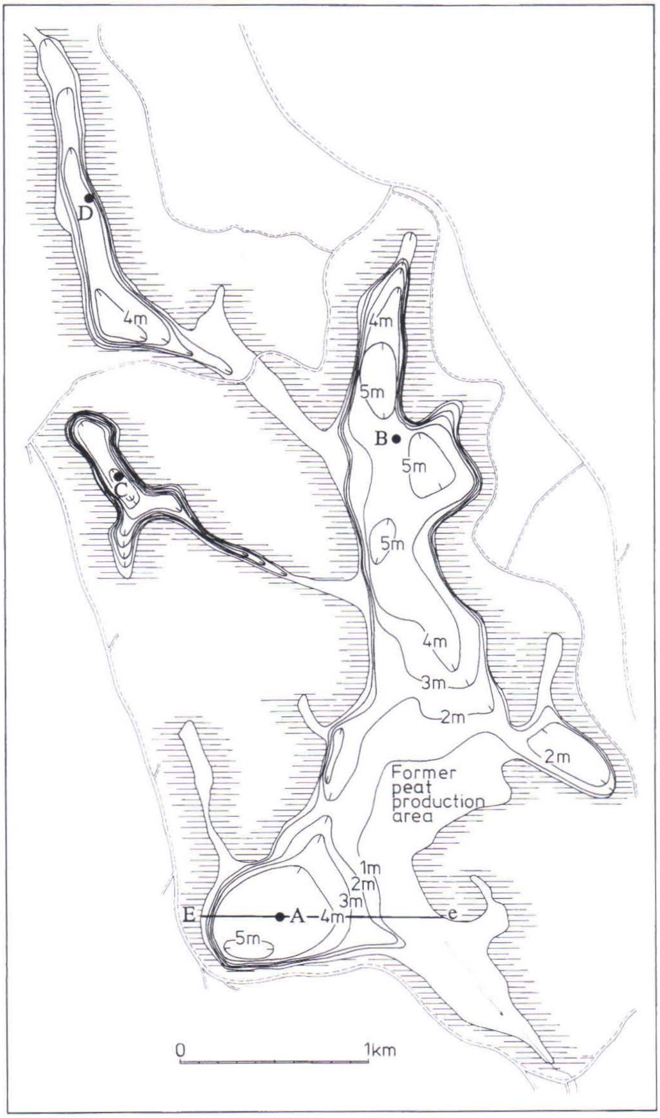

Fig. 43. Peat thicknesses in the Gishoma swamp. The peat deposit of the southern part has become thinner due to peat mining, and also due to compression in the vicinity of the production area. A - D show the locations of sites mentioned in the text. The stratigraphic sequence of line E - e is shown in Figure 44.

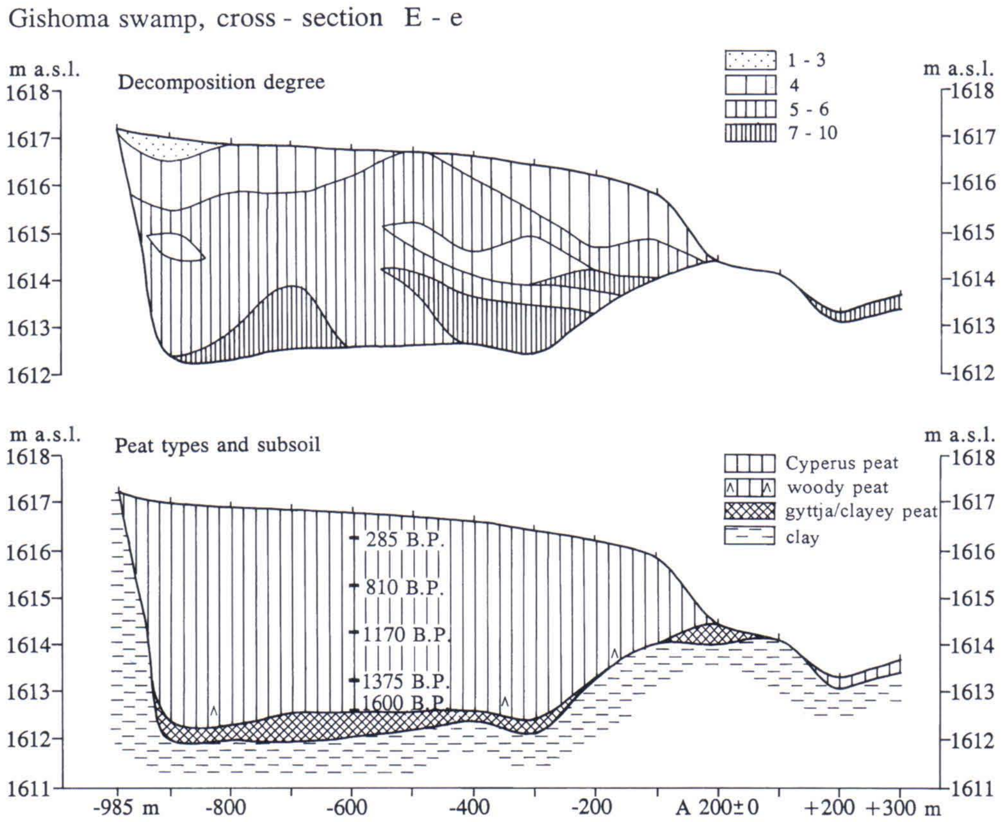

Fig. 44. Cross-section of the southern part of the main basin of Gishoma. The gyttja layers were formed during the lake phase preceding terrestrialisation. The survey line extends to the former peat mining area (on the right).

dry matter (Fig. 46) shows that the accumulation has continued regularly until the present day. The curve is somewhat convex, indicating a slight slowing of the accumulation rate.

The average rate of thickness increment varies from area to area. At site A it is 2.77 mm $a^{-1}$, at site B 3.35 mm $a^{-1}$ and at site C 3.98 mm $a^{-1}$ (Table 9). The average accumulation rates for dry matter, carbon and energy vary accordingly. In the bay towards the west the average for total dry matter is 189 g $m^{-2}$ $a^{-1}$, for carbon 106 g $m^{-2}$ $a^{-1}$, and 3.8 MJ $m^{-2}$ $a^{-1}$ for energy. The average accumulation rates in the main basin are somewhat smaller, and those in the Gishoma swamp as a whole are small in comparison with deposits of the same age in the Akanyaru area.

The rates of thickness increment and the rates of accumulation vary considerably more from layer to layer than they do areawise. The total dry matter accumulation rate, e.g., varies according to layer, ranging 89 - 188 g $m^{-2}$ $a^{-1}$, and that of carbon ranging 52 - 107 g $m^{-2}$ $a^{-1}$. The greatest rates of thickness increment and accumulation were found in the layer formed 1400 - 1200 B.P. and the smallest ones in the layer formed during the last 300 years.

### Interpretation

The initiation of mire formation occurred in the Gishoma basin fairly late, as the accumulation of peat started approximately 2000

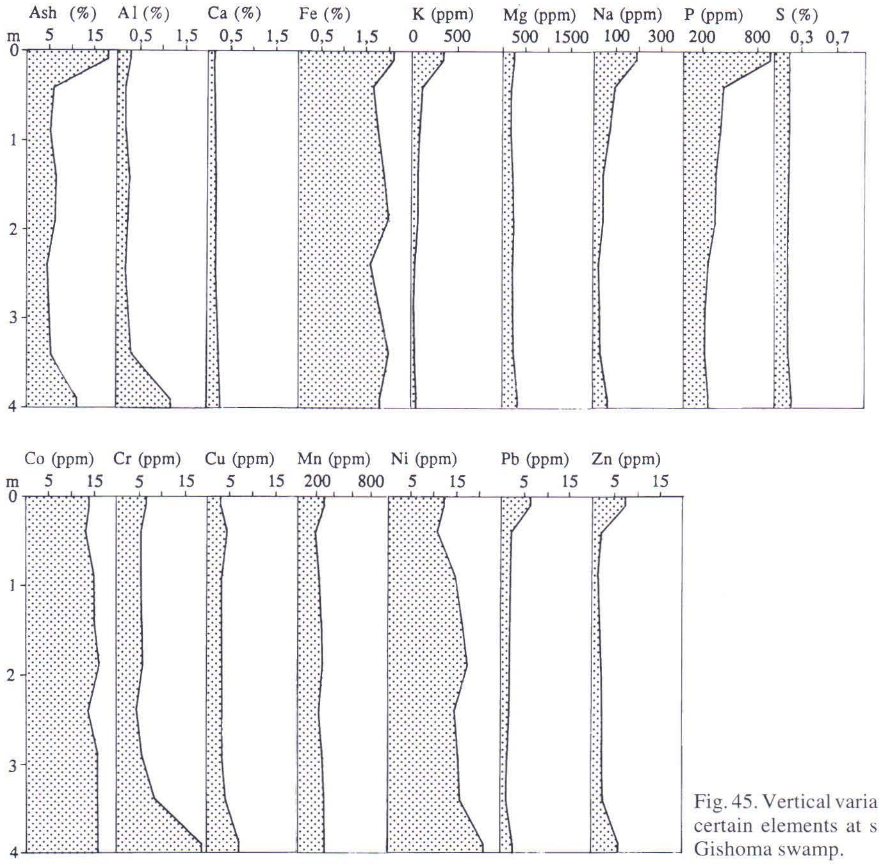

Fig. 45. Vertical variation in the concentrations of certain elements at site A, southern part of the Gishoma swamp.

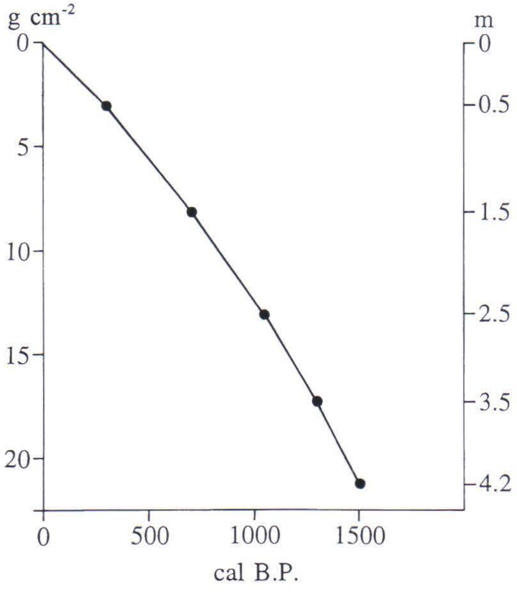

Fig. 46. Cumulative mass of total dry matter below the surface in relation to calibrated ages at site A on the Gishoma swamp.

years ago. The southern part of the main basin was terrestrialised about 1600 years ago, and the peatland spread to the northern part of the basin during the following two centuries. The terrestrialisation occurred during a period of fairly dry climate. A fairly dry climate may lower the water surface of a basin and thus favour filling-in of a water body. The peat initiation in the western basin was caused by landslides, which dammed the valley leading to the main basin. Landslides also contributed to the onset of peat deposition in the bay towards the northwest.

The fact that the climate turned more humid about 1400 years ago is reflected in the rates of accumulation. The accumulation maximum was found in the part of the deposit formed 1400 - 1200 B.P. The climatic change may have raised the water level of the basin and thus favoured the accumulation of peat. When the basin was filled with peat, the accumulation rates started to slow. The climatic changes explain the terrestrialisation of the main basin and the accumulation maximum provided that the basin during the driest period was a closed one. If the basin had an effluent all the time, the climatic changes did not have an equally great influence on the water level of the basin nor on the development of the peatland. The changes in land use within the drainage basin were not as important as in the Buyongwe and Cyili swamps, because the Gishoma swamp forms a considerably greater part of the drainage basin than they do. The history of the bays towards the west and northwest was controlled by non-climatic factors.

The present peat volume in the Gishoma swamp is 9.47 million $m^3$ and the energy content 11.06 million GJ. The accumulation of this amount of peat and energy took 2000 years. An average of 4700 $m^3$ $a^{-1}$ of new peat has been formed and an average of 5.53 million MJ $a^{-1}$ has accumulated. The accumulation of peat and energy has varied according to changes in accumulation rate and horizontal growth of the peatland. During the initial stage (2000 - 1600 B.P.) peat was deposited only in the small western bay, and thus the amount of peat formed annually was small. Increasing volumes of peat were formed starting about 1400 B.P., when the peatland had spread to the northern part of the main basin and the peat accumulation rate per unit area was at its maximum.

Table 9. Accumulation of dry matter, carbon and energy in the Gishoma swamp.

| Period | Thickness increment | Accumulation rates | | | | |
|---|---|---|---|---|---|---|
| | | Total dry matter | Organic matter | Mineral matter | Carbon | Energy |
| $^{14}$C yr B.P. | mm $a^{-1}$ | g $m^{-2}$ $a^{-1}$ | g $m^{-2}$ $a^{-1}$ | g $m^{-2}$ $a^{-1}$ | g $m^{-2}$ $a^{-1}$ | MJ $m^{-2}$ $a^{-1}$ |
| Core A | | | | | | |
| 285 - 0 | 1.75 | 89 | 83 | 6 | 52 | 1.9 |
| 810 - 285 | 2.44 | 134 | 126 | 8 | 74 | 2.8 |
| 1170 - 810 | 2.86 | 138 | 131 | 7 | 80 | 3.0 |
| 1375 - 1170 | 4.35 | 188 | 178 | 10 | 107 | 4.0 |
| 1600 - 1375 | 3.00 | 179 | 159 | 20 | 97 | 3.3 |
| 1600 - 0 | 2.77 | 153 | 144 | 9 | 86 | 3.2 |
| Core B | | | | | | |
| 1440 - 0 | 3.35 | 188 | 169 | 19 | 99 | 3.7 |
| Core C | | | | | | |
| 2000 - 0 | 3.98 | 189 | 176 | 13 | 106 | 3.8 |

## The Mashya basin

The Mashya bog is located approximately 8 km north of the Gishoma swamp at the upper courses of the river Katabuvuga. The size of the drainage basin is 1.25 km$^2$, 0,3 km$^2$ or 24 % of which is covered by the bog (Fig. 47). The surface altitude of the bog is 1703 m, while the altitudes in the drainage basin range from the surface of the mire to 1867 m a.s.l. These differences in altitude are great considering the size of the drainage basin. The surface of the bog is in the central part 15 - 20 cm higher than the laggs or marginal parts.

