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GEOMORPHOLOGY AND SEDIMENTARY STRUCTURES OF UPPER PLEISTOCENE TO HOLOCENE ALLUVIUM WITHIN THE NYABARONGO VALLEY (RWANDA). PALAEO-CLIMATE AND PALAEO-ENVIRONMENTAL IMPLICATIONS

ABSTRACT: WASSMER P., SCHWARTZ D., GOMEZ C., WARD S. & BARRÈRE P., *Geomorphology and sedimentary structures of Upper Pleistocene to Holocene alluvium within the Nyabarongo Valley (Rwanda). Palaeo-climate and palaeo-environmental implications*. (IT ISSN 0391-9838, 2013).

At the confluence of the Nyabarongo River with the Mukungwa River, to the North of present Rwanda, there are thick alluvial sedimentary sequences, which can reach 30 m in thickness, where they are capped by tufa deposits. From these deposits, two different sedimentary sequences have been identified, with (i) a first sedimentation stage characteristic of an obstructed valley controlled by contrasted seasonal flows during a dryer and cooler climate than at present, and (ii) on top of this unit a more recent sequence of alluvial terraces that were emplaced during a wetter and warmer context allowing the development and stabilisation of the rainforest. Palynological data and their comparison with a database at the East African regional scale have proven that the first rapid sedimentation stage started around 40,000 BP and might have ended abruptly around 14,000 BP. This process has been then followed by a natural embanking stage of the alluvial corridor. These different terraces have been dated thanks to a series of proxies: the discovery of a Stenoece animal remains in the upper part of a terrace confirmed the palaeo-origin of the sequence; a bone harpoon with typical manufacturing characteristics that indicated a human settlement around 9,000 BP on another terrace; and the tufa deposits provided a maximum age for the terraces below 7,000 years. This multi-proxy approach, therefore, provides an interesting series of benchmarks for the development of the palaeoenvironment in Northern Rwanda and is of high importance for the reconstruction of the river bio-geomorphological adaptation to climatic changes.

KEY WORDS: Rwanda, Nyabarongo and Mukungwa rivers, Alluvium terrace, Sedimentary structures, Upper Pleistocene to Holocene palaeoenvironment.

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It is an honour for all of us to contribute to this special issue dedicated to our colleague Monique Fort, excellent and enthousiastic geomorphologist and unweary explorer of Himalaya Mountains who is an example for the young researcher generation and the older one as well. Our thoughts go to our colleague Pierre Barrère who contributed to this work. This great field geographer who liked most of all wandering the vast world, passed away two years ago. The authors gratefully acknowledge G. Arnaud-Fassetta, É. Cossart and the anonymous reviewers who helped improving this manuscript.

PREAMBLE

This research was conducted within the scientific framework of the then beginning «Laboratory of Soil and Sediment Analysis», which the first author was leading at the Université Nationale du Rwanda, Nyakinama Campus, Ruhengeri, North Rwanda, between 1981 and 1987. Our investigations were focused on a thick alluvium terrace laying at the confluence of the Nyabarongo and the Mukungwa rivers (fig. 1). Fossilised by tufa formation, this deposit is probably one of the only (if not the only formation as suggested by Holtzförtster & Schmidt, 2007) relict of the Neogene to late Quaternary clastic formations on the uplifted strongly eroded eastern shoulder of the Nile-Kivu segment of the Western Rift. Fieldwork was mostly carried out in early 1983 and a first version of this paper was writ-