The vegetation of the central part of the bog differs from that of the laggs. Deciduous trees (*Syzygium*) and *Sphagnum* mosses form the dominating vegetation of the central part. The southern and western laggs are covered by *Cyperus* species and the northern bay by *Miscanthidium* grass. The bog is almost completely in a natural state.

### Stratigraphy

The bottom of the Mashya basin is covered with black clayey gyttja and gyttja clay. The thickness of the peat deposit is a little more than 4 m. The most significant peat-forming plants have been *Cyperus* species at the margins and trees in the centre of the bog. Abundant wood occurs from surface to base, at the surface in the form of undecomposed bog wood and deeper down in the form of partly decomposed remains. In the surficial 2 m thick layer the ratio of bog wood is 2.0 percent by volume. The low $\delta^{13}$ values (-26 - -29 ‰) show that the peat deposit in the central part has been formed mainly by $C_3$ plants. The present vegetation in the central part consists almost entirely of trees (*Syzygium cordatum*) and *Sphagnum* mosses, both of which are $C_3$ plants. There is, however, a distinct difference in their $\delta^{13}$ values. Aucour et al. (1994) report -23.7 ‰ as the $\delta^{13}$ value of *Sphagnum* and -27.1 ‰ as that of *Syzygium cordatum*. Judging from these figures the peat deposit in the central part was formed almost entirely of wood remains. Like in the Buyongwe swamp, the *Sphagnum* mosses have not here contributed significantly to the formation of peat.

The average decomposition degree of the peat is 6.0, and it varies from layer to layer. The peat of the surficial layer (0 - 0.7 m) is poorly decomposed. It is underlain by an about 0.3 m thick highly decomposed layer containing signs of burned vegetation. The peat is moderately decomposed at a depth of 1 - 2 m and highly decomposed at greater depths.

### The physical and chemical properties of the peat

The average water content of the peat is, on the basis of the sample series from the central part (site A, Fig. 47), 92.2 %, the dry bulk density 76 kg m$^{-3}$ and the ash content 2.7 %. The ash content of the surficial samples collected at the margins is slightly higher. The calorific value averages 20.5 MJ kg$^{-1}$, increasing with depth.

The pH of the peat is low, in the range 3.0 - 3.8, averaging 3.4. In the basal part the pH is a little higher than in the surficial part. The peat contains an average of 55.9 % carbon, 5.5 % hydrogen and 1.3 % nitrogen. In the uppermost sample of the series the carbon content is lower than in the other samples, whereas the concentrations of hydrogen and nitrogen are the same in the surficial and the basal part.

The concentrations of the main elements are very low in the sample series of site A (Fig. 48). The potassium concentration of the uppermost sample forms an exception, as it is approximately tenfold compared with the other samples. The calcium concentrations of the central part are less than 0.1 % from base to surface.

The sulphur concentration is in the range

0.08 - 0.22 %, averaging 0.16 %. The concentrations in the surficial samples (0 - 2 m) are slightly higher close to the southern and eastern margins of the bog. Except for zinc, the concentrations of trace elements are low with small vertical variations.

## Accumulation of peat

The Mashya bog is fairly recent. However, its peat deposit has grown to a thickness of more than 4 m. The cumulative mass versus age curve of the central part of the bog (site A) is nearly straight (Fig. 49). The upper part of the curve is somewhat convex, indicating a slight decrease in the accumulation rate after 900 cal. B.P. The total dry matter accumulation rate is on an average 163 g $m^{-2}$ $a^{-1}$, that of carbon 91 g $m^{-2}$ $a^{-1}$ and that of energy 3.4 MJ

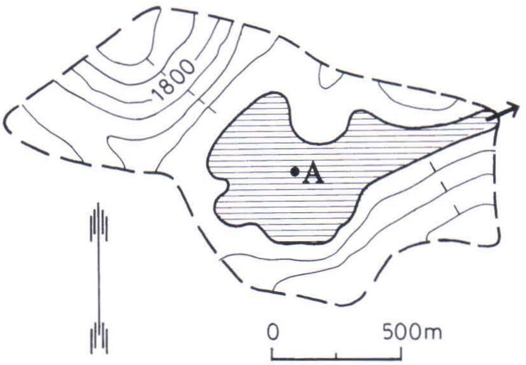

Fig. 47. The Mashya bog is situated at an altitude of 1700 m a.s.l. and covers 24 % of the drainage basin. The waters of the basin flow along the wet marginal lagg without any actual channel. The samples for chemical analyses and dating are from site A.

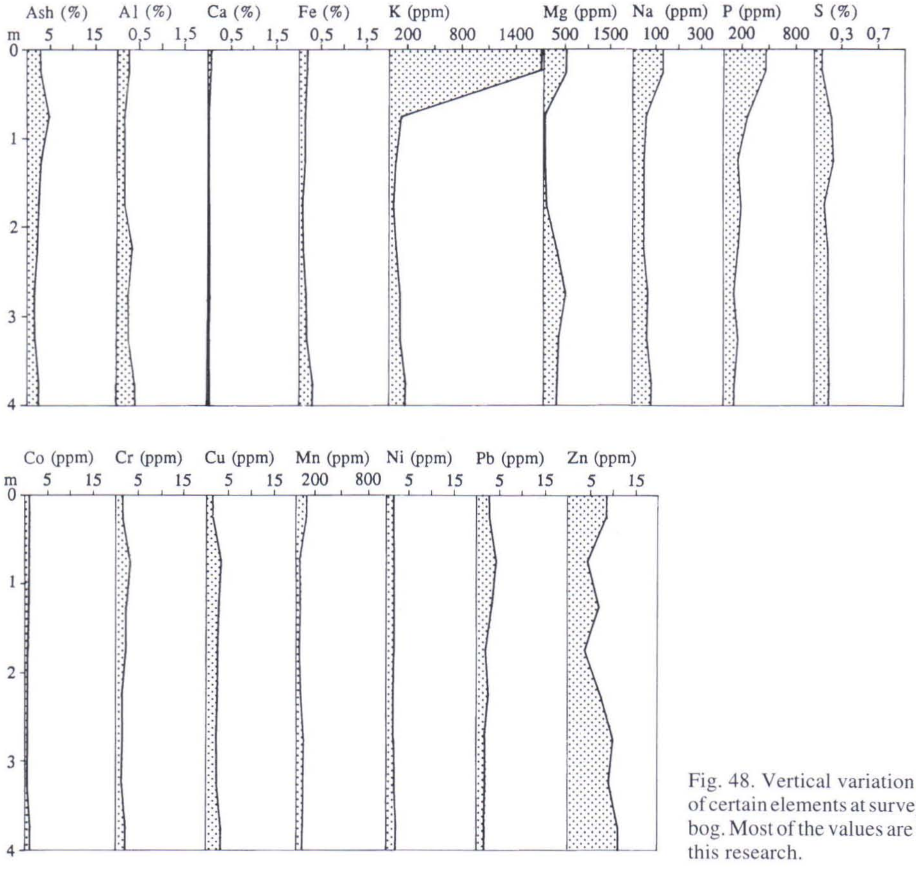

Fig. 48. Vertical variation in the concentrations of certain elements at survey site A on the Mashya bog. Most of the values are the lowest recorded in this research.

$m^{-2}$ $a^{-1}$ (Table 10). The ratio of mineral matter in the dry matter accumulated is extremely small. The accumulation rates are similar to those of the Gishoma swamp, although the peat-forming vegetation is different.

## Interpretation

The central part of the Mashya bog receives nutrients almost only with rain water, and thus the nutrient content is considerably lower than in the river valleys. Vertically the concentrations of various elements vary only slightly, which indicates that the peat deposit has developed regularly. High concentrations are generally found in the surficial and basal parts of raised bogs, and low concentrations in the central part of the deposit (e.g. Sillanpää 1975). In the surficial part of the Mashya bog the concentrations of potassium, sodium and phosphorus are higher than average. The same is also true for raised bogs of high latitudes (e.g. Damman 1978). The minerotrophic phase of the basal part is generally reflected by high concentrations of aluminium, calcium, iron and manganese (Clymo 1983). In the development of the Mashya bog no minerotrophic phase can be distinguished on the basis of these elements, and judging from this the mire turned into a raised bog at a very early point.

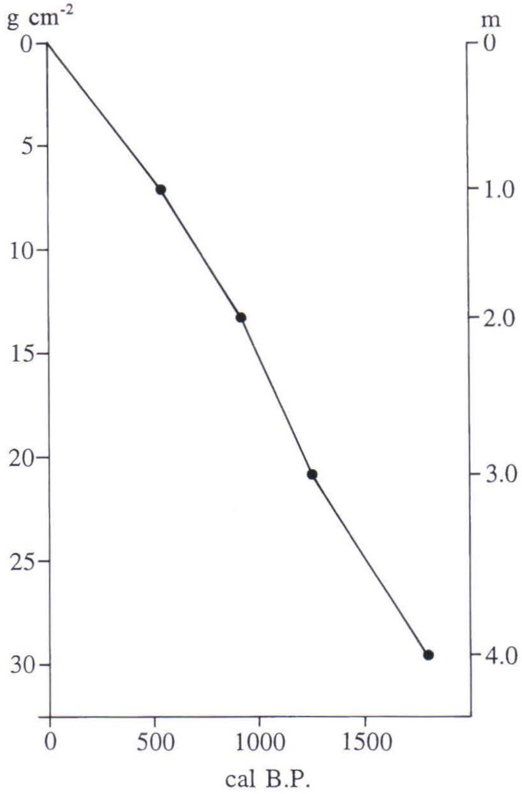

Fig. 49. Cumulative mass of total dry matter below the surface in relation to calibrated ages at site A on the Mashya bog.

Since Mashya is a raised bog the climatic changes have had a crucial effect on the initiation of mire formation and development of the peatland. Peat started to accumulate about

Table 10. Accumulation of dry matter, carbon and energy in the Mashya bog.

| Period | Thickness increment | Accumulation rates | | | | |
|---|---|---|---|---|---|---|
| | | Total dry matter | Organic matter | Mineral matter | Carbon | Energy |
| $^{14}$C yr B.P. | mm $a^{-1}$ | g $m^{-2}$ $a^{-1}$ | g $m^{-2}$ $a^{-1}$ | g $m^{-2}$ $a^{-1}$ | g $m^{-2}$ $a^{-1}$ | MJ $m^{-2}$ $a^{-1}$ |
| 510 - 0 | 1.79 | 135 | 129 | 6 | 72 | 2.6 |
| 980 - 510 | 2.56 | 159 | 154 | 5 | 88 | 3.3 |
| 1305 - 980 | 2.94 | 220 | 215 | 5 | 127 | 4.6 |
| 1855 - 1305 | 2.04 | 162 | 159 | 3 | 93 | 3.5 |
| 1855 - 0 | 2.25 | 163 | 159 | 4 | 91 | 3.4 |

1900 B.P., when according to lake level data (Street and Grove 1979, Haberyan and Hecky 1987) a fairly dry climatic phase was prevailing. In palynological studies of the Burundian mountain region it was, however, found that a short humid phase occurred 2000 - 1800 B.P. (Fig. 60, p. 88; Roche and Bikwemu 1989), which fits well with the time of mire initiation. The accumulation of dry matter was the quickest 1300 - 1000 B.P. or nearly at the same time as in the Gishoma swamp. The accumulation maximum of the Mashya bog is probably related to the change of climate towards greater humidity. The lowest rates of dry matter accumulation occur in the uppermost metre of the deposit, a layer with considerable variations in decomposition degree. It is thus probable that the accumulation rates also vary within this layer. The seemingly high accumulation values of the surface partly compensate for the effect of the highly decomposed layer, which has formed after 500 B.P. Its deposition is apparently related to the climatic change during what is called the 'Little Ice Age'.

## The Cyabaralika basin

The drainage basin of Cyabaralika occupies 0.55 km$^2$, 0.17 km$^2$ or 31 % of which is covered by peatland (Fig. 50). The altitude of the peatland is approximately 1 840 m. The valley has originally been open toward northwest. A lava flow has raised the threshold point of the valley, but the direction of water flow has remained the same. In the south and east the peatland is bordered by Precambrian bedrock, which is covered by reddish-brown fine-grained weathering residue.

This swamp was earlier used for production of fuel peat. The peat production was, however, given up due to drainage problems and today the swamp is covered by a vegetation of *Cyperus latifolius*.

### Stratigraphy and the properties of the peat

The peat deposit of Cyabaralika has been formed mainly by sedges, and the vegetation included both $C_3$ and $C_4$ plants. The peat deposit of Cyabaralika is compact and highly decomposed, the decomposition degree varying from 7 at the surface to 9 at the base. The bottom of the basin is irregular because it consists of lava rocks.

The average water content at site A is 86.3 % and the dry bulk density 143 kg m$^{-3}$. The water content of the uppermost sample is low although the surface of the swamp was very watery during the sampling. Highly decomposed peat is not easily penetrated by water, nor does the water accumulating on the surface of the swamp during the rainy season necessarily increase the water content of the peat.

The ash content is in the range 5 - 26 %, the highest values in the surficial part of the deposit and the lowest ones at a depth of 2 - 4 m. The calorific values are 15 - 21 MJ kg$^{-1}$, with a vertical variation that is inversely proportional to the variation in ash content.

The average pH of the peat is 4.7, with the least acidity in the uppermost sample, although the vertical variations are small. The carbon content averages 52.6 %, with the minimum in the sample from the surficial part, containing abundant ash. The peat contains an average of 4.8 % hydrogen, 1.6 % of nitrogen and 26.4 % of oxygen. The chloride concentration is varied, 19 - 30 ppm.