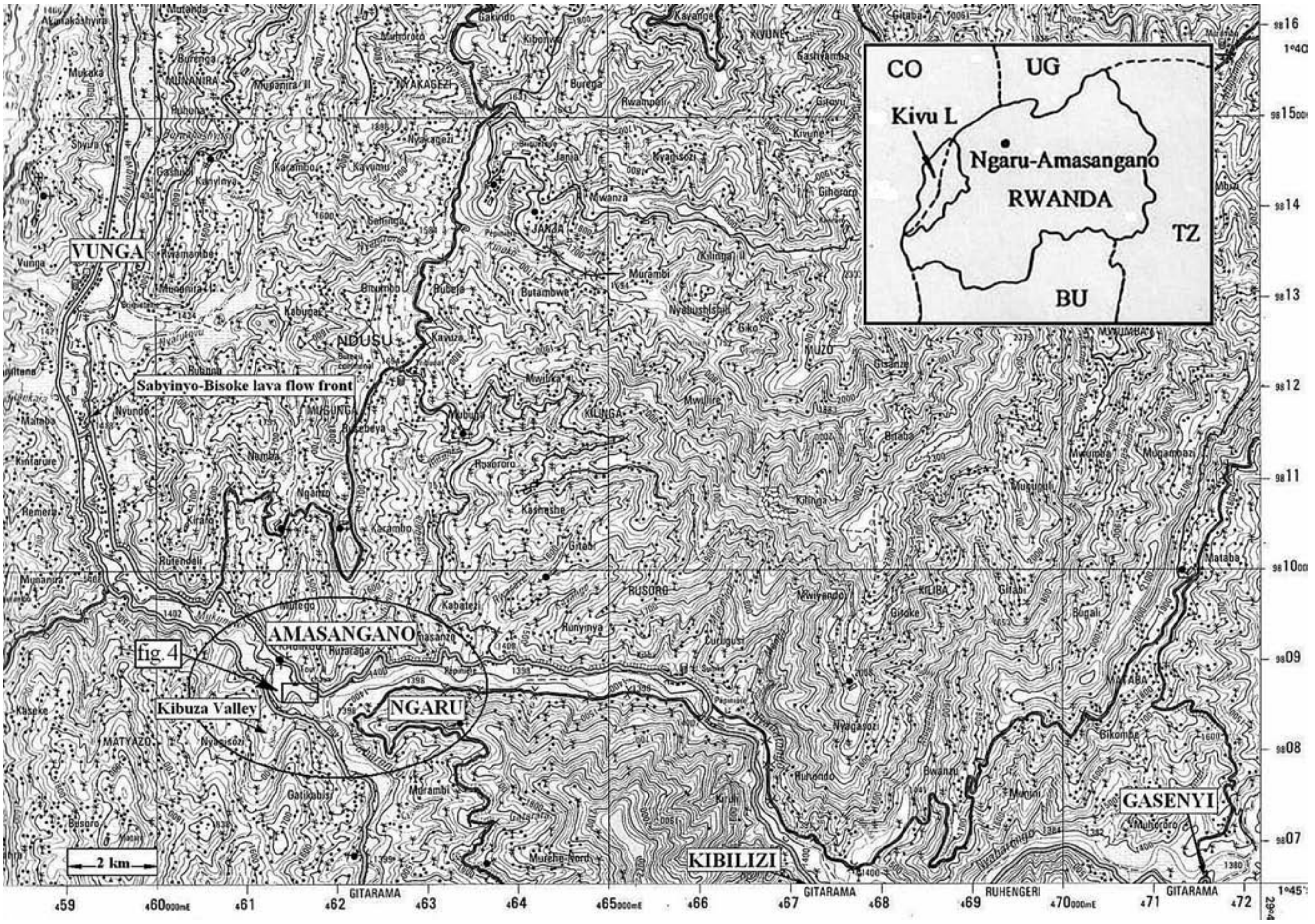

FIG. 1 - Location map: Ngaru-Amasangano site at the confluence of Nyabarongo and Mukungwa Rivers. Rwanda topographic map, 1988, Ruhengeri (scale: 1:50,000).

ten within the following two years. The paper was then buried under a dense layer of various other papers in a forgotten drawer. Like an interesting geological strata, we recently unearthed it and turned it into the present contribution. While the authors have kept most of its original form – like the hand-drawn illustration – a more contemporary twist has also been added. Since 1985 time has passed and while working on the manuscript we were pleasantly surprised to find recent research in the same area. Within these contributions, the brilliant paper written by Holtzförtster & Schmidt (2007) is based on the same site, but where these authors focus on the palaeo-Nyabarongo drainage reversal, the present focuses on the palaeo-environment's evolution, bringing unpublished data of high interest for the investigated site. Although, the recent publications and the contribution we are presenting are the products of different currents in the construction of knowledge and how scientific research is being carried out. At the end of the present contribution, the main results provided by Holtzförtster & Schmidt (2007) will be summarised, highlighting similarities, oppositions and differences inferred to epistemological reasons.

INTRODUCTION

Regional context

The aim of the present contribution is to reconstruct the late Quaternary palaeo-environments evolution in the North of Rwanda on the base of: (i) the internal structure of sedimentary records and composition of ancient high terraces remains lying at the confluence of the Nyabarongo and the Mukungwa rivers, (ii) the local morphology and the geomorphometry (valley bottom, slopes…). The two latter elements are strongly tied to the geological settings of the investigated area located on the eastern shoulder of the African Rift's western branch. The formation of this western part during the Neogene is linked to a collapse of the Proterozoic basement rocks vault following a doming in an extension system. The normal faulting due to the rift formation produces an accumulation of oblique stress along which volcanism occurs (Demange & Rancon, 1983). Strongly associated to the rift tectonics, this volcanism seems more related to the distensions resulting from the horizontal movements than the vertical throws of large fractures (Pouclet, 1977).

A volcanic field extends from Congo Kivu to Uganda through the threshold separating Kivu Lake and Albert Lake drainage basin (fig. 2). It is characterised by a line of eight main structures roughly oriented along a W-E axis and resting upon a substratum located at the altitude of 1,200 m (Rossi, 1980). Five of these large volcanoes delimit the Rwanda to the North. From east to the edge of the graben, Muhabura, Gahinga and Sabyinyo are aligned E-W. They are connected by the NE-SW alignment of Sabyinyo, Bisoke and Karisimbi (fig. 2). This large volcanic field is dated Quaternary, - 0.64±0.02 Ma to present for the old Bisoke (Demange & Rancon, 1983). It is likely that the strong uplift of the East shoulder of the Western Rift produces an eastward warping of the Rwanda-Burundi block. This tilting and the Virunga formation created (i) a complete river drainage reversing. In the North of Rwanda, the palaeo-Nyabarongo and other numerous northbound rivers were dammed, and (ii) the conditions of an intense dissection of the relief and an important sediment transfer in the rivers. Along the contact between the crystalline bedrock and the lava field lakes and swamps are numerous. These lakes (Lake Ruhondo, Lake Bulera) all display typical drowned ria-like coastlines. All the swamps show a direct contact with the lava while on the bedrock they present a coastline characteristic of flooded valleys: Mukungwa, Kinoni, Bihinga, Nyamukongoro, Sebeya, Pfunda (fig. 2). Originating from the lava field of the Sabyinyo-Bisoke system, a narrow lava flow filled the palaeo-Nyabarongo Valley oriented S-N and progressed 15 km beyond the southern limit of the lava field, ending its run 3 km North of the present Nyabarongo-Mukungwa confluence (fig. 2) creating the conditions of a congestion of the river network and the subsequent settling of important amounts of sediments in the dammed valleys. Locally, these sediments have been conserved over the course of time due to the conjunction of a position in the low-energy sides of the valley and to fossilisation under a cap of tufa formations.

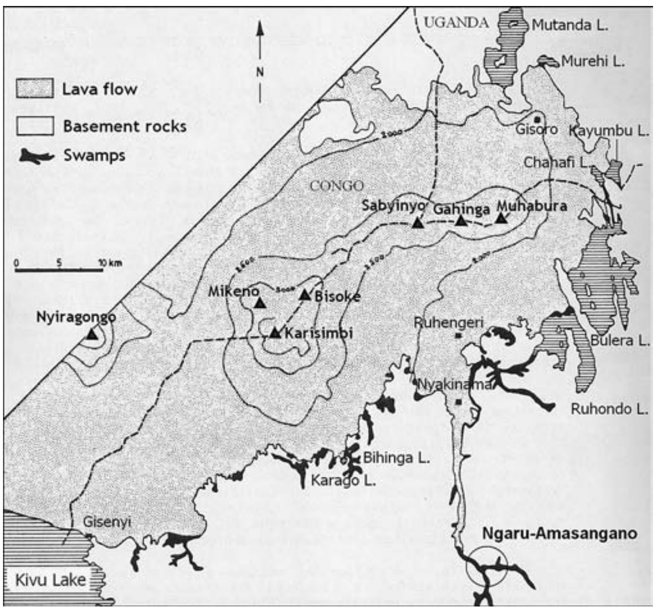

FIG. 2 - Virunga volcanic field (modified from Jost, 1987).

Local settings

In the North of Rwanda, right at the South toe of the Virunga volcanic complex, the Ruhengeri region presents a dissected topography associated with the typical structure of a metamorphic platform. Burundian terrains are affected by sharply folded rocks that appear at the surface as alternate bands of schists and quartzites in a ribbon-like disposition that characterises the fold belt roots. The quartzite summit crests are following a meridional orientation and reach 2200 to 2300 m a.s.l. Low points have been eroded in shale material and appear as long and narrow perched corridors, draining towards the Nyabarongo River and its main tributary, the Mukungwa River. The two valleys, diametrically aligned on the compass, converge at Ngaru (fig. 1) flowing around 1600 m a.s.l. in a deep and narrow rigid-shaped corridor corresponding to a large shale layer and a fault zone delimiting the Ruzizian and Burundian lithologic systems. Downstream from Ngaru, the Nyabarongo River drastically changes direction, from a general northerly orientation to a south-easterly orientation, immediately after having crossed the quartzitic bars through a narrow gap.

To the South of Ruhengeri, and up to one kilometre downstream from the Marketplace of Vunga, a recent basaltic lava flow constitutes the valley bottom of the Mukungwa River. This lava deposit that originates from the Sabyinyo-Bisoke system in the Virunga volcanic field lies on the former alluvial sedimentary formations. Downstream of the lava deposit, the floodplain of the Mukungwa River displays two types of morphologies: (i) in narrow sections, where the valley bottom is 200 m wide, the sediment material of the floodplain (mainly sandy) is regularly remobilised through meandering and channel cut offs; (ii) in the wider sections of the floodplain, discontinuous terraces made of sand and gravels dominate the present river to a 12 to 15 m extent upstream and up to 25 m downstream. The terraces' discontinuities are due to the vertical erosion caused by the river. In the narrow sections, the sedimentary material of the terraces has been removed by the thalveg shifting during a recent incision.

Similar lithological formations can be found in the Nyabarongo gorges. Their extension is poor and they have been preserved in the low-energy sides of the river channel with edge slopes not clearly differentiated from the valley walls, especially at Gasenyi and at Kibilizi. These sediment formations are voluminous enough to display variations that allow evidencing of various phases in the morphological evolution.

Methods

The investigations were carried out in the vicinity of the confluence of the Mukungwa and the Nyabarongo rivers. Sedimentological and geological data were retrieved from existing outcrops and trenches. The descriptions are based on a fine visual observation of the characteristics of the sediment material. A precise and fine observation of the morphology characteristics of the valley and slopes was performed. Additional observations were made at the laboratory of the Université Nationale du Rwanda located 20 km north of the Site: morphoscopy of the sands, rough grain-size analysis (the laboratory was far from being well equipped at this time). Bone samples were collected and brought to the laboratory of the MRAC (Musée Royal de l'Afrique Centrale) in Tervuren, Belgium, for identification (samples were sent to Utrecht University for ^{14}C dating but the weak content of collagen incapacitated the dating).

STRUCTURE OF THE MAIN TERRACES

At Ngaru-Amasangano, in the sector of Kabingo, a main terrace dominates the confluence of the Nyabarongo and the Mukungwa rivers for 20 m (fig. 3). The lateral erosion of the terrace's edge due to the meander migration offers a large natural outcrop. The teachings of this outcrop are completed by several anthropogenic excavations located at the contact between the terraces and the slopes. These trenches and boreholes cut into tufa deposits, which have covered and fossilised most of the sedimentary deposits in this location. These sedimentary deposits are divided between two main units: a thick sandy deposit at the bottom and well differentiated fluviatile deposits and colluvium on top.

At the base, the ochre micaceous sand

The ochre micaceous sand is a homogenous formation of 20 m in thickness. Sand is coarse and angular, slightly coloured by the iron oxydes and contains a high proportion of muscovite crystals. The clear stratification, strongly dipping towards the slope that can be seen in fig. 3, is emphasised by consolidated levels. This inclination is not due to tectonic activity, but has to be related to the emplacement process of the ochre sand, on an alluvial fan issuing from the small tributary valley of Kibuza on the opposite site of the valley. The general orientation of the layer is more complex in the details and presents inter-stratified formations, typical of a micro-delta. The inter-fingering is, however, best observed at other sites, such as on the left bank of the Nyabarongo River, in the sand quarry of Gasenyi, and on the right bank at Kibilizi River where frontal beds dip in the same direction as the valley. At both locations, one can also observe the presence of lateral channels and deposits, for which the source of material could only be the near-by slopes. In the gorge, sediment emplacement processes correspond to alternation or combining of longitudinal and lateral deposition.

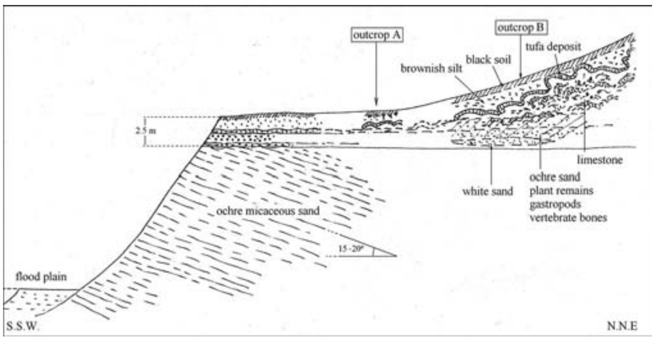

FIG. 3 - General sketch of the terrace's main outcrop (drawing P.W.)

The upper-part of the sedimentary sequence

From 2 to 2.5 m thick, the sedimentary sequence on top is more complex than the one it lies on. Its characteristics vary greatly depending on the position from the slope.

On the terrace edges, from bottom to top, the following sequences have been observed (fig. 4A; see location in fig. 1):

– A thick bed of coarse gravels, well rounded and horizontally stratified, is in sharp erosive discordance with the ochre sand of the previous unit located below. The quartz pebbles can reach 5 cm (long axis) and they alternate with sand lenses containing evidence of a micro-lithic stone industry on milky quartz of large size reaching up to 8 cm (long axis). This level is mostly consolidated by a carbonate matrix.

– Small centimetre size gravels correspond to a 1 m thick layer. Well rounded and stratified, these gravels still contain an important fraction of coarse sands. Numerous pipe-shaped carbonate concretions can be observed in this layer while they are only sparse in the lower part of the unit. These sheath-shaped concretions are deposited by hydrothermal water on vegetal stems, and are the only remains after the disintegration of the organic material.