Among the main elements, the concentrations of aluminium, calcium, iron, magnesium and sodium follow the variations in the ash content (Fig. 51). The concentrations are high, especially in the uppermost sample. The phosphorus concentrations are high in the uppermost two samples. The concentrations of manganese and sulphur are low nor do they show any notable vertical variation. The

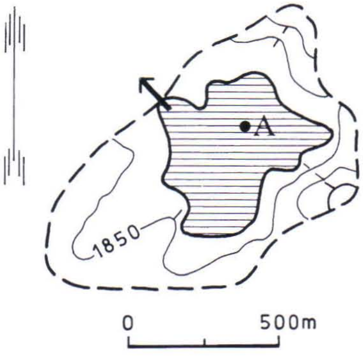

Fig. 50. The Cyabaralika swamp covers 31 % of the drainage basin. It is bounded by lava beds in the NW, and these partly extend beneath the peat. The laboratory samples are from site A.

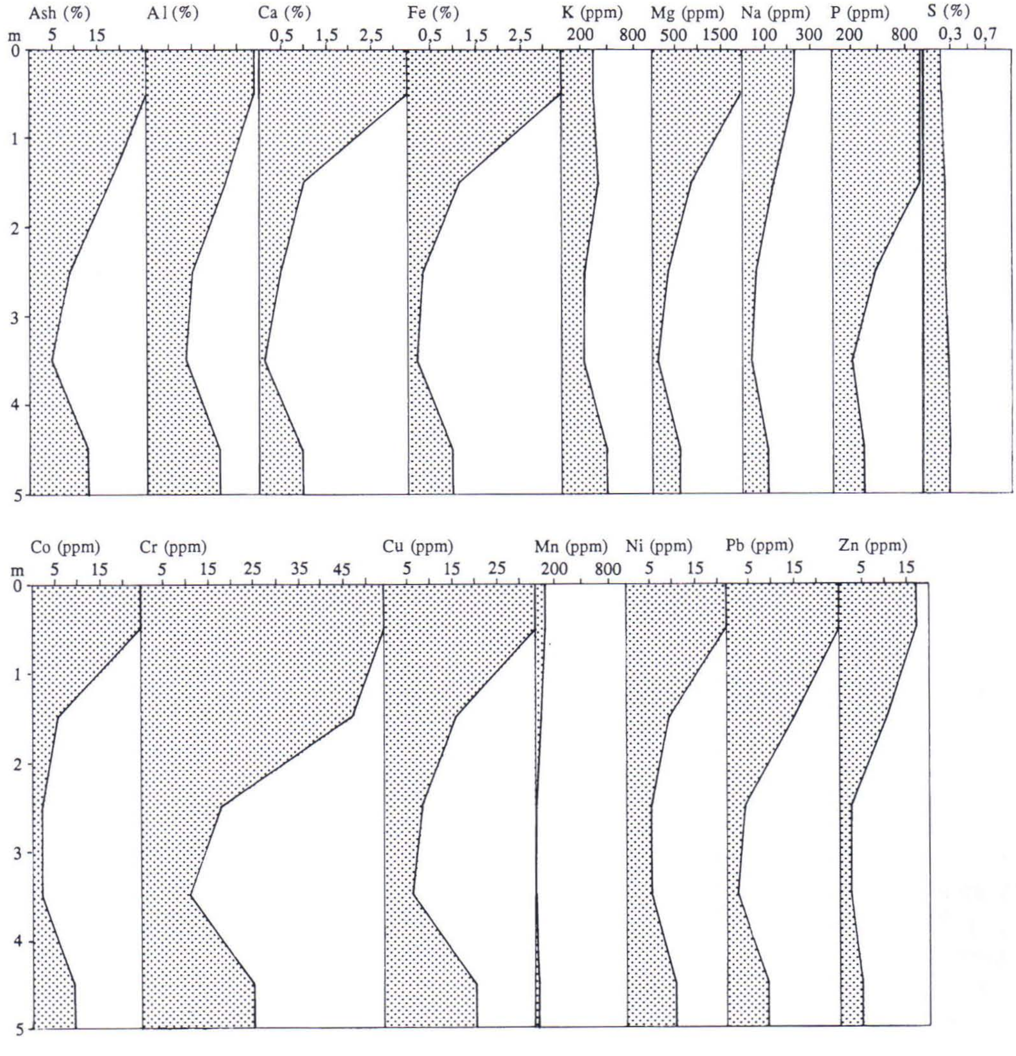

Fig. 51. Vertical variation in the concentrations of certain elements at site A on the Cyabaralika swamp. The majority of the maximum values were found in the uppermost sample.

heavy metal concentrations are high in the surficial part (0 - 2 m), where the concentration of chromium is as high as 54 ppm and that of copper 34 ppm. At a depth of 2 - 4 m the heavy metal concentrations are ordinary, increasing again in the basal part.

### Accumulation of peat

It is possible to study the accumulation of peat in the Cyabaralika swamp for a period of about 7500 years. The valley was terrestrialised about 10 500 $^{14}C$ years ago, and by 3500 B.P. the peat deposit grew 4.3 m thick, the average rate of thickness increment being 0.46 mm $a^{-1}$. This rate is approximately the same as that of the nearby Rugezi swamp, calculated on the basis of dating results presented by Roche (1985) and Chateauneuf et al. (1988). The cumulative mass versus age curve is almost straight (Fig. 52). The total dry matter accumulation rate was somewhat faster than average 8000 - 9000 cal. B.P., the average rate being 61 g $m^{-2}$ $a^{-1}$. The carbon accumulation rate averages 33 g $m^{-2}$ $a^{-1}$ and that of energy 1.2 MJ $m^{-2}$ $a^{-1}$ (Table 11). The rates of thickness increment and accumulation in the Cyabaralika swamp have been considerably lower than those in Rusizi or the Akanyaru area.

### Interpretation

The late Pleistocene/Holocene climate was already changing towards greater humidity during the time of mire initiation in the Cyabaralika basin. The accumulation of organic dry matter, carbon and energy was at its greatest during the postglacial humidity maximum, whereas the lowest accumulation rates are found in the layers deposited after the humidity maximum 7200 - 4500 $^{14}C$ years ago. The accumulation rates in the uppermost layer, deposited 4500 - 2900 $^{14}C$ years ago, are again considerably higher. The increase of accumulation rates in the uppermost layer is in conflict with the climatic changes.

The Cyabaralika basin is partly bordered by recent, very permeable lavas. Probably the basin was formed considerably earlier than the peat started to accumulate. No lake sediments were found on the bottom of the basin, and consequently it must have had an underground outlet before the peat initiation. The blocking of the underground outlet or the opening of a new one had a crucial effect on the hydrology of the basin and the accumulation conditions of the peat.

The highly decomposed peat deposit contributes to the explanation of the low accumulation rates compared with other areas. Since the peatland is small and bordered by permeable recent lavas, it may be assumed that oxygen-rich water has flowed also in the weakly decomposed parts of the peat deposit. As the decomposition progresses the permeability decreases considerably so that the conditions in the peat layer become anaerobic. The decomposition of the organic matter was also favoured by the fairly high concentration of nutrients in the water flowing from the area of Quaternary volcanites (cf. Thompson and Hamilton 1983).

## The Kiguhu basin

The Kiguhu swamp is located deep in a valley dammed by a lava flow. According to a map by Battistini and Prioul (1981) the lava is from the volcano of Sabinyo. The age of the lava determined by Bagdasaryan et al. (quoted by De Mulder and Pasteels 1986) is approximately 140 000 years. The Kiguhu swamp is in the east bordered by Quaternary volcanites, elsewhere by Precambrian rocks. The ancient bedrock is covered by a fine-grained, reddish-brown weathering residue. The size of the drainage basin is approximately 3 $km^2$, covered to 15 % (0.46 $km^2$) by peatland (Fig. 53). The altitude of the swamp is about 1 770 m. The altitude differences are great, since the highest point of the drainage basin rises to a

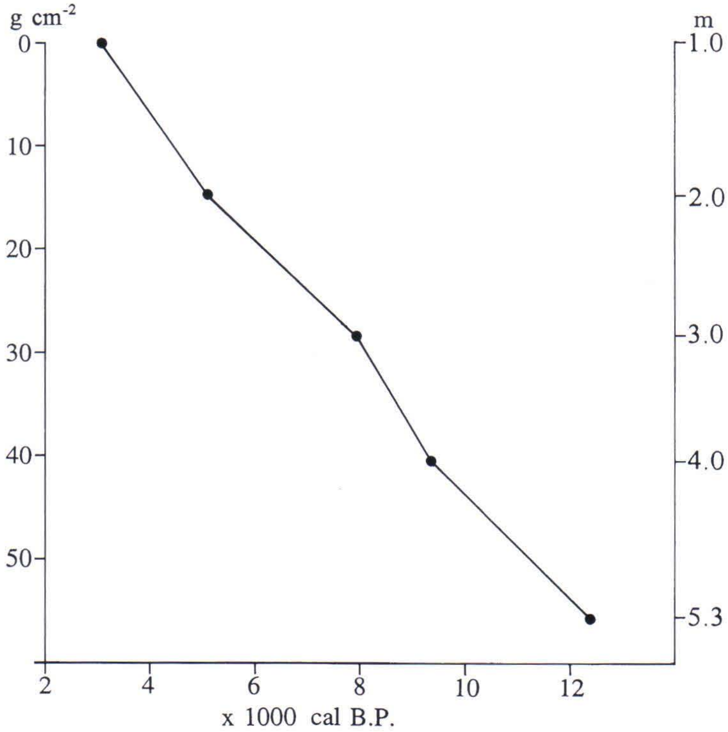

Fig. 52. Cumulative mass of total dry matter below the uppermost dated sample (3080 cal. B.P.) in relation to calibrated ages at site A on the Cyabaralika swamp.

Table 11. Accumulation of dry matter, carbon and energy in the Cyabaralika swamp.

| Period | Thickness increment | Accumulation rates | | | | |
|---|---|---|---|---|---|---|
| | | Total dry matter | Organic matter | Mineral matter | Carbon | Energy |
| $^{14}$C yr B.P. | mm a$^{-1}$ | g m$^{-2}$ a$^{-1}$ | g m$^{-2}$ a$^{-1}$ | g m$^{-2}$ a$^{-1}$ | g m$^{-2}$ a$^{-1}$ | MJ m$^{-2}$ a$^{-1}$ |
| 4500 - 2940 | 0.49 | 73 | 60 | 13 | 36 | 1.3 |
| 7150 - 4500 | 0.35 | 47 | 43 | 4 | 27 | 1.0 |
| 8340 - 7150 | 0.71 | 86 | 82 | 4 | 51 | 1.9 |
| 10470 - 8340 | 0.43 | 51 | 45 | 6 | 27 | 0.9 |
| 10470 - 2940 | 0.46 | 61 | 54 | 7 | 33 | 1.2 |

height of more than 2000 m.

Mining of fuel peat from the swamp started in 1974, and approximately 5000 t of peat is produced annually (Karega 1992). The peat is used in the drying of *Pyrethrum* flowers. There is no natural vegetation at all on the peatland.

### Stratigraphy and the properties of the peat

Judging from the low $\delta^{13}C$ values of the samples for dating, the peat deposit of Kiguhu was formed almost completely by $C_3$ plants. The decomposition degree of the peat deposit is in the range 5 - 9, highest near the surface and lowest near the base. The drainage of the swamp has lowered the groundwater table and thus promoted the decomposition of organic matter in the upper part of the deposit. The peat deposit is underlain by grey gyttja clay. Although the swamp is located near active volcanoes, no volcanic ash layers were observed in the peat layers.

The Kiguhu swamp has been effectively drained for the production of peat. This is also evident from the laboratory results of site A (Fig. 53). The water content is low and the dry bulk density values are high to a depth of 1.5 m. The ash content averages 13.4 %, with a more than threefold figure in the surficial part compared with the basal part, resulting from the rapid decay of the organic matter following the drainage. The average calorific value of the peat is 19.6 MJ $kg^{-1}$, and the lowest values were obtained for the surficial samples, rich in ash.

The pH is approximately 5.5 in nearly the whole sample series. The carbon content of the main part of the deposit is 57 - 58 %, with figures lower than average in the surficial part due to the high ash content. The average hydrogen concentration is 4.8 % and that of nitrogen 1.6 %. The concentrations of calcium, iron, magnesium and sulphur are fairly high and those of sodium and manganese are low (Fig. 54). The vertical variations of the calcium and magnesium concentrations are very similar and do not follow the variation in ash content as in the Cyabaralika swamp. The potassium and phosphorus concentrations of the surficial samples are high. The sulphur concentration is strongly varied, averaging 1.10 %. The lowest concentrations were found in the uppermost and lowermost sample. The chromium concentration of the surficial layer of the Kiguhu swamp is 35 ppm and that of copper 36 ppm. The concentrations of other heavy metals are also fairly high near the surface and low in the middle and basal parts of the deposit.

### Accumulation of peat

The dated samples from the Kiguhu swamp cover a time period of approximately 4 000 years from the late glacial stage to the beginning of the Holocene. The $^{14}C$ age of the lowermost sample is 13 490 B.P. and that of the uppermost one 9520 B.P. The accumulation of dry matter in the 3 m thick dated part of the deposit has been 32 g $cm^{-2}$. The rate of accumulation was at its maximum about 14 000 cal. B.P. (Fig. 55). The average rate of thickness increment in the peat deposit has been

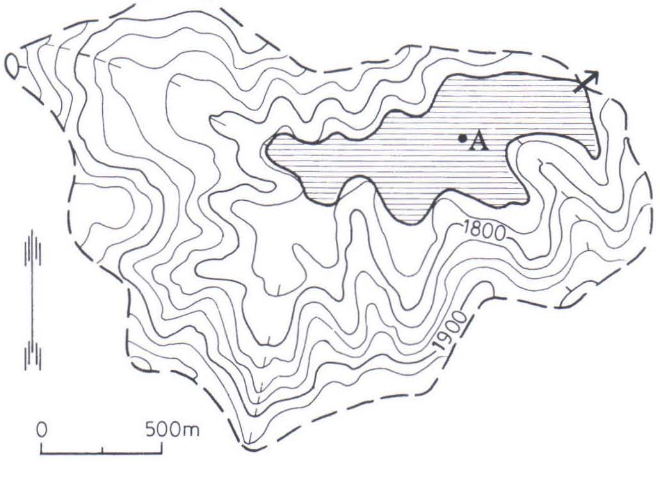

Fig. 53. The hills surrounding the Kiguhu swamp rise more than 200 m above the peatland. The area of the drainage basin is 3 $km^2$, of which the peatland covers 15 %. The peat deposit is bordered in the east by Quaternary volcanites and elsewhere by Precambrian terrain. The laboratory analyses were performed on samples from site A.

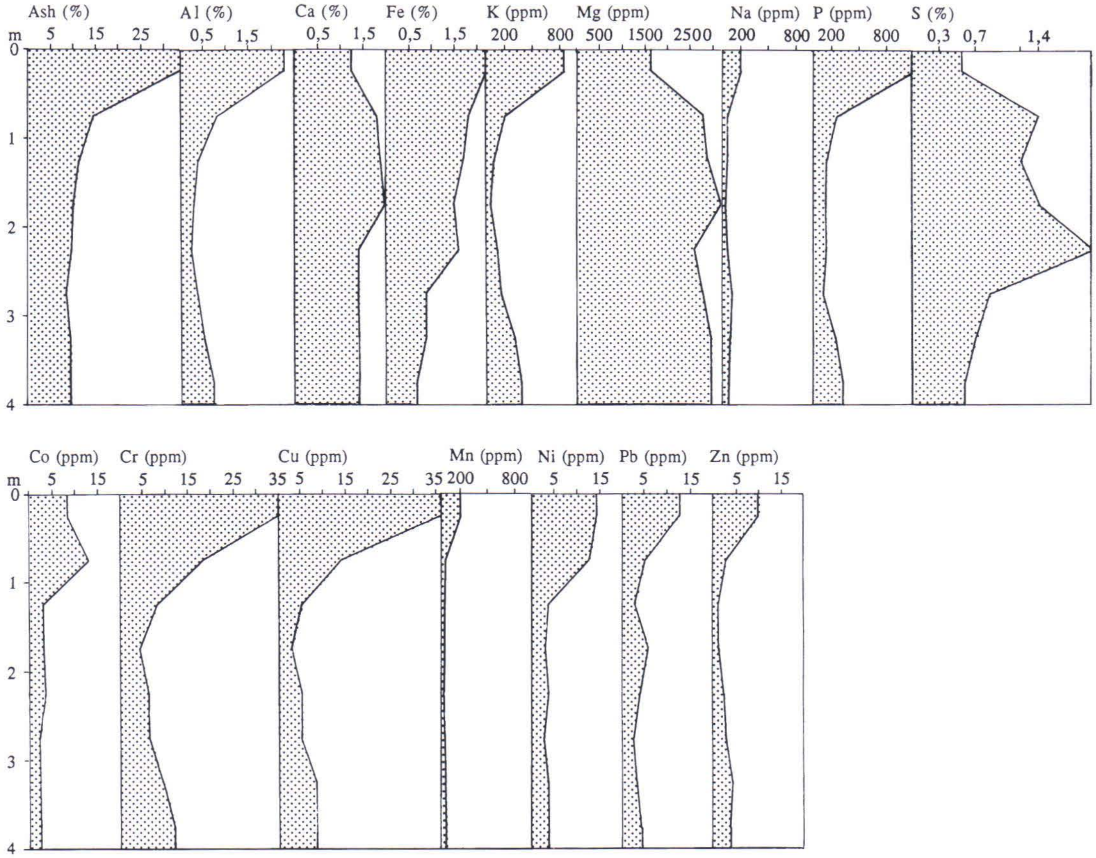

Fig. 54. Vertical variation in the concentrations of certain elements at site A of the Kiguhu swamp.

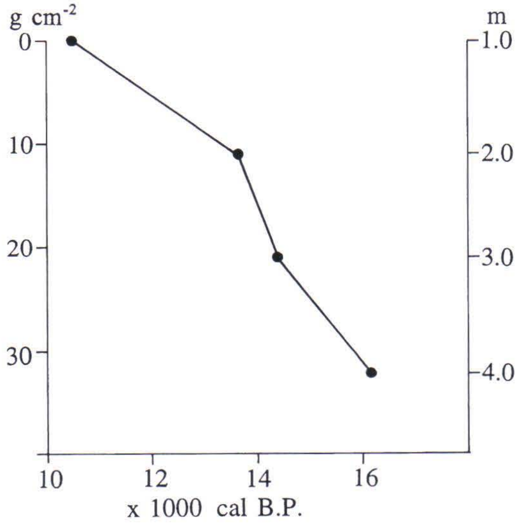

Fig. 55. Cumulative mass of total dry matter below the uppermost dated sample (10 150 cal. B.P.) in relation to calibrated ages at site A on the Kiguhu swamp.

0.53 mm $a^{-1}$ (Table 12). The total dry matter accumulation rate has been on an average 54 g $m^{-2}$ $a^{-1}$, that of carbon 31 g $m^{-2}$ $a^{-1}$ and that of energy 1.1 MJ $m^{-2}$ $a^{-1}$, which are similar to those of the Cyabaralika swamp.

### Interpretation

At the time of mire initiation in the Kiguhu basin approximately 13 500 $^{14}C$ years ago a fairly dry climate still prevailed in tropical Africa (Street and Grove 1979). The accumulation rates were at their maximum about 12 000 B.P. During the accumulation maximum the first signs of a climatic change towards greater humidity already appeared. During the four millenia following the accumulation maximum, the humidity of the climate has increased. However, the accumulation rates have decreased to a fourth of the maximum values. The climatic changes do not support the time of mire initiation nor the variations in accumulation rates, and thus the development of the swamp was controlled by non-climatic factors.

Table 12. Accumulation of dry matter, carbon and energy in the Kiguhu swamp.

| Period | Thickness increment | Accumulation rates | | | | |
|---|---|---|---|---|---|---|
| | | Total dry matter | Organic matter | Mineral matter | Carbon | Energy |
| $^{14}C$ yr B.P. | mm $a^{-1}$ | g $m^{-2}$ $a^{-1}$ | g $m^{-2}$ $a^{-1}$ | g $m^{-2}$ $a^{-1}$ | g $m^{-2}$ $a^{-1}$ | MJ $m^{-2}$ $a^{-1}$ |
| 11680 - 9520 | 0.32 | 35 | 31 | 4 | 20 | 0.7 |
| 12300 - 11680 | 1.35 | 138 | 125 | 13 | 79 | 2.9 |
| 13490 - 12300 | 0.56 | 62 | 56 | 6 | 36 | 1.3 |
| 13490 - 9520 | 0.53 | 54 | 49 | 5 | 31 | 1.1 |

## DISCUSSION

### Onset of peat deposition

Only a part of the African wetlands of today may be classified as mires. The prevailing vegetation does not always indicate peat accumulation. The vegetation may be identical on both wetlands underlain by peat and those underlain by mineral soil (cf. Thompson and Hamilton 1983). By dating basal peat samples the time of peat initiation is obtained, i.e. the point when a wetland started accumulating peat. The accumulation of peat may have been preceded by a long wetland period.

The mires of Rwanda and Burundi were formed either by terrestrialisation of lakes or by paludification of mineral soil areas. Terrestrialisation has been significant in the central part of the Akanyaru swamp complex and in the main basin of Gishoma. The other basins have started accumulating peat without a lake stage.

Mire formation in the river valleys of the area is favoured by soils with low permeability. The lower parts of the slopes usually consist of highly weathered fine-grained material and the valley floors of sand and fines, deposited by the rivers. The paludification of mineral soils require an increase in the water content of the soil, which may be caused either by climatic changes or non-climatic factors.

The most significant climatic changes promoting paludification are increased precipitation and decreased evaporation. Both changes influence the hydrology of the rivers by increasing the discharges and expanding the flood plains. The climate of the last ice age in tropical Africa was considerably drier than that of today. The increase in humidity and the resulting increase in discharge of the rivers was strongest after 10 000 B.P. Another, however smaller, increase in humidity occurred approximately 1400 B.P.

Non-climatic factors may cause significant changes in the hydrology of a basin. Tectonic movements may promote mire formation by changing the gradients of the river so that the stream velocity is slowed down and the flood plains grow. Basins may form in river valleys due to tectonic inclination, tectonic faulting, lava flows and landslides. This kind of basins may be favourable for the onset of peat deposition. Later a mire may extend upstream by paludification of mineral soil areas. The area of Rwanda and Burundi is tectonically active, and thus non-climatic factors frequently contribute to the formation and development of mires.

In the Akanyaru river valley the mire formation started in the southern part of the present swamp complex. Since fluvial and alluvial sediments have been deposited along the main river, the oldest peat deposits occur in the lower parts of the small tributary valleys. The mire formation has spread from these parts toward the upper courses in the form of paludification. In the southern basin of Ndurumu, the peat accumulation started approximately 20 000 $^{14}$C years ago. Due to the small area of the drainage basin the deposition of fluvial sediments has been minor. In the lower part of the Buyongwe valley, however, the deposition of fluvial sediments continued for thousands of years after the initiation of peat formation in the southern basin of Ndurumu. Peat started accumulating as late as about 12 000 $^{14}$C years ago. The onset of peat formation occurred in the Kinamba valley approximately 10 000 $^{14}$C years ago and about 2 500 $^{14}$C years ago in the Cyili valley. Due to the large area of the drainage basin the deposition of mineral matter in the Cyili valley has continued longer than in the other tributary valleys studied.

The peat is limited to lake sediments in the Nyavyamo valley, in the main river valley of the Rwamiko area and in the lower part of the Kinamba valley. The gyttja layers in the Akanyaru valley indicate the former existence of an extensive lake, which was at its maximum a little more than 10 000 years ago. The area of the lake decreased and the mire area increased due to overgrowth. As concerns Rwamiko, the lake was overgrown about 8000 $^{14}$C years ago and today only the small lakes at the far end of the bays towards the east remain.

The Gishoma basin was formed as a consequence of tectonic faulting. In the main basin a lake was formed, which was terrestrialised by overgrowth approximately 1600 B.P. The overgrowth occurred during a fairly dry climatic period. Landslides have contributed to the onset of peat deposition in the bays extending towards the west and northwest. The Mashya peat deposit started to form during a short humid climatic period about 1900 $^{14}$C years ago.

The Cyabaralika and Kiguhu swamps were formed in valleys dammed by lava flows, the former about 10 500 $^{14}$C yars ago and the latter about 13 500 $^{14}$C years ago. The valleys were probably dammed considerably before the mire formation. The Kiguhu basin started accumulating peat during an very dry climatic period, and consequently the reasons for the mire formation must be non-climatic. When the Cyabaralika peat deposit started to form the climate was already turning more humid, and so the onset of peat deposition may have been caused by both climatic and non-climatic factors.

## Accumulation of dry matter

In the upper part of a peat deposit there is always a fairly oxygen-rich surficial layer, the acrotelm, in which the bulk of the plant material produced by the mire ecosystem is decayed. Since the acrotelm contains both living and recently produced plant matter, the accumulation values measured in this zone are greater than the actual rates of accumulation. The decay of plant matter continues, however slowly, in the anaerobic zone, the catotelm. As the peat deposit grows thicker, the total decay occurring in the catotelm increases. The peat deposit reaches a steady state when the total decay in the catotelm reaches the amount passing from the acrotelm to the catotelm. Theoretical models of the growth of the peat deposits of raised bogs have been presented by, e.g. Damman (1979), Ingram (1982, 1983) and Clymo (1984, 1991, 1992). They stress the significance of the internal factors of the mire for the accumulation of peat. The mires studied here are, with one exception, limnogenic river valley swamps, and so the influence of external factors is much greater in them than in raised bogs. The accumulation of peat in the river valleys is thus to be considered as a part of the processes occurring in the drainage basin.

### Primary production in the mire ecosystem

The production of biomass in tropical mires is varied due to the diversity of the mire ecosystems. The papyrus swamps are the most productive mires of the study area (Fig. 56). Thompson et al. (1979) has published data on the biomass and productivity of papyrus swamps in Zaire and Uganda. The biomasses of the papyrus swamps increase with absolute altitude and are smaller in the central parts of the swamps than in the marginal parts. The biomass production in the central part of a valley swamp in Kampala is approximately 9000 g $m^{-2}$ $a^{-1}$. At Lake George the production in the central part of the papyrus swamp is approximately 10 600 g $m^{-2}$ $a^{-1}$ and in the marginal part 12 400 g $m^{-2}$ $a^{-1}$. Thompson et al. (1979) conclude that the climate is a factor that limits the amount of biomass and the supply of nutrients a factor limiting the productivity.

The primary production of the most common mire plants of tropical Africa are clearly surpassed by the production of the papyrus reed. Howard-Williams and Gaudet (1985) estimate the net productivity of *Typha* to be of the order 2500 - 3000 g $m^{-2}$ $a^{-1}$ in the tropics. Denny (1991) report 3000 - 7000 g $m^{-2}$ $a^{-1}$ as the primary production of *Typha* and *Phragmites* and 4000 g $m^{-2}$ $a^{-1}$ as that of *Potamogeton*.

The primary production on the minerotrophic mires of the temperate zone is in general 1500 - 2000 g $m^{-2}$ $a^{-1}$ and on the ombrotrophic ones 300 - 1000 g $m^{-2}$ $a^{-1}$ (Bradbury and Grace 1983). The primary production on the woody mires of Finland is generally considerably greater than that of the treeless mires (Laine and Vasander 1986), whereas in the tropics the production of the papyrus swamp may surpass that of the swamp forest. The primary production of natural mangrove forest in Malesia has been 1800 g $m^{-2}$ $a^{-1}$ (Ong 1993) and that of *Melaleuca leucadendra* swamp forest in Thailand approximately 930 g $m^{-2}$ $a^{-1}$ (Samati 1987). The production of the *Melaleuca* forest was only about one tenth of the production of the Ugandan papyrus swamps.

### Decay of plant matter

According to Clymo (1983) the most important factors contributing to the decay of plant matter are the temperature, the water supply, the oxygen supply, the nature of plant matter and the nature of the microorganisms and invertebrates in the peat.