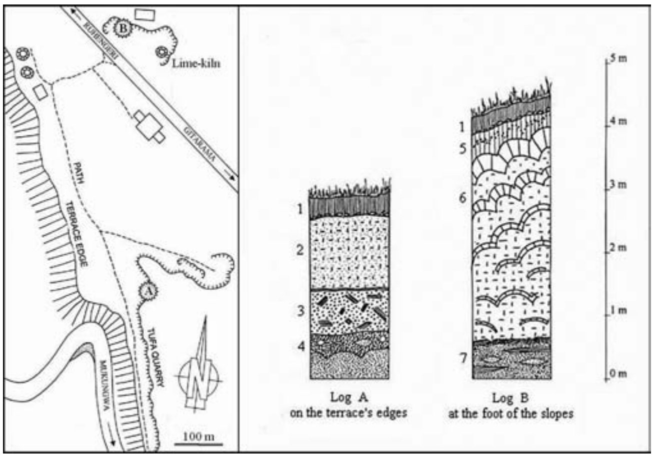

FIG. 4 - Log at the foot of the slope and terrace's edges (see location in fig. 1). 1: black soil with fine quartz micro-lithic industry at the base; 2: fine carbonated matrix-supported sand with thin carbonates sheets; 3: coarse gravels, carbonated matrix; 4: coarse gravels with white sand pockets and rough lithic industry; 5: brownish to reddish silts with angular coarse gravels; 6: carbonate precipitation and dome-shaped tufa bulbs; 7: ochre sand with layers and lenses of clay and dense agglomeration of carbonated sheath at the top (drawing P.W.).

– A layered crust, 5 to 20 cm thick, comprises two or three finely laminated and slightly undulating indurate layers. This formation is usually due to the deposition of silty clay that settles in water puddles of dry riverbed. For this formation, the crust process is emphasised by groundwater percolation through the gravel bed located above.

– A 1.5 m thick layer of fine sand with a pulverulent carbonate matrix containing debris of plants.

– A black humus horizon with a polyhedral structure, 30 to 40 cm thick. It includes at the base evidence of an abundant micro-lithic industry on milky-vein quartz, but finer and more elaborated than the one located at the bottom of the formation.

At the foot of the slopes, close to the slopes, the fluviatile formation includes transitional formations between fluviatile structures and colluvium and is mixed with tufa deposits. These latter are only located on the upper part of the terraces and unveil the top sedimentary formation, in which one can find from bottom to top (fig. 4B; see location in fig. 1):

– Remobilised ochre sand: the observed deposits are 0.4 to 1 m thick. They contain lenses of washed-off white sand with fine clay layers. At the top, large carbonated pipes (Ø≤5 cm) can be found in abundance, sometimes displaying a welded mass. At Shiraalo, 500 m to the North of Amasangano, the upper part of the remobilised sand eroded the lower part and differs from it by a neat iron-oxidation and light solifluction morphology. These remobilised layers are of high interest as they contain a high density of fossils, which can also be found at the bottom of the tufa deposits. The bones are not the results of a natural accumulation, but are associated with a bone industry; they can be linked to prehistoric activity (see below). The principal identified species are: for the mammals, adult and young *Hippopotamus amphibius* (Hippopotamus), *Hylochoerus meinertzhaegeni* (Giant Forest Hog), identified from canine teeth, and one *Taurotragus oryx* (Cape Eland), identified from the bones of its ankle by Dr Wim Van Neer, M.R.A.C. (Royal Museum of Central Africa), Tervuren, Belgium. For molluscs: various *Limnaea* sp. and *Planorbarius* sp. A bone industry has been associated with these fossils. It contains most notably the extremity of a harpoon with a double row of dents carved from a hippopotamus bone; a femoral head, which was most probably used as a pestle, as attested by the rounded and polished shape of the bone break indicating a long use, and a sharp bone (mandible?) with anthropogenic markings (fig. 5).

– Thick tufa deposits of several metres. They are irregularly consolidated and always include remains of *in-situ* petrified plants, which are located either in coarse sand, or in large carbonate blocs, presently being quarried to feed limekilns. The tufa deposits display dome-shaped layers, the structure of which is underlined by several levels of voids. In the deep parts, the structure declines. At the top of the formation, the last line of petrified bulbs, 20 to 30 cm in thickness, is by comparison very compact (fig. 3). These tufa deposits punctuate the long fracture of the Mukungwa-Nyabarongo axis. Similar formations can also be found on the upper Mukungwa River, close to Ruhengeri, near the power plant of Gacaca. The dome-shaped lobes apparently oriented and dipping toward the valley is not here linked to mass movement, but rather to the growth characteristics of the vegetation that acted as support for the carbonate concretions. We have observed similar patterns on the bank of Lake Kivu in Katanam (Congo) where tufas are forming in present days.

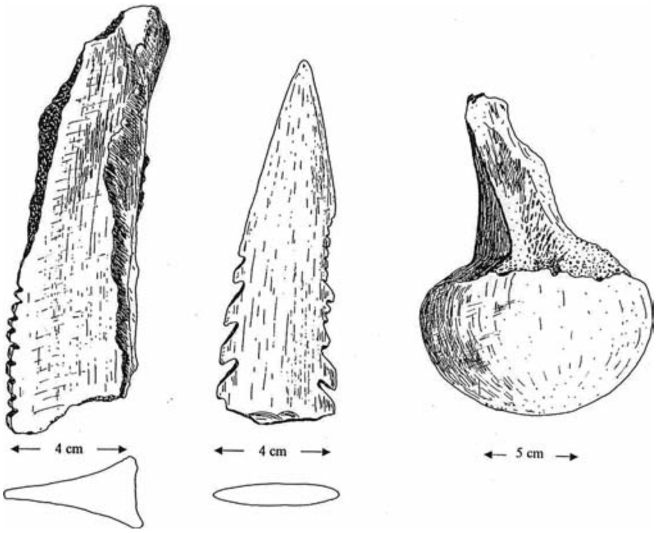

FIG. 5 - Elements of bone industry (drawing P.W.).

– Alluvial light-brown silts, sometimes reddish, of variable thickness, which can reach up to two metres. The deposits' structure is polyhedral and the grain size is homogenous. They also display obvious solifluction lobes. They are underlined by thin festoon-shaped layers of stones. In Shiraalo, one can also find quartzite blocks of 30 cm to 60 cm in the alluvial silts. This colluvium material drapes the lower part of the slopes, fossilising the tufa in their primitive position.