Under aerobic conditions the decay process

Fig. 56. The biomass production of papyrus may even exceed that of many plants cultivated using fertilizers. View of the northern part of the Buyongwe swamp.

produces carbon dioxide and under anaerobic conditions both carbon dioxide and methane. Thus a lowering of the groundwater level by draining increases the carbon dioxide emissions of the mire. The greatest methane emissions have been measured on wet minerotrophic mires (Martikainen et al. 1992). Since the methane production increases with temperature, the natural mires and the rice fields of the tropics are significant sources of methane on a global scale (Bouwman 1990). The long-term variations of the methane emissions are mainly due to variations in humidity and temperature caused by either climatic or nonclimatic factors (Crill et al. 1992). Methane is approximately 30 times as effective a greenhouse gas as carbon dioxide (Martikainen et al. 1992), and thus special attention is paid to the study of its sources and sinks in the research on climatic change. On a continental scale, Africa has been a net sink of carbon during the last deglaciation but has become a source of carbon after 6000 B.P. (Branchu et al. 1993).

Most of the plant matter produced by the mire ecosystems is decayed. In the mires of high latitudes only 10 - 20 % of the plant matter produced ends up in the catotelm (Clymo 1984). The parts of the plant above ground are especially prone to decay in a warm climate, and so the peat is mainly formed by the underground parts of the plant. The deeper its roots penetrate, the greater are its chances of forming peat. *Typha* and papyrus reed have an especially great ratio of underground parts. Howard-Williams (quoted by Howard-Williams and Gaudet 1985) has obtained 52 % as the ratio of underground biomass in *Typha*. The ratio formed by roots and rhizome of papyrus reed is according to Thompson et al. (1979) 25 %.

The fungi and bacteria are important for the decay of plant matter. The bacteria are more effective than the fungi, and are the most important decay organisms at a pH above 5 - 5.5 (Thompson and Hamilton 1983). A low pH slows the microbic action and thus promotes the formation of peat. The most favourable pH

Fig. 57. The vegetation of the central part of the Mashya bog is formed by *Syzygium* trees and *Sphagnum* moss. The activity of microorganisms that decompose organic matter is limited by the low pH.

conditions for peat deposition prevail in the Mashya bog, where the average pH is only 3.4 (Fig. 57). In the Akanyaru area the pH is generally 5 - 6, while the highest average pH (6.2) was found in the Cyili swamp. Besides the pH, the nutrient content of the peat also affects the rate of the decay processes. Clymo (1983) has stated that a high nitrogen concentration in plants increases the rate of decay.

The altitude difference between the uppermost and the lowermost mire is approximately 500 m. The average temperature decreases by 0.6°C with each 100 m of increased altitude (Bidou et al. 1991). Thus the average temperature of Cyabaralika is about 3°C lower than in the Akanyaru area. The decrease in temperature at the ground surface slows down the action of decay organisms, and so the temperature conditions are more favourable for peat formation in the Virunga area than in the Akanyaru area.

The most important decay organisms of organic matter are aerobic fungi and bacteria, and so the decomposition occurs mainly in the oxygen-rich surficial layer, the acrothelm. The deeper the groundwater level, the thicker the layer in which the aerobic decay organisms are able to live and the poorer the conditions for peat formation. If the mire water flows, significant decay may take place below the groundwater level, too.

The oxygen concentration of the water is considerably higher in Akanyaru (40 - 50 %) than in Buyongwe (2 - 4 %). The conditions for the action of aerobic decay organisms are thus considerably better in the flood plain of Akanyaru than in the Buyongwe swamp. The oxygen content of Akanyaru was measured in the channel, where the flow of the flooding river is the strongest. The oxygen concentration of Akanyaru decreases probably toward the margins of the flood plain. The differences in oxygen concentration of the water partly explain the variations in decomposition degree of the peat in the Akanyaru swamp complex.

The seasonal fluctuation of the water level is one of the most significant factors affecting

Fig. 58. When mires are taken into use for cultivation the accumulation of organic matter comes to an end and they may change from carbon sinks into carbon sources. View of the Gishoma swamp at site D.

the decay of plant matter and the accumulation of peat. In most of the tropical area the rains are periodical, according to the seasons. The alternation of rainy and dry seasons cause changes in the discharge of the rivers and fluctuations in the water level of the mires. The greater these variations, the better are the conditions of the aerobic micro-organisms. In the Akanyaru area the fluctuations of the water level are greatest on both sides of the main channel and smallest in the bays that lack a central channel. The average degree of peat decomposition also reflects the fluctuations in water level. The most highly decomposed peat is found in areas with a strongly fluctuating water level and the peat with the lowest decomposition degree in areas with a steady water level (cf. Eggelsmann et al. 1993). Especially watery and floating peat deposits may by changes in volume compensate for the variation in water level (Tallis 1983). Such areas are the bays extending towards the east from Akanyaru and a part of the Gishoma swamp, in which the fluctuations of the mire surface level decrease the relative fluctuations of the water level.

In the history of mire ecosystems, there is frequently an alternation between phases of higher and lower wateriness than average. These phases are longer than those of the seasonal variation. As the mire becomes drier, the oxygen-rich surficial layer grows thicker, which favours decay of plant matter. The drier phases are visible in the stratigraphy in the form of decomposed layers. Correspondingly during the watery phases the acrotelm is thin and the peat is accumulated in a less decomposed state. If the dry phase is long, the decay of the plant matter surpasses the production of biomass and the peat deposits start to wear off. The wear of the peat deposits may be due to natural causes as in Senegal (Korpijaakko 1985) and in places in Indonesia (Sieffermann et al. 1988) or to artificial drainage (Fig. 58). The wear of peat deposits in agricultural use has been measured in Florida, where it is 1.3 - 7.6 cm $a^{-1}$ (Hofstetter 1983) and in Malesia (2 - 3 cm $a^{-1}$) (Mutalib et al. 1992).

Table 13. Thickness increment and peat accumulation in tropical and subtropical environment.

| Location | Elevation | Period | Thickness increment | Accumulation rates | | Source |
|---|---|---|---|---|---|---|
| | | | | Total dry matter | Carbon | |
| Mire and country | m a.s.l. | $^{14}$C years B.P. | mm $a^{-1}$ | g $m^{-2}$ $a^{-1}$ | g $m^{-2}$ $a^{-1}$ | |
| Siak Kanan, Indonesia | | | | | | |
| Core 1 | | 4460 - 0 | 0.2 | 16 | | Diemont and Supardi 1987 |
| Core 2 | | 4470 - 0 | 2.2 | 143 | | Diemont and Supardi 1987 |
| Core SK-5 | 12 | 5220 - 0 | 0.84 | | | Supardi et al. 1993 |
| Core SK-7 | <15 | 4915 - 0 | 0.26 | | | Supardi et al. 1993 |
| Core SK-8 | 10 | 4700 - 0 | 1.35 | | | Supardi et al. 1993 |
| Core SK-11 | <15 | 3620 - 0 | 2.25 | | | Supardi et al. 1993 |
| Bengkalis Island, Indonesia | | | | | | |
| Core BK-6 | 10 | 4740 - 0 | 1.65 | | | Supardi et al. 1993 |
| Katingan-Rungan, Indonesia | <100 | 8000 - 6000 | 2.0 | | | Sieffermann et al. 1988 |
| Danau di Atas Swamp, Indonesia | 1535 | 22370 - 0 | 0.65 | | | Newsome and Flenley 1988 |
| Telago Swamp, Indonesia | 1550 | 9105 - 0 | 1.10 | | | Newsome and Flenley 1988 |
| Baram Swamp, Malaysia | <50 | 4270 - 0 | 2.81 | | | Anderson 1964 |
| Pekan Nanas, Malaysia | <100 | 4900 - 0 | 0.11 | | | Haseldonckx 1977 |
| Muthurajawela, Sri Lanka | <10 | 7420 - 0 | 0.60 | 80 | | Ekono 1985, Lappalainen 1987 |
| Muthurajawela, Sri Lanka | <10 | 6910 - 0 | 0.67 | 76 | | Lappalainen 1987 |
| Badda, Ethiopia | 4040 | 11500 - 0 | 0.26 | | | Hamilton 1982 |
| Cherangani, Kenya | 2900 | 12650 - 0 | 0.23 | | | Van Zinderen Bakker 1964 |
| Cherangani, Kenya | 2900 | 17000 - 0 | 0.22 | | | Coetzee 1967 |
| Koitoboss Bog, Kenya | 3940 | 6505 - 0 | 0.31 | | | Hamilton 1982 |
| Ahakagyezi Swamp, Uganda | 1830 | 4670 - 0 | 2.09 | | | Hamilton et al. 1986 |
| Ahakagyazi Swamp, Uganda | 1830 | 3360 - 0 | 2.46 | | | Taylor 1990, 1993 |
| Muchoya Swamp, Uganda | 2250 | 6570 - 0 | 0.68 | | | Morrison 1968 |
| Muchoya Swamp, Uganda | 2230 | 7460 - 0 | 0.77 | | | Taylor 1990, 1992 |
| Muchoya Swamp (MC3), Uganda | 2250 | 16260 - 0 | 0.78 | | | Taylor 1990 |
| Busoro, Rwanda | 1350 | 3515 - 0 | 0.43 | | | Chateauneuf et al. 1988 |
| Cyili Swamp, Rwanda | 1350 | 2495 - 0 | 3.48 | 209 | 113 | present study |
| Kinamba Swamp, Rwanda | 1350 | 8270 - 0 | | | | present study |
| Gishoma Swamp, Rwanda | | | | | | |
| Core A | 1620 | 1600 - 0 | 2.77 | 153 | 86 | present study |
| Core B | 1620 | 1440 - 0 | 3.35 | 188 | 99 | present study |
| Core C | 1630 | 2000 - 0 | 3.98 | 189 | 106 | present study |

| | | | | | | |
|---|---|---|---|---|---|---|
| Mashya Bog, Rwanda | 1700 | 1855 - 0 | 2.25 | 163 | 91 | present study |
| Kiguhu Swamp, Rwanda | 1770 | 13490 - 9520 | 0.53 | 54 | 31 | present study |
| Ruhondo, Rwanda | 1800 | 4670 - 0 | 0.54 | | | Roche 1985 |
| Cyabaralika Swamp, Rwanda | 1840 | 10470 - 2940 | 0.46 | 61 | 33 | present study |
| Kamiranzovu Swamp, Rwanda | 1950 | 37630 - 13575 | 0.45 | | | Hamilton 1982 |
| Rugezi, Rwanda | 2050 | 1315 - 0 | 0.46 | | | Chateauneuf et al. 1988 |
| Rugezi, Rwanda | 2050 | 5770 - 0 | 0.31 | | | Roche 1985 |
| Buyongwe, Burundi | 1370 | 5080 - 0 | 2.95 | | | Chateauneuf et al. 1988 |
| Buyongwe Swamp, Burundi | 1370 | 11770 - 0 | 2.03 | 230 | 125 | present study |
| Ndurumu Swamp, Burundi | 1370 | 20200 - 0 | 1.62 | 125 | 65 | present study |
| Kuruyange, Burundi | 2000 | 7650 - 0 | 1.29 | | | Bonnefille et al. 1991 |
| Kashiru, Burundi | 2100 | 31000 - 0 | 0.23 | | | Bonnefille and Riollet 1988 |
| Kashiru, Burundi | 2150 | 21870 - 0 | 0.27 | | | Roche and Bikwemu 1989 |
| Wonderkrater, South Africa | 1100 | 14180 - 0 | 0.33 | | | Scott 1982 |
| Aliwal North, South Africa | 1360 | 4320 - 0 | 0.78 | | | Coetzee 1967 |
| Rietvlei, South Africa | 1480 | 7130 - 1290 | 0.18 | | | Scott and Vogel 1983 |
| Maluti Mts, Lesotho | 3200 | 8020 - 0 | 0.25 | | | Van Zinderen Bakker and Werger 1974 |
| Touba Ndiaye, Senegal | <50 | 9370 - 4980 | 0.57 | | | Korpijaakko 1985 |
| Negril Morass, Jamaica | | | | | | |
| Core 1 | <20 | 5970 - 0 | 0.96 | | | Digerfeldt and Enell 1984 |
| Core 3 | <20 | 6220 - 0 | 1.09 | | | - " - |
| Core 4 | <20 | 5680 - 0 | 0.78 | | | - " - |
| Core 5 | <20 | 5100 - 0 | 0.77 | | | - " - |
| Core 7 | <20 | 6960 - 0 | 1.35 | | | - " - |
| Core 8 | <20 | 8070 - 0 | 1.61 | | | - " - |
| Core 9 | <20 | 6610 - 0 | 1.16 | | | - " - |
| Black River Morass, Jamaica | | | | | | |
| Core 1 | <20 | 6500 - 0 | 1.08 | | | Digerfeldt and Enell 1984 |
| Core 2 | <20 | 4140 - 0 | 0.64 | | | - " - |
| Core 3 | <20 | 3590 - 0 | 0.50 | | | - " - |
| Core 4 | <20 | 5470 - 0 | 0.56 | | | - " - |
| Core 5 | <20 | 6080 - 0 | 0.76 | | | - " - |
| Core 6 | <20 | 4410 - 0 | 0.44 | | | - " - |
| Core 7 | <20 | 6470 - 0 | 1.03 | | | - " - |
| Core 8 | <20 | 6030 - 0 | 0.85 | | | - " - |
| Core 9 | <20 | 3890 - 0 | 0.60 | | | - " - |
| Core 10 | <20 | 5950 - 0 | 1.18 | | | - " - |
| Core 11 | <20 | 6220 - 0 | 1.04 | | | - " - |

## Rates of thickness increment

The average rates of thickness increment in the peat deposits studied are between 0.46 and 3.98 mm $a^{-1}$. The peat deposits of the Virunga area have grown in thickness more slowly, although their development cannot be followed to the present day. The deposits with the highest rates of thickness increment are the bay of the Gishoma swamp extending towards the west (C) and the Cyili swamp. The rate of thickness increment has varied during the various phases of the history of the mires. The greatest differences are shown by the Ndurumu swamp, where the average rate of thickness increment is 1.06 mm $a^{-1}$ and that of the layer at a depth of 5 - 10 m is 7.07 mm $a^{-1}$.

The rate of thickness increment in the peat deposits of Africa varies from the negative values of the eroded layers to several millimetres a year. The values for the mires located at great altitudes (2900 - 4000 m a.s.l.) in Ethiopia, Kenya and Lesotho are 0.2 - 0.3 mm $a^{-1}$ (Table 13), whereas the values for the mires located at an altitude of 1800 - 2300 m in Uganda, Rwanda and Burundi are higher (0.2 - 2.5 mm $a^{-1}$), however, considerably varied from basin to basin. The rate of thickness increment of the Kamiranzovu swamp during the last ice age was 0.45 mm $a^{-1}$. Since the thickness growth has ceased for natural reasons, a better picture of the average thickness growth is obtained by calculating it up to the present day. The average rate of thickness increment will then be 0.31 mm $a^{-1}$. The greatest average values (2 - 4 mm $a^{-1}$) were obtained for the mires in Rwanda and Burundi at an altitude of 1300 - 1700 m a.s.l., studied here. For peat deposits that started forming as early as during the last glacial stage (e.g., those of Ndurumu and Kashiru), the values are smaller than for other mires in the corresponding altitude zone. The data from South Africa in Table 13 concern spring water mires, and in them the rate of thickness increment has remained below 1 mm $a^{-1}$.

According to the dating results presented by Korpijaakko (1985) the average rate of thickness increment obtained for a certain peat deposit in the Nyayes area, Senegal, is 0.57 mm $a^{-1}$. This peat deposit comprises only the first half of the Holocene. Probably the thickness growth has come to an end at some point during the second half of the Holocene, and the wear of the deposit has started. The surface of the present peat deposit is approximately 5000 years old. If the rate of thickness increment is calculated up to the present day, the net value obtained is 0.30 mm $a^{-1}$.

The peat deposits of minerotrophic coastal mires grow in thickness during the transgression stages of the ocean and may be worn off during the regressive stages (cf. Cobb et al. 1989). In the case of Senegal the Holocene fluctuation of the sea level has been only one of the factors influencing the hydrology of the mire, whereas the fluctuation of the sea level has had a more pronounced effect on the development of the coastal mires of Jamaica and Sri Lanka. Digerfeldt and Enell (1985) have even compiled a curve depicting the rise in sea level on the base of the ages of the basal peat samples from the mire. The average rate of thickness increment for the peat of Negril Morass was 1.10 mm $a^{-1}$ and that of Black River Morass 0.79 mm $a^{-1}$. The values are higher in the older parts of the mires than in the younger parts (Table 13), which is due to the slowing of the sea level rise during the later half of the Holocene. The average rate of thickness increment in a certain coastal mire of Sri Lanka is considerably smaller (0.6 - 0.7 mm $a^{-1}$) than that in a peat deposit of the same age in Jamaica, which reflects the different rates of sea level rise in different parts of the world.

The average rate of thickness increment of the central parts of the raised bogs of Southeast Asia is a little more than 2.0 mm $a^{-1}$ (e.g. Siak Kanan cores 2 and SK11, Katingan-Rungan and Baram Swamp, Table 13). In most sections the rate slows down towards the surface (Anderson 1964, Diemont and Supardi 1987, Sieffermann et al. 1988, Neuzil and Cecil 1992, Supardi et al. 1993). In some cases the thickness growth of the peat deposit has come to an end and possibly turned into wear. Sieffermann et al. (1988) concludes that the peat deposit of Katingan-Rungan reached its maximum thickness 2500 years ago. After that the peat deposit has started to wear off, and the present rate of wear is 1 mm $a^{-1}$. In laggs with thin peat layers the average rate of thickness increment has remained below 0.3 mm $a^{-1}$ (e.g., Siak Kanan cores 1 and SK7 and Pekan Nanas, Table 13).

The thickness increments of the peat deposits are greatly varied in all climatic zones. Tolonen (1973) has obtained a fivefold difference between the basal and surficial parts of the deposits. The higher values of the surficial part are mainly due to the fact that the basal parts of the deposits are more compacted than are the surficial parts. Aaby and Tauber (1975) have obtained similar results concerning a raised bog they studied in Denmark. Zurek (1976) reports 0.45 mm $a^{-1}$ as the average rate of thickness increment of the peat and gyttja deposits in Eurasia. Franzén (1992) has compiled a summary of data from studies including, e.g. North America, according to which the average rate of thickness increment as concerns mires in the northern hemisphere is 0.6 mm $a^{-1}$.

The differences in thickness growth do not necessarily reflect the true rising of the mire surface. Due to compaction of the deposits the samples may have sunk deeper than the ancient mire surface level. The thickness increment of the peat deposits also gives a very inadequate picture of the dry matter accumulation rate, reflecting the true accumulation only when the dry bulk densities of the two deposits are equal. This is not generally the case, however, since up to fivefold differences may exist between the figures for layers in a natural mire. A corresponding difference may exist between accumulation rates, regardless of equal rates of thickness increment.

### Rates of dry matter accumulation

In the old peat deposits of the Akanyaru area (Buyongwe, Ndurumu, Rwamiko and Kinamba) the average dry matter accumulation rate is in the range 110 - 220 g $m^{-2}$ $a^{-1}$ and that of carbon 55 - 110 g $m^{-2}$ $a^{-1}$. In the Buyongwe swamp the accumulation of dry matter was at its maximum 10 000 - 9000 B.P. (Fig. 59). During the same period the accumulation rates in the nearby Ndurumu swamp were low. The long sample intervals made it impossible to distinguish the period of rapid accumulation during the early Holocene. In the Kinamba swamp the dry matter accumulation maximum dates to the early Holocene, although to a later time than in the Buyongwe swamp. The dry matter accumulation rates in the Buyongwe, Ndurumu and Kinamba swamps were lower than average 4500 - 3000 B.P. and higher than average after 1500 B.P. (Fig. 59).

The peat deposits of Cyili, Gishoma and Mashya were formed during the last 2500 years. The average dry matter accumulation rate in the Cyili swamp exceeds 200 g $m^{-2}$ $a^{-1}$, whereas in the Gishoma and Mashya peat deposits it is somewhat smaller (150 - 190 g $m^{-2}$ $a^{-1}$). The accumulation of dry matter was, in spite of higher temperature and nutrient content, more rapid in the Cyili swamp. The accumulation of dry matter, carbon and energy was in all three peat deposits at their maximum 1400 - 1000 years ago.

The average rates of dry matter accumulation in the Virunga area were considerably lower (about 60 g $m^{-2}$ $a^{-1}$) than in the Akanyaru or Rusizi area. The average accumulation rates are not completely comparable, since the youngest parts are lacking in the peat deposits of Cyabaralika and Kiguhu. The peat accumulation rates in the Virunga area are low, even compared with parts of corresponding age in the Akanyaru deposit. The maximum accumulation of dry matter, carbon and energy has taken place 8000 - 7000 B.P. in the Cyabara-

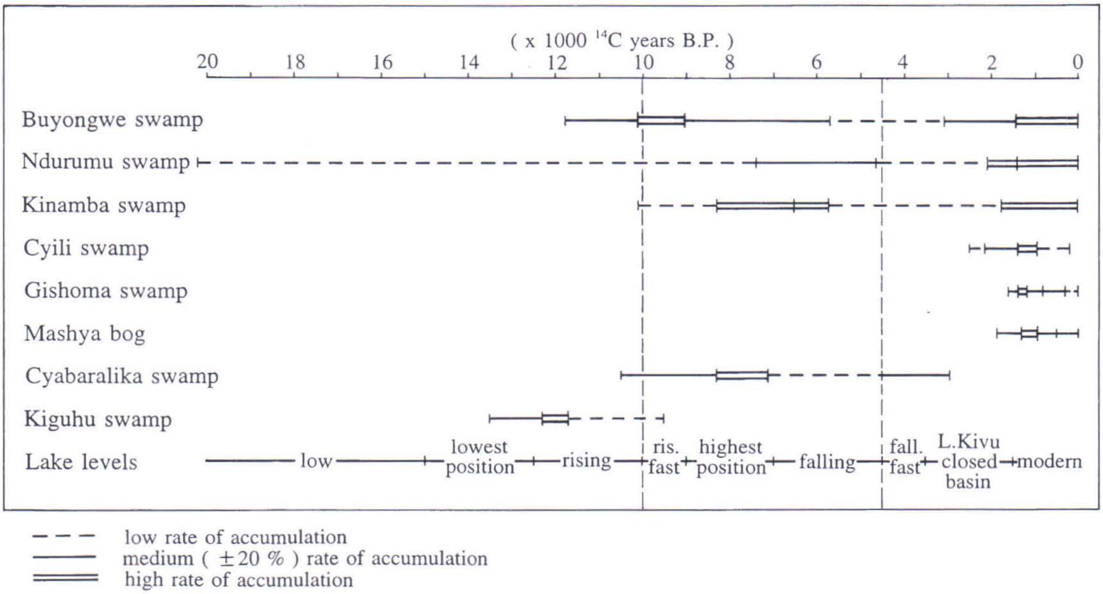

Fig. 59. Variation in the rate of total dry matter accumulation in relation to the average accumulation rate for the mire concerned. Lake level fluctuations in tropical Africa after Street and Grove (1979) and Haberyan and Hecky (1987).

lika sample series and approximately 12 000 B.P. in that of Kiguhu (Fig. 59).

Diemont and Supardi (1987) obtained as the dry matter accumulation rate in a dated sample series from Indonesia 240 g $m^{-2}$ $a^{-1}$ for the period 4500 - 3500 B.P. and 100 g $m^{-2}$ $a^{-1}$ for the period 3500 - 0 B.P. On the basis of data from Sri Lanka (Ekono 1985, Lappalainen 1987) the average accumulation rate obtained for dry matter is 70 - 80 g $m^{-2}$ $a^{-1}$. In the temperate climatic zone the accumulation rates are generally lower. According to Tolonen (1979) the long-term accumulation rates for dry matter in the mires of Northern Europe range between 19 and 68 g $m^{-2}$ $a^{-1}$ for ombrotrophic peat and between 11 and 60 g $m^{-2}$ $a^{-1}$ for minerotrophic peat. Regardless of the short growth season, quite high accumulation rates may also occur locally in the mires of the boreal zone. Ikonen (1993) reports a dry matter accumulation rate up to 208 g $m^{-2}$ $a^{-1}$ in a certain section of *Sphagnum* moss. This value already compares to the average accumulation rates in the Akanyaru area.

The long-term carbon accumulation rates in the Canadian mires range between 10 and 35 g $m^{-2}$ $a^{-1}$, decreasing towards the north (Ovenden 1990). Results of the same order have been reported from Finland, where the carbon accumulation rates are in the range 13 - 41 g $m^{-2}$ $a^{-1}$ in raised bogs and 8 - 25 g $m^{-2}$ $a^{-1}$ in aapa mires (Tolonen et al. 1992a). Gorham (1991) estimated the average carbon accumulation rate in northern mires to be 29 g $m^{-2}$ $a^{-1}$, while Franzén (1992) arrived at a somewhat lower estimate, 21.4 g $m^{-2}$ $a^{-1}$. The long-term average carbon accumulation rate in the mires of high latitudes is approximately one fourth of the corresponding values for the mires of Rwanda and Burundi.

## Factors influencing changes in accumulation rate

The changes in peat accumulation rates are due to changes either in the production of biomass or in the activity of decay organisms. The primary production may vary with the normal development of the mire, so that the productivity changes as changes occur in the peat-forming vegetation. The decay process again is affected by numerous factors, most of which related to the hydrology of the mire. Since the accumulation percentage of the peat is the result of a number of factors, the changes in accumulation rate may also be due to a number of reasons. Some of the synchronous changes may favour accumulation, others slow it down. It is hard to distinguish between these various factors (cf. Frenzel 1983).

The changes in plant material decay rate are, however, more significant than the changes in biomass production. In many peat deposits great changes in accumulation rate are observed without notable changes in vegetation. According to Damman (1979) the accumulation of peat is mainly controlled by slow decay of organic material, not by rapid production. The changes in effectivity of the decay process are mainly due to changes in the hydrology of the mire, which may in turn be due to climatic changes or non-climatic reasons.

### Climatic changes

At the time of peat initiation in the southern Ndurumu basin the water levels of the closed lakes were low and a dry climatic phase prevailed in East Africa (Street and Grove 1979). The discharge of the rivers was then smaller than today and their geomorphological activity at its minimum (Thorp and Thomas 1992). During the last glacial stage the peat formation was very slow. The Kiguhu swamp started accumulating peat approximately 13 500 B.P., when the climate was at its driest. At the same time as the water levels of the lakes showed the first signs of a change toward a more humid climate, peat formation began in the lower parts of the Buyongwe valley and in the Cyabaralika basin, and the accumulation of peat was at its maximum in the Kiguhu swamp. As the water levels of the lakes rose rapidly and the discharge increased during the early Holocene, the peat deposit of Buyongwe started growing rapidly in thickness, and the dry matter and energy accumulation rates were at their maximum. During the Holocene humidity maximum (9000 - 7000 B.P.) the accumulation rates were at their maximum in the Kinamba and Cyabaralika swamps.

The climate became drier after the mid-Holocene which shows in the form of decreasing accumulation rates in the Akanyaru swamp complex. In the Cyabaralika swamp, however, the accumulation rates increase. In spite of the fairly dry climate the initiation of peat formation occurred in the basins of Cyili, Gishoma and Mashya 2500 - 1600 B.P. In a pollen diagram from the mountain area of Burundi, Roche and Bikwemu (1989) distinguish a short humid period 2000 - 1800 B.P. (Fig. 60), during which peat started accumulating in the Mahya bog. The same study showed that this humid period was followed by a very dry period 1600 - 1500 B.P., during which the initiation of peat formation occurred in the main basin of Gishoma. The change into a more humid climate following this dry period is synchronous with the accumulation maxima of the Cyili, Gishoma and Mashya peat deposits. The change into a more humid climate approximately 1400 B.P. may also have contributed to the increasing accumulation rates in the upper parts of the Buyongwe and Kinamba peat deposits.