– Black isohumic soil – already mentioned above for the terrace's edges – can also be found here, thick, but highly variable, resulting from erosion in the alluvial silts. This soil drapes the concave base of the slope, on which it is retained by vigorous vegetation. At the contact between the soil land the alluvial silts, a festoon-like line of angular colluvial material contains abundant micro-lithic industry artefacts. The size of the artefacts is very different from the ones mentioned in the lower layer, although their morphological typology is very similar. At other sites, the outcrop in the upper formation is truncated, more especially in the Nyabarongo gorge. The absence of tufa-welding has reduced the protection for the alluvial deposits. In Gasenyi, one can notice that above the lower formation of ochre sands the colluvial reworking was very limited. In Kibilizi, the colluvial formation has an erosional contact with the micaceous ochre sand and is limited to the homogenous clayey silt that suggests important lateral sediment input of several metres in thickness at the base of the slope.

THE MORPHOGENETIC EVOLUTION OF THE LATE QUATERNARY

The characteristics of the two large outcrops in these deposits suggest very varied processes of deposition, linked to global modifications of the environment.

The phase of alluvial high sedimentation

The lower ochre sand can be related to one long-term phase, during which the deposition processes have remained unchanged. The micro-deltaic cross-bedded stratifications with channels reveals palaeo-river flows those were irregular with a high sediment load leading to deposition of washed sands and clay in still-water settling areas, such as in abandoned channels.

The main outcrop in Amasangano provides evidence of the domination of lateral sedimentary contribution, with internal bedding inclined between 15 to 20 degrees (fig. 3). This orientation corresponds to the mediatory line of a large sedimentary fan originating from the small Kibuya valley on the right bank of the Mukungwa River. This small valley is still obstructed by sedimentary material of the same type at the same level but they are truncated by the shifting of Mukungwa's meanders above which it is perched.

Hence, the sedimentary sequences depict a palaeo-valley obstructed with vast lateral coalescent fans, in between which the river twisted and turned to find its way through, leaving at the end of the wet season sparse lenses of fine material, which settled in still-water (fig. 6A). This system corresponds to seasonally contrasted flows. The slopes on the side of the floodplain were covered at best by sparse vegetation, which would allow for an erosional and dissection phase to fix the main characteristics of the present valley system morphology: secondary dissection of the crest lines, upper catchment in a crow's foot and other associated patterns.

On the slopes, erosion processes export huge amounts of old weathered rocks, from which only the coarse fraction became deposited in the main valley, due to the low-angled longitudinal slope.

This environment, however, did not experience drastic changes. It was most certainly comparable to the present environment, which is characterised by 1200 to 1300 mm of rainfall a year and phenomenon similar to those evidenced by the ochre sand, if the anthropogenic influence gives a little help to trigger slope erosion. For example, the two tributary gullies on the true right of the Mukungwa River, downstream from the village of Vunga, host fluviatile fans limited by the lateral walls of the gullies. The longitudinal slope of the fan is steep and the agriculture is precarious. The fans are fed by material originating from fully cultivated steep-slope watersheds. There are numerous indications of soil degradation, evolving to badlands with deep gullies, where the flow concentrates.

Likewise, coming out on the right bank in the Nyabarongo gorge, several kilometres downstream from the confluence of the Nyabarongo and Mukungwa rivers, Kigina's dell displays, at the mouth of an eroded gully, a cone of sandy material that recently ceased to be active. The sandy cone apex is covered by coarse material evolving progressively to fine sand. The latter are indurated at the top by a water table pisolitic-type crust that supports a banana tree plantation. The cone edge is reworked in «false terrace» by the Nyabarongo River shiftings. The cone-dam system might have been reactivated locally in a recent period while it was absolutely widespread during the ochre sand deposition.

The phase of terraces' construction

The emplacement of the upper unit permits the envisioning of an important shift in the river palaeo-flow. The clear basal discordance with the underlying ochre sand indicates that lateral input lost importance in the floodplain sedimentation scheme, and that a more continuous river-flow remobilised the ochre sand that were commanding most of the floodplain. A channel, more or less calibrated,

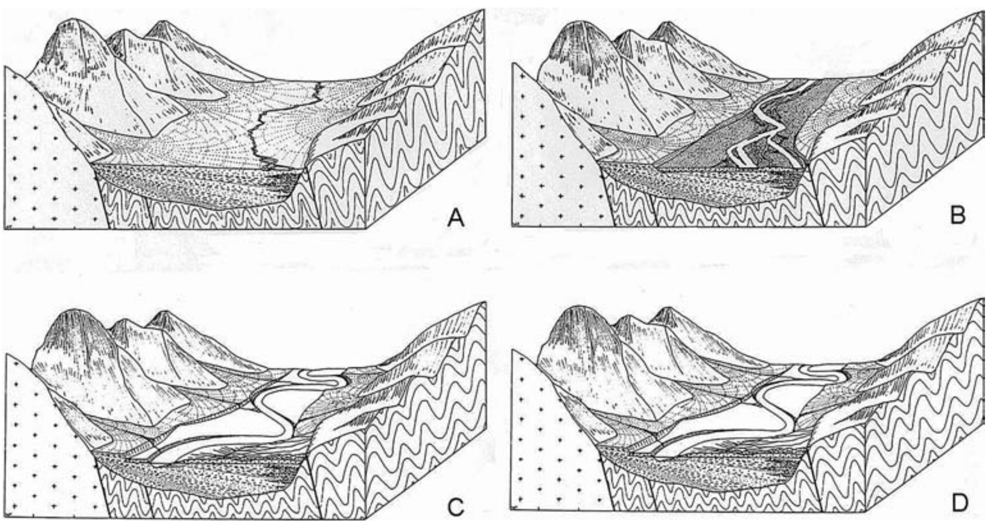

FIG. 6 - Block diagram. A: The phase of alluvial high sedimentation; B: The phase of terrace's formation; C: Beginning of incision and formation of tufa deposits linked to hydrothermal activity (front side right); D: Incision of the main valley and fossilisation of lower formations by tufa deposits. (drawing P.W.)

flows sinuously in the flood plain, cutting through the distal part of the fans (fig. 6B).

The size of quartz and quartzite rich gravels deposited in the reworked floodplain is derived mostly from a sorting and a segregation of the ochre sand in which the same grain size were present but very sparse. The presence of gravel cannot be explained by any brutal morphogenic event, such as erosive remobilisation of sediments. Evidence tends to prove the contrary. The volume of imported sediment is less important than in the previous phase. This modification happened concomitantly with ecosystem transformations. From this period, the floodplain was covered by dense vegetation, which has been evidenced by the presence of concretion pipes contained in the gravels. These vegetation proxies would indicate that the ecosystem was grassland with various *Poaceae* and lacustrine plant species.

In sediment records, bones of large mammals bring some further elements of explanation to understand the vegetation at the local to regional scale. These have confirmed the dense vegetation at and around the site. From the knowledge of the ecosystems those mammals live in, we can deduce that the environment was a patchwork of forested and open grass vegetation. Cape Oryx is often to be found in grasslands and savannah, even if its environment can stretch to forested habitats. Therefore, the presence of Oryx is not an absolute proxy of a forested space. The giant forest hog (*Hylocherus*) is a typical stenoece *Suidae* species (*i.e.*, a species that has strict ecological constraints). This animal lives below dense forest cover, and while it does leave the forest for grassland to feed, it never wonders far from the safety of the forest edge. In deep valleys, riparian forests can alternate with riverine wetlands. The later were essential for the development of hippopotamus communities. Human settlements began with the emplacement of the terraces, which provided a rich environment for hunting and fishing activities.

The impression of a wet climatic context is enhanced by the nature of the deposits at the toe of the slopes, which are the lateral equivalent to the terrace. Solifluction processes appear at different levels in the remobilised ochre sand located at the base of the recent formations. They have also been more widely evidenced in the light-brown alluvial silts, which cover the tufa, where the garlands of colluvial elements resulted from the emplacement of successive lobes of solifluction. Sometimes, the lobes include material of larger size. The events were rather quick, because there are no traces of pedogenesis until the final stabilisation of the slope. Therefore, the humid crisis seems to begin abruptly, and is concordant with the important change that occurred around 13,250 BP. It corresponded to a relatively fast return of the mountain rainforest (Bonnefille, 1987; Roche, 1991).

At the top of the formation, on the regularised slopes, the beginning of an already evolved and active pedogenesis coincided with new human settlements. The climatic conditions do not exclude slow soil movements, which records at least an accentuated creeping. The vegetation cover is dense enough to retain the soil and to provide an important amount of humus over a long period, which is attested by the advanced stage of transformation. This confirms integral stabilisation of the soils and slopes by the vegetation. This stabilisation was most probably as strong as at present, without taking into account anthropogenic degradations. The flow is concentrated in a unique channel. One can notice the beginning of a vertical incision of the stream, and the local formation of tufa by hydrothermal activity (fig. 6C). In this setting, the tufas have been very effective in the preservation of fossil-rich sediments, but they do not have any direct climatic signification. They are essentially linked to tectonic or volcanic activity. According to Stoffers & Hecky (1978), this formation could have been contemporaneous with the important phase of hydrothermal activity that took place in the Kivu Lake Basin between 6000 and 7000 BP (Verhaeghe, 1963).

The climatic characteristics could be deduced from the vegetal species, which contributed to the tufa formation. There are clear differences in the diameter of the concretion-pipes. Near the terrace edge, the pipes are thin with diameters of a few millimetres, whereas in the central part of the tufas, they correspond to thick calcite sleeves. Therefore, there are specific variations of the hygrophilous vegetation, depending on the distance from the river. The thick concretion-pipes were formed on the flank of the tufa lobes by carbonate precipitation on stolons and stems of the self-propagating grass.

The climatic reconstruction built upon vegetation proxies has to be cautiously interpreted, because in the present case the distribution of the vegetation is more controlled by the hydrothermal temperature and the ability of the vegetation to live in a high carbonate context, than by the local climatic characteristics.

At the bottom of the sequence, the lack of tufa or any other carbonate elements suggests that the hydrothermal activity had not yet started. Therefore, this unit might be anterior to the formation of the volcanic field of Virunga or at least to the latest eruption phase, which reactivated the faults and triggered the hydrothermal activity due to an extensional tectonic regime. The formation of the upper terrace must have been anterior to the last significant volcanic activity, and more especially to the emplacement of the Nyakinama lava-flow deposit. The lava flowed up to a distance of 3 km to the site of Ngaru, infilling the bottom of the valley. Despite this large volume, there are no volcanic elements to be found in the terrace material. Consequently, the edge of the terrace was already formed when the lava flowed into the valley.

The lowering of the alluvial bottom of the main valley to its present level is therefore a recent process at the Quaternary scale. It occurred after the formation of black soils. This incision was not transmitted to the first order tributary dells, the bottom of which is obstructed by alluvial and colluvial deposits (fig. 6D). It is therefore difficult to link the incision with a regional scale morpho-climatic signification. The global increase of the relief of the Virunga volcanic field is triggered by the uplift of the crystalline shield. The construction of the volcanic cones over 4000 m has generated deep modifications to the flow conditions in the upper basin of the Mukungwa River and in the mid- to low Nyabarango River (Salée, 1927; Moeyersons, 1976). The steep longitudinal profile in the upstream part of the river; the increase of precipitation on a catchment that became larger; all confer to increase the energy of the flow. This flow is responsible for the incision of the thalweg in the primary alluvial filling. The terrace is only «climatic» during the construction phase of the present floodplain during the Holocene, because of the abrupt return of a humid context.

DISCUSSION

No absolute dating was performed on the sedimentary deposits the authors describe in the present contribution. However, the deposition processes provide a series of proxies for the Late Quaternary palaeo-environments at the regional scale.

Firstly, hydrothermal activity and archaeological remains link the sedimentary formation to the early Holocene. The previous scientific research presented above – by Stoffers & Hecky (1978) – have clearly linked the tufa deposits to a phase of hydrothermal activity that started between 6000 and 7000 BP in the Kivu Basin. Moreover, among the various archaeological data found in the upper part of the sedimentary sequence, the bone harpoon with double row of barbs present a similar form of craftmanship to the harpoons found in the «main fossil-rich layer» of the Ishango site, located on the shores of Lake Edward in Congo (de Heinzelin de Braucourt, 1957, 1962). The presence of this harpoon at the Ngaru-Amasangano site suggests an extension of the early stage of the «lacustrine-bound civilisation» from the Ishango open grassland to the wide deep valleys of the oriental mountain borders of the Kivu-Edward Graben. Remains from the «culture of Ishango» have been dated using radiocarbon by de Heinzelin de Braucourt (1957), who has proven that the civilisation extended between 7000 and 9000 BP, but could be even older (Brooks & Smith, 1987). If we transpose the absolute dating to the site of Ngaru, it does correspond well to the evidence gathered at the site, just before the fossilisation of the alluvial formations by tufas.