The most significant Holocene climatic changes in the study area occurred about 10 000 B.P. and 4500 B.P. If the increased humidity had lead to expansion of the mire areas, the times of peat initiation shown in Figure 59 would be concentrated to the early Holocene. As shown by the material here this is not, however, the case. Five of the mire basins studied (those of Buyongwe, Rwamiko, Kinamba, Mashya and Cyabaralika) started accumulating peat during the fairly humid climatic stage and the remaining four (the basins of Ndurumu, Cyili, Gishoma and Kiguhu) during the fairly

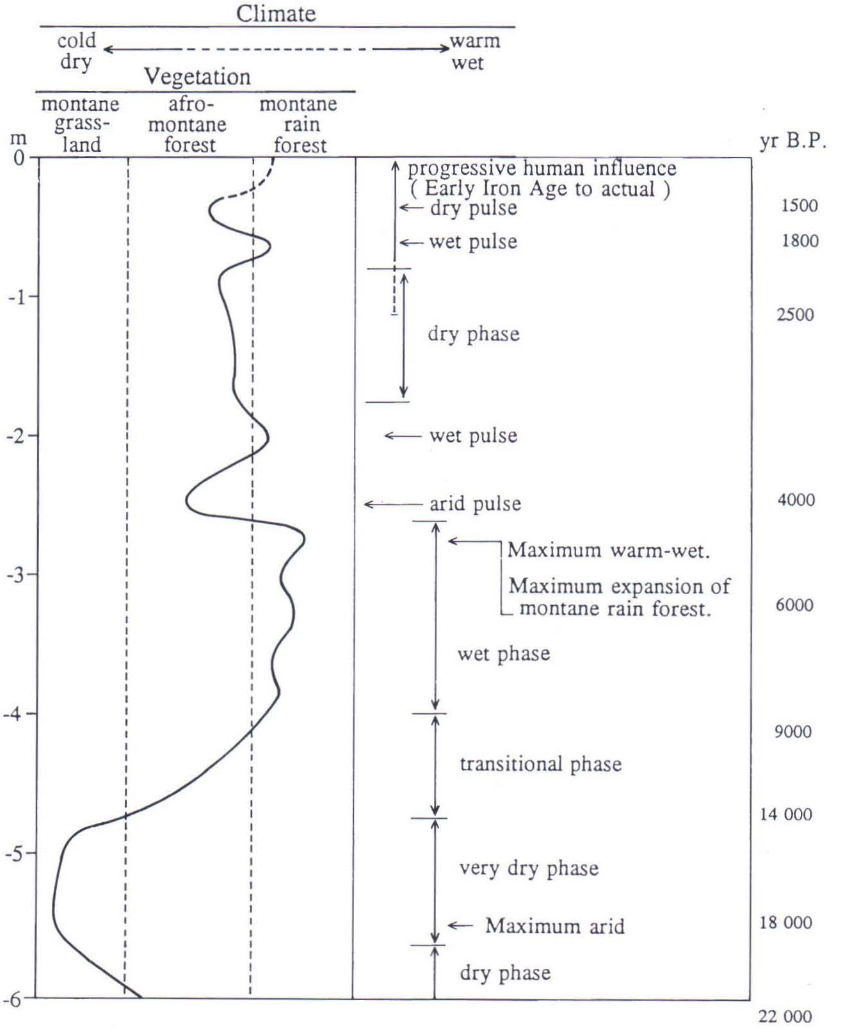

Fig. 60. Climatic history of Burundi at the end of the last ice age and during the Holocene according to a pollen analysis from the Kashiru peat deposit. Redrawn after Roche and Bikwemu (1989).

dry stage. If it is assumed that the increasing humidity made the conditions favourable for accumulation of peat and increasing dryness made them unfavourable, the periods of higher than average accumulation rates should be concentrated to the early Holocene and those of slow accumulation to the late Holocene. The increased humidity of the climate is not as clearly distinguishable in the accumulation rates as the increasing dryness. In the mires of the Akanyaru area (the Buyongwe, Ndurumu and Kinamba swamps, Fig. 59) the dry period after the mid-Holocene is reflected by accumulation rates that are below average. In most of the mires there have been periods of accumulation at higher than average rates during the last two millenia, caused by the increased humidity of the climate and also by non-climatic factors.

In the basins that have an effluent the climatic changes have influenced the discharge of the central channel and the extent of the flood plain. If the mire is situated at the shore of a lake with an effluent climatic changes do not affect the development of the mire to any notable degree. In closed basins, however, climatic changes have a more marked effect on the surface level. In some cases a fairly dry spell may even favour the formation of mires (cf. Korhola 1992). Dry climate may have lowered the water surface in the Gishoma basin, thus favouring the filling in of the water body.

The climatic changes influence the development of the raised bogs directly. The development of the Mashya bog started during a short humid phase. The highly decomposed layer (0.7 - 1.0 m) may be a consequence of a drier phase after 1450 A.D. On Kilimanjaro, Mount Kenya and Ruwenzori it has been found that glaciers have advanced 1500 - 1800 A.D. (Hamilton 1982). The layer indicating a drier phase of development in the Mashya bog is synchronous with the phase of glacier advance. The raised bog of Mashya is located at a fairly low altitude, and so it may be more sensitive than average to climatic changes. The raised bogs of Africa are usually located considerably higher, where the cool climate lessens the evaporation, increases the humidity and thus favours the accumulation of peat.

The Kamiranzovu peat deposit, studied by Hamilton (1982), is situated at a distance of 25 - 30 km from those of Gishoma and Mashya. The peat formation in the Kamiranzovu swamp began approximately 37 630 B.P. and continued without interruption until 12 600 - 11 000 B.P. Hamilton (1982) concludes that the cool climate during the last ice age was favourable to the formation of peat, which consequently ended when the climate turned warmer and more humid about 12 000 - 10 000 B.P. The changed climatic conditions caused an increase in the decay rate of organic matter and the development of the mire came to an end, i.e. the increased temperature would have had a greater effect than the increased humidity. I find it improbable, however, that the accumulation of peat would have ended 12 000 - 10 000 $^{14}C$ years ago and that the production and decay of organic matter would have stayed in balance since then. It seems more probable that the development of the mire would have continued to the mid-Holocene and that only the drying of the climate around 4500 B.P. would have led to the wear of the peat deposit (cf. Sieffermann et al. 1988). This is indicated by, e.g. the high ash content in the surficial part of the deposit. The Kamiranzovu swamp is situated at a greater altitude than the mires studied here and its central part is higher than its margins, and thus the climatic changes have affected its development more than that of the river valley swamps studied here.

Meadows (1988) has studied 26 dated peat sections from Southern Africa, comparing the initiation dates of peat accumulation and the accumulation rates with the climatic changes. He states that the initiation dates of deposition and the periods of rapid accumulation correspond to the humid climatic periods. Since Rwanda and Burundi are located in a tectonically active area, the effect of other than climatic factors on the accumulation of peat is here considerably greater than in Southern Africa.

The current PANASH Project (Paleoclimate of the Northern and Southern Hemispheres) organizes research on interhemispheric climate mechanisms and coupling (Bradley et al. 1995). The scientific activities are linked in a series of Pole - Equator - Pole transects. One of these transects (PEP III) runs through Europe and Africa. In the PEP III transect, Gasse (1995) pays attention to the extent of climatic change during the 'Little Ice Age' and the 'Medieval Warm Period'. Also the coupling of the dry spell, observed around 11 000 - 10 000 B.P. in several African sites (e.g. Roberts et al. 1993), and the European Younger Dryas cold event is still uncertain. In the present data, the highly decomposed peat layer of the Mashya bog is synchronous with the 'Little Ice Age'. The maximum rate of peat accumulation occurred in the Cyili and Gishoma swamp and in the Mashya bog about 1400 - 950 B.P. It is slightly older than the 'Medieval Warm Period', which occurred in Europe around 900 - 1200 A.D. (Eronen 1991). In the old peat deposits, the time intervals between the $^{14}C$ ages are too long for the dry spell around 11 000 - 10 000 B.P. to be identified.

### Non-climatic factors

The Earth's crust was inclined towards the east in connection with the formation of the Western rift valley. As a consequence the flow direction of Nyabarongo changed (e.g. Rossi 1980, Battistini and Prioul 1981). Ruvuvu has flowed via the upper courses of Kagera and via Nyabarongo to the northwest (Fig. 61). As the crust was inclined the flow of Nyabarongo slowed down. Finally a new effluent opened towards the Rusumo Falls at the junction of the present Kagera and Ruvuvu.

The crust is inclined towards the southeast in the area of the Akanyaru swamp complex. The altitude contrast between the southern part of the swamp and the junction of Nyabarongo is a little more than 20 m and the distance about 75 km. The deepest peat deposits of the Ndurumu swamp reach about 10 m below the surface in the northern part. The thickness of the peat deposits in the northern part is a little less than 10 m, and so at present the deepest peat deposits reach approximately the same level in the entire Akanyaru area. If it is assumed that the valley was sloping towards the north before the formation of the peat deposit, the northern part of the present swamp complex must have risen more rapidly than the southern part. The different shapes of the river valley in the southern and northern part of the mire area also indicate a change towards a more gentle inclination. The slopes bordering the swamp area are more gentle in the northern than in the southern part (Sections B and C, Fig. 9, p, 19). The width of the mire area is, however, fairly constant. The pre-Quaternary river valley has in the southern part been considerably deeper than that of today and its floor considerably lower than that of the northern part. The inclination of the crust towards the southeast is also reflected by the gentle gradient and extremely watery peat deposit of the Nyavyamo swamp.

The northern part of the Akanyaru swamp complex may have risen more rapidly also due to stepwise faults. In the Akanyaru valley there is probabbly a fault line, which is crossed by several fault lines in the direction southwest - northeast (Carte Géologique, Burundi 1981, Carte Géologique du Rwanda 1991). One of the fault lines is located between the southern basin of Ndurumu and the Akanyaru valley. It is possible that the river valleys in a southeastern direction in the Ndurumu area were deepened due to the vertical faults.

The inclination of the Earth's crust has caused swamp complex to expand further in the eastern than in the western tributary valleys of Akanyaru (Figs. 10 p. 20 and 61). Since the water level rises faster in the bays extending eastward than in those extending westward, it is also probable that the peat accumulation rates are higher in the former ones than in the latter ones. Accordingly the peat accumulation rates in the southern part of the swamp complex should be higher than in the northern part. The present data are from the central and southern part near the main river valley, and thus it does not serve to prove the effect of the tectonic movements on the variation in accumulation rates.

The connection between the tectonic inclination of the crust and paludification was found at an early stage in southern Sweden (De Geer 1893) and in Finland (Tolvanen 1917, Auer 1924a). Auer (1924b) stated that changes in water level caused by the inclination of the crust causes paludification on the shores of the lake Vanajavesi and controls the thickness growth of the shore peatlands. The same kind of hydrological changes that

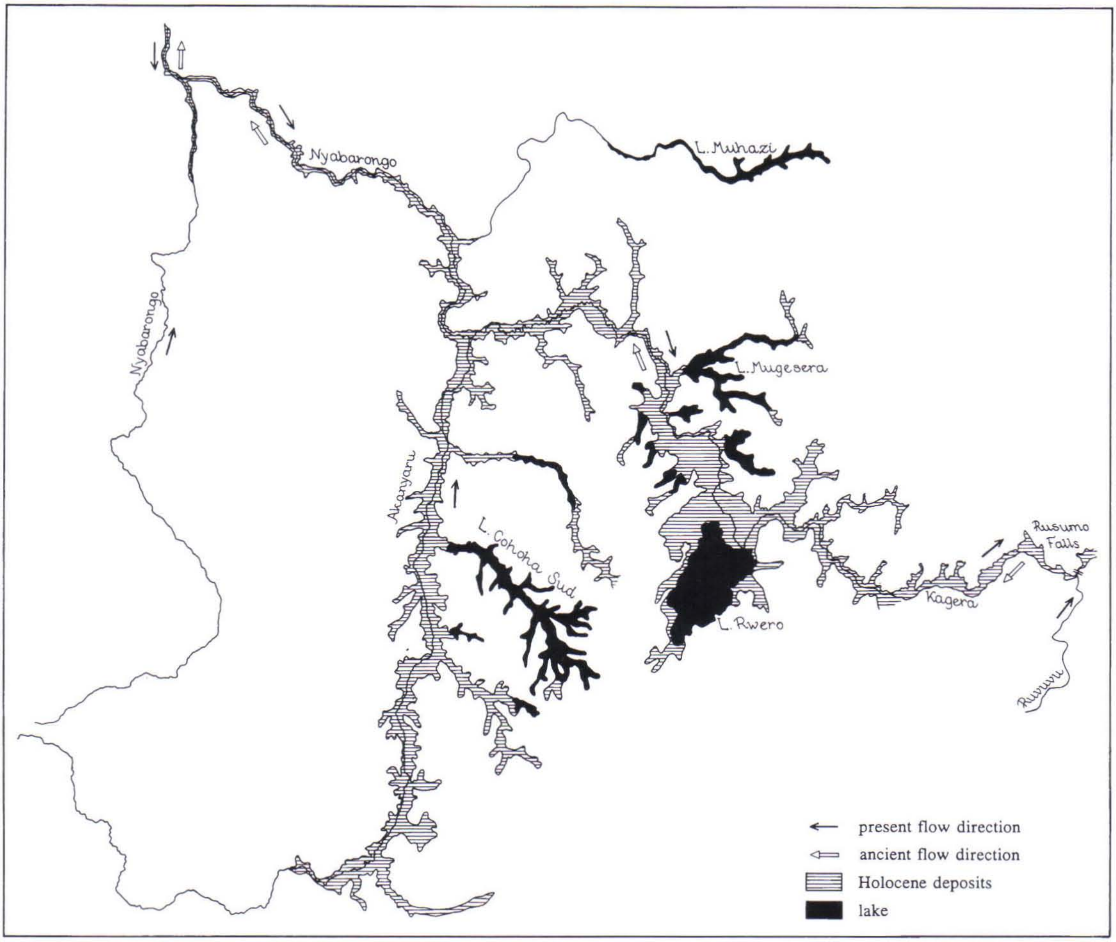

Fig. 61. As a result of the formation of the Western rift valley, the crust became inclined towards the east or southeast, which changed the direction of flow of the Rivers Nyabarongo and Kagera. The gradients of the rivers flowing westward became more gentle and transgressive lakes such as Muhazi, Mugesera and Cohoha Sud formed in their river valleys.

occur as a large lake basin is inclined, may also occur as a large mire basin is inclined. On one shore of the basin peat formation may occur while on the other shore mires dry up. Huikari (1957) has stated that mires expand more in the direction of the inclination of the crust than against it. Correspondingly the rate of thickness increment for the peat has been higher in the direction of the inclination than in the opposite direction.