Secondly, all the previous studies of Quaternary palaeoenvironment carried out in mountainous Central Africa concur. They depict the establishment of identical evolution patterns, even if the chronology details vary, depending on the location, the methods and their accuracy. This latter point being dependant on how recent the methods used are. We shall keep in mind (Bonnefille, 1987) that a cool and humid stage, characterised by the presence of a coniferous forest (*Podocarpus* sp.), is followed around 30,000 BP by grass vegetation attesting to a drier and cooler climate between 30000 and may be 13,250 BP. Present humid conditions seem to have been established around 13,000±500 BP and correspond to the extension of a mountain rain-forest, and sometimes, as a function of the altitude, to an open zambesian forest (Vincens, 1993). While Roche (1991) considers that this trend continued for a long period of time with short interruptions *ca*. 3500 BP and *ca*. 1550 BP, many other authors estimate that a major change had occurred *ca*. 4000/3500 BP, with the climate becoming dryer. This forced the forests to recede even after the climate became humid again, because the phenomenon was amplified by anthropogenic activity that lasted for at least 2000 years. This evolutionary pattern does not only apply to the present regional setting, but is also a proxy applicable for the all Atlantic Central Africa as described in the synthesis of Lanfranchi & Schwartz (1990).

The results we provide in the present contribution do fit into this framework. The processes that triggered the «phase of alluvial high sedimentation» can be related to the dry hypothermic period, which was largely evidenced between 50,000 and 15,000 BP, reaching a maximum aridity between 22,000 and 15,000 BP. This phase would correspond to the last glacial maximum in the areas of present temperate climate. The study of pollens carried out on the peat-bog in Rwanda (Hamilton, 1982; Bonnefille & Riollet, 1984; Roche & van Grunderbeek, 1985; Roche & *alii*, 1988) in Burundi (Bonnefille, 1987; Bonnefille & Riollet, 1988; Roche & *alii*, 1988) and on the pollens trapped in the sediments of Lake Tanganyika (Vincens, 1989, 1993) confirm that all types of forests regionally receded, while grassland dominated in a dryer and colder environment.

Authors do not fully agree on the values of temperature decrease. According to Bonnefille (1987), the average temperature decreased by 2.5 to 3 °C, while Vincens (1989, 1993) suggested a 5 to 6 °C reduction for the period that extended between 30,000 and *ca*. 13/15,000 BP. This dating coincides with the report of Degens & Hecky (1974) who linked the important lowering of the water level in Lake Kivu, around 14,000 BP, to a dryer and colder climate than the present one (–50% for precipitation, ~3 °C for temperatures). Examining the geomorphological processes of this period, Alexandre-Pyre & Seret (1969) wrote in a comparative study on valley deposits in Shaba, East Angola and in Zambia that valleys and ravines tended to be filled by unsorted sediments. They have linked this infilling phase with a climate dryer than the present one.

During the same period, in the region of Kinshasa in Congo, de Ploey (1965) relates a phase of intense erosion providing abundant ochre sand deposits to a forest recession. He attributes this receding to a significant xeric period. In the Zambezian Region, Roche (1991) worked on the geomorphology, sedimentology, and palynology. He concluded that a xeric climatic phase, which extended between 50,000 and 15,000 BP, has favoured the extension of savannah open-vegetation. For the studied region, Roche (1991) wrote that between 22,000 and 18,000 BP, an expansion of savannah and shrubs as well as a noticeable receding of forest formations towards high-altitude refuge on the Congo-Nil Ridge occurred.

The return of forest formation, linked to an increase of temperatures and/or precipitation, has also been attested by pollen analysis carried out in the region *s.l.* (Roche & van Grunderbeek, 1985; Bonnefille, 1987; Vincens, 1989, 1993). Bonnefille (1987) considers that the installation of this humid crisis was abrupt. Further, Roche (1991) and Roche & *alii* (1988) consider that this transformation went through a transitional phase between 12,000 and 9000 BP. The re-colonisation of the environment by rainforest species – from 9000 BP – would have been preceded by transitional heterogeneous formations dominated by heliophilous taxa, with a maximum extension of the dense rainforest *ca*. 6500 B.P.

This re-colonisation continues until the present day, with only two short interruptions *ca*. 3500 BP and *ca*. 1550 BP (Roche & *alii*, 1988; Roche, 1991). The authors have also observed weaker variations, but they do not hold any real chronological significance. One knows that depending on the inter-annual variation of precipitation, the triggering of solifluction lobes and mudflows is a random phenomenon, both temporally and spatially. This phenomenon has not ceased to occur since the establishment of the humid period. This phenomenon's manifestation is particularly strong in the upper part of the catchments of the second order valleys, or in the catchments of the first order dells.

At the outlet of the tributary catchments, the thalweg is often obstructed by muddled humps or by convex lobes, which are still well-preserved and that were emplaced after the formation of the sandy cones like in the dells of Kigina as mentioned above. At present, similar events can turn into catastrophic events on the integrally cultivated slopes, as attested by the events of June 1987 in the region of Base (Rwanda, Central Plateau), and May 1988 in the region of Vunga, where 60 people perished.

Considering processes, the observation by Alexandre-Pyre & Seret (1969) in East Angola, Shaba (Congo), and Zambia, drove the authors to link the return of precipitation to vertical erosion phases that correspond to the mechanisms of terrace construction that we have observed at the confluence between the Nyabarongo and Mukungwa rivers.

The number of scientific research projects on the East and Central African Region has grown since 1985. Among these contributions one can note the work of Gasse & *alii* (2008) who re-investigate the climate evolution in equatorial and southern Africa between 30,000 and 10,000 years ago. This compilation of an abundant literature is an important synthetic work focused on palaeo-climatology but not on palaeo-environments. They confirm the general scheme of climate evolution and bring new points of view on the seasonality. The work of Ivory & *alii* (2012) is focused on the seasonality and shedding a different light on the role of seasonality on the ecosystem establishment. They show that the strengthening of the S.W. «tradewinds» contributed to determine dryer winters since 11,800 BP. The paper of McGlynn & *alii* (2013) is more interesting from a palaeo-ecological point of view. Unfortunately, their recording starts only around 8000 BP. They evidence a change around 5,000 BP characterised by aridity reinforcement.