The conditions for peat formation are considerably poorer in the Nyabarongo valley than in that of Akanyaru. The crust slopes in the present flow direction of Nyabarongo. The rate of uplift of the crust decreases from the margin of the rift valley towards the east. Near the middle of the Nyabarongo valley an extensive lake has been formed, which has gradually been filled with sediments and peat (Fig. 61). Due to the filling of the basin the lake has divided up into a number of separate basins. The mineral matter transported by Nyabarongo is deposited in this area of mires and lakes. The clearing of the water and the disappearance of the levees can be observed in aerial photographs. In a downstream direction levees of sand start to appear along Kagera approximately 20 km before the Rusumo Falls. The sand transported from the drainage basin of the present Nyabarongo is deposited much earlier, and so the sand must originate in the drainage basin of Ruvuvu. It has been deposited before the change in flow direction. After the shift in flow direction the water surface has sunk constantly due to erosion of the threshold point, and so the conditions have not been favourable for accumulation of thick peat deposits.

Tectonic movements have formed basins with favourable conditions for mire formation in the Rusizi area. In the drainage basin of Gishoma the bedrock has been broken by tectonic faults into several small blocks (Pajunen and Karega in press), and the mire basin has been formed as the consequence of vertical movements of these blocks. In the main basin a lake was formed and later terrestrialised. Landslides in the narrow valleys have also formed basins favourable to mire formation. The landslides may have been caused by earthquakes related to the tectonic movements.

The mire basins in the Virunga area were formed by Quaternary volcanic eruptions. The hydrological conditions in the basins have later changed to become favourable to mire formation and peat accumulation mainly for reasons unrelated to the climate.

In a study carried out in Tanzania (Sandström 1995) the recent increase in flooding was found to be caused mainly by changes in land cover. Human activities in the drainage basin have also influenced the hydrology of the rivers in the present study area. The decrease of forests in the drainage basin has increased the amounts and the annual fluctuations of the discharge, and expanded the flood plains. The conditions have turned more favourable for the accumulation of peat due to the increased wateriness. In some cases the increased wateriness has led to a decrease of the swamp forests. The influence of human activities is limited to the time after the beginning of the Iron Age (approximately 2000 B.P., Van Grunderbeek et al. 1983). The production of iron implements made it possible to expand the tilled fields. In addition the production of iron required abundant charcoal, which contributed to the diminishing of the forests.

## Variations in ash content of the peat

The ash of the peat comes either from plant material (primary ash) or from mineral soils (secondary ash). The ash of peat from raised bogs is mainly primary, whereas that from river valley mires is mainly secondary. In the Akanyaru swamp complex the variations in ash content are largely due to variations in the content of secondary ash.

Discharge peaks caused by occasional, exceptionally great precipitation amounts are typical of the study area. During these, exceptional amounts of mineral matter are deposited on the flood plains of the rivers, and so the ash content of the peat accumulated within the range of influence of the floods is greatly varied. The ash content is highest in areas where the deposition of mineral matter is strongest. If the mire is longer than the sedimentation area of the central channel, the effect of the central channel does not extend to the ash content of the lower part.

The ash content is low in areas that have been consistently beyond the range of the floods, e.g. most small bays beyond the flood plain of the main river (Fig. 62). They may be considered independent drainage basins. The discharge of the brook flowing into the mire is so small that no channel is formed, and so the mineral matter eroded from the drainage basin is deposited at the margin of the mire. The ash content of the peat formed in the mire area is low. Examples of such areas are the small bays of the Buyongwe swamp and the southern basin of the Ndurumu swamp.

For the purpose of surveying the peat resources it is of significance to know the mechanism of deposition. The drainage basins may be defined and divided into areas of erosion and deposition according to prevailing processes on the basis of topographic maps and aerial photographs. In the simplest cases the mineral soils in the drainage basin form the area of erosion and the mire the area of deposition. The average ash content of the peat may be assumed to be the lower, the greater the part of the drainage basin is covered by the mire. The variation in ash content within the mire may be estimated on the basis of the shifts in the deposition areas of mineral matter.

The changes in ash content of the peat may also reflect changes in land use within the drainage basin. If, e.g., the cultivated areas expand at the cost of the forests, both the erosion of mineral soils and the deposition of mineral matter on the mire will increase. It raises the concentration of secondary ash in the peat or even leads to the formation of layers of mineral matter. The effects of changes in land use in the drainage basin are especially pronounced in the flood plain of Akanyaru. The expansion of the flood plains and the increased sedimentation of mineral matter is limited to the time since the early Iron Age. The deposition of mineral matter has been especially abundant since the mid-19th century. According to Hamilton et al. (1989) the amount of mineral matter deposited in the mires of Uganda increased as early as around 1300 B.P. Observations show that in the Akanyaru area during that time, the swamp forests decreased and the peat accumulation rate increased, which both may be results of changes in land use in the drainage basin. Changes in land use have also led to an expansion of the levees in the Black River Morass of Jamaica during the last few centuries, although the levees started to form as early as 2000 - 3000 B.P. due to climatic changes (Björk and Digerfeldt 1991).

The ash content is least influenced by the properties of the drainage basins in the raised bogs, and so the ash content figures of the Mashya bog are the lowest recorded in this research. The mineral matter eroded from the drainage basin has been deposited on the laggs, and the ash content of the central part of the Mashya bog is equal to that of the ombrogenic part of peat deposits in Southeast Asia (Polak 1975, Anderson 1983).

The ash from volcanoes may be evenly deposited on a mire and thus raise the ash content of a certain layer. Volcanic ash deposited in the drainage basin may also be transported into the mire and participate in the normal processes of sedimentation. Although the mires studied are located in the vicinity of active volcanoes, no ash layers were found between the peat layers. However, volcanic ash has been found in lake deposits 200 km to the north (Livingstone 1967), and thus the type of eruption and the wind direction at the time were evidently unfavourable to the deposition of ash in the swamps of Cyabaralika and Kiguhu.

Since Karisimbi erupted approximately 10 000 years ago (De Mulder and Pasteels 1986), ash layers generated by it should be found either in the basal part of the Cyabaralika peat deposit or in the surficial part of that of Kiguhu. Taylor (1990) has dated several layers of volcanic ash from the Muchoya swamp on the Ugandan side of the border. The most recent ash layers are more than 16 000 years old, and so they are not found in the peat deposits of Cyabaralika and Kiguhu. Morrison and Hamilton (1974) conclude that the lava flows damming the mire basins of Butongo and Katenga are 8000 - 10 000 years old. During that eruption ash was also deposited, which reportedly affected the vegetation during the early stages of the mires. When studying a lake deposit from Ruwenzori, Livingstone (1967) found volcanic ash, the $^{14}C$ age of which was found to be 4670 ± 80 B.P. The

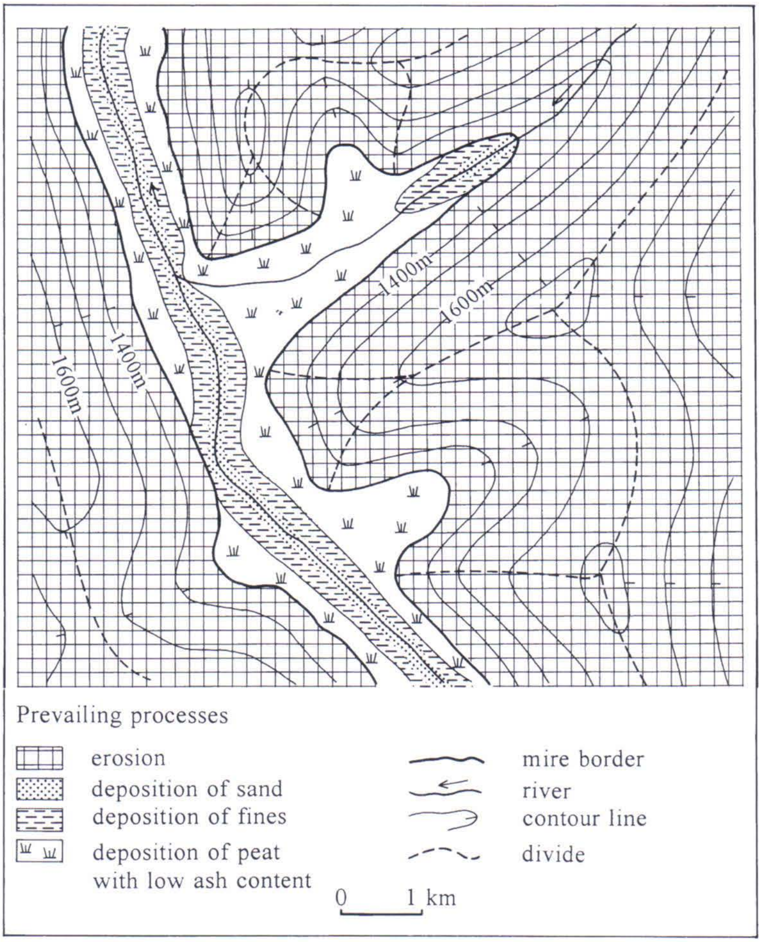

Fig. 62. Schematic representation of the deposition of mineral matter in the mires of the River Akanyaru valley in Rwanda and Burundi. The larger the drainage basin, the greater the discharge and the farther the mineral matter is transported. The sand is deposited in the river channel and on the banks while the fines are transported farther, to the flood plains. No open channel is formed on the mires of small drainage basins, but the mineral matter is deposited in a narrow marginal zone. The ash content of the peat is lowest in areas that have been continuously beyond the flood plains of the rivers.

synchronous part of the Cyabaralika peat deposit is located at a depth of 2 m.

The ash content of the peat is also affected by many factors, related to the accumulation process of the peat and unrelated to the drainage basin. Changes in the relation between production and accumulation of biomass (the accumulation percentage) affect the content of primary ash, which may also be affected by changes in the peat-forming vegetation. On the other hand, changes in the rate of organic matter accumulation affect the content of secondary ash. If the amount of mineral matter deposited per unit area remains constant and the rate of organic matter accumulation is doubled, the content of secondary ash decreases by a half. Correspondingly, with a decreasing accumulation rate, the ash content increases. The variation in ash content may thus also reflect variations in the rate of organic matter accumulation.

High ash content figures are typical of the tropical limnogenic mires. In Jamaica the average ash content obtained for Negril Morass is 16 % and for Black River Morass 21.5 % (Blackwood and Robinson 1985). Both mires are located on the coast and contain layers of both saltwater and freshwater peat. The higher ash content in the Black River Morass is due to deposition of mineral matter eroded from the drainage basin by the rivers flowing through the mire area. Geologically the location of the Muthurajawela mire in Sri Lanka is similar to that of Negril Morass in Jamaica. According to Lappalainen (1987) the part of Muthurajawela feasible for production has an average ash content of 14.9 %. Considerably higher ash content figures have been reported from Guinea, Lesotho, Mozambique (Bord Na Móna 1984), Senegal, etc. (Chateauneuf et al. 1986). The properties of the drainage basin, mainly its topography, soil type and land use, affect the ash content of the mires, especially of those situated in river valleys and deltas.

## SUMMARY

The formation of the nine mire basins studied in Rwanda and Burundi, at altitudes of 1350 - 1840 m a.s.l., has been controlled by tectonic movements, volcanic activity and landslides.The inclination of the Earth's crust to the east or southeast, related to the development of the Western rift valley, has created favourable conditions for the formation of the Akanyaru swamp complex, while the Gishoma basin, situated in the Western rift valley, was formed as a result of vertical faults. The Cyabaralika and Kiguhu basins were formed in valleys dammed by lava flows.

The times of mire initiation in the basins vary in the range 20 200 - 1600 B.P. Five of the mires studied were initiated during fairly humid climatic periods and four during fairly dry periods. Local non-climatic effects may have increased the wateriness of the river valleys, making the initiation of peat formation possible even during a fairly dry climatic period. The dry climate may have been a factor promoting terrestrialisation in the lake basins.

The most significant peat-forming plants are *Cyperus papyrus*, *C. latifolius*, *Miscanthidium violaceum*, *Cladium mariscus* and various trees. The nutrient content of the rivers and the water flowing from the drainage basin has influenced the location of the vegetation zones. Papyrus reeds occur mainly along the rivers and at the margins of the mineral soils, *Miscanthidium* grass in the bays beyond the flood plains, and *Cladium* in the most nutrient-rich areas. Fluctuations in the water level, promoting the decomposition of the peat, are most pronounced in the flood plains of the rivers, which are dominated by papyrus. Hence the papyrus peat is generally more markedly decomposed than is the peat formed by other plant associations.

As a river discharges into a mire area its gradient decreases, as also does its ability to transport mineral matter. The coarse mineral matter is deposited in the immediate vicinity of the channel and the fines farther onto the flood plain. Areas of deposition of mineral matter distinguishable in the stratigraphy of the deposits show that the most significant change in its deposition has occurred since the mid-19th century, as changes in land use within the drainage basin have expanded the flood plains to the mire and increased the deposition of mineral matter.

The irregular deposition of mineral matter causes differences in the ash content of the peat in the river valley mires. The figures range from less than 5 % upwards, with the highest ones in the upper part of the mire area on the flood plain of the central channel. If the mire is longer than the sedimentation area of the central channel, the latter no longer increases the ash content of the lower part of the mire area. The lowest values for ash content were found in small bays that lack a central channel of their own and have consistently been situated beyond the flood plain of the main river.

Long-term average rates of dry matter accumulation are in the range 110 - 220 g $m^{-2}$ $a^{-1}$ in the mires of the Akanyaru area and 150 - 190 g $m^{-2}$ $a^{-1}$ in those of the Rusizi area, and approximately 60 g $m^{-2}$ $a^{-1}$ in those of the Virunga area. The variations in accumulation rates are due to hydrological changes in the

basins, which have in turn been affected both by climatic changes and by many non-climatic factors. The effect of human activities on the rate of peat accumulation becomes all the more significant the closer we come to the present day, and it may totally obscure the effect of small climatic changes such as the 'Medieval Warm Period' and the 'Little Ice Age'.

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