Among the recent publications, the most important contribution that relates to the present subject is undoubtedly the work of Holtzförster & Schmidt (2007). Aiming at reconstructing the palaeo-Nyabarongo river drainage reversal, they produced a finely documented work based on the very same site and probably outcrops we explored 24 years before. They investigated in detail 10 sedimentological sections in slopes and cliff exposures in order to find proof of this drainage reversal that followed the Virunga formation. The drainage reversal in this region is far from being unknown and numerous researchers mention it: Ojani (1971) suggests that the main part of the Rwanda-Burundi was drained to the North and the Congo Basin through a palaeo-Nyabarongo River, the bed of which might stay at the present emplacement of the Virunga River. The river flowed into a proto-Kagera River. Sirven & *alii* (1974) assume that the damming of the northbound valleys by the Virunga lava field explain the formation of Lakes Ruhondo and Bulera (fig. 2) and the reversal toward the Akagera of all the drainage system of Byumba Region's Appalachian relief. Rossi (1980), on the basis of physical and morphological evidence try to reconstruct the trajectory of the palaeo-Nyabarongo River from Amasangano to the North. He shows that before the reversal, the drainage of the Rwanda and Burundi was divided in three basins: the Akagera-Nyabarongo Basin, draining the water to the north to rift lakes Edward and Albert; the Rubuvu Basin, draining to the N-E and North to the same rift zone; and the Malagarazi Basin, draining to the South toward Tanganyika Lake (fig. 7A). After the drainage reversal, the drainage of the region was and is still organised in two basins: Akagera Basin (Nyabarongo is the upper Nyabarongo system) draining eastward to Lake Victoria and the Nile River and the Malagarazi Basin draining southward to Lake Tanganyika and Congo River (fig. 7B). Rossi (1980) identifies the point of capture of the Nyabarongo-Akanyaru network by the Akagera River, South of Kibungo, in the locality of Mutenderi, at the level of the confluence between the Kibaya and the Kagera rivers (fig. 7A, 7B). Bishop (1969) considers that the drainage reversal of the Kagera, and by then the Nyabarongo to the East, occurred around the middle Quaternary.

The work of Holtzförster & Schmidt (2007) is fourfold: (i) they precisely described the characteristics of the sedimentary material, linking each lithofacies identified to a precise hydrodynamics context; (ii) they used heavy minerals as a proxy to reconstruct the direction of the flow that emplaced the sand in Ngaru-Amasangano. This allowed them to confirm the drainage reversal at Nyabarongo-Mukungwa confluence; (iii) they identified numerous microfossils and fossils that permit them to establish «pre-», «syn-» and «post-tufa» palaeobiological constraints. Additionally, the fossil assemblages confirm the presence of a palaeo-lake at the confluence after the damming of the northbound valley by lava flows produced by Virunga Volcanos; (iv) they proposed to adopt the stratigraphic name «Masangano Formation» for these rare and well-conserved sediment formations.

The present contribution, based on the same sedimentological recordings, was aiming to reconstruct the palaeo-environment evolution in this area. If we evidenced a lack of efficient drainage during the phase of the ochre sand

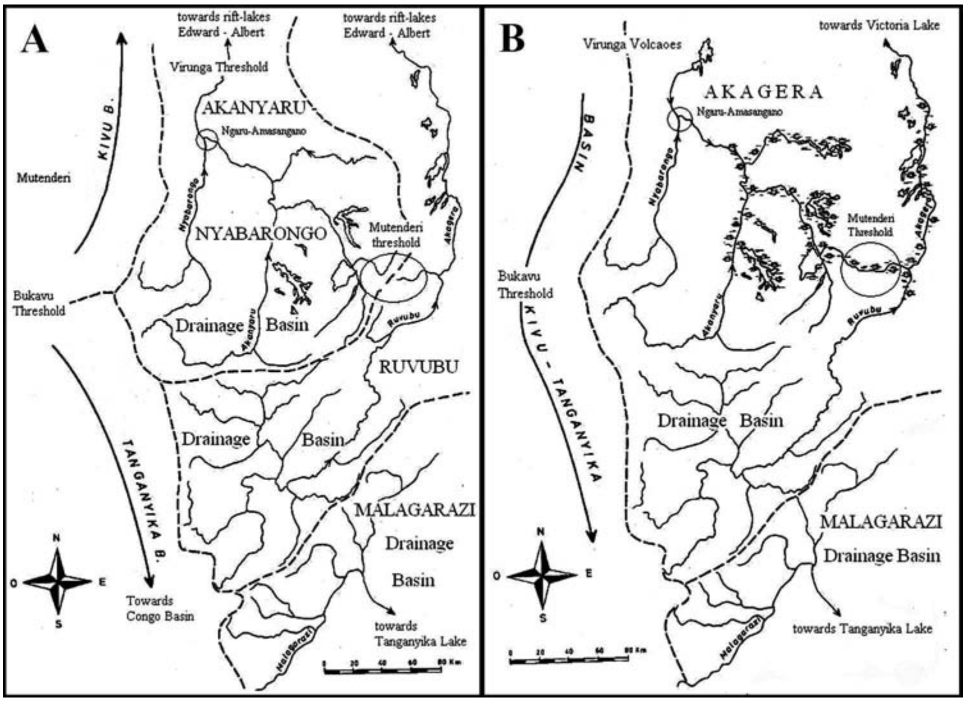

FIG. 7 - Drainage network before and after the reversal in Ngaru-Amasangano (modified from Rossi, 1980).

emplacement, we did not evidence the presence of a perennial lake but only temporarily flooded areas or swamps in which micro-deltas emplaced. The main valley was impeded by large debris fans issuing from the lateral dells or little valleys. In the distal part of these fans, weak depth long lasting water impoundment might have occurred as attested at Gasenyi where a regular succession of 5 couplets each composed of a 10 cm layer of varved clay at the base capped by a 10 cm layer of multi-coloured angular sand was observed in 1988. This succession provides evidence of the bi-modal origin for the local sedimentation: clay settling in shallow lakes and lateral contribution of angular sand of nearby origin.

Considering the role of sediments in infilling the main valley with ochre sand, the present research does not concur with Holtzförster and Schmidt's interpretation of the sedimentary structures of the large outcrop at Masangano. They link these sedimentary structures to the large-scale foreset beds of the northward prograding palaeo-Nyabarongo delta in a dammed lake. Our observations at this site evidenced a plunging of the sedimentary structure towards the NNE (towards the outcrop shown in fig. 3). Bed inclination is comprised between 15° and 20° and the outcrop cut perpendicularly the distal part of a large sedimentary fan the median line of which was oriented (at least during the first stages of the fan formation) between points 2 and 4 in fig. 8. This explains the rough dome shaped sedimentary structure visible in fig. 8. On the right, *i.e.* upstream (considering the Nyabarongo), the structure is not horizontal but lightly tilted upstream. The fan apex was located in the small valley of Kibuza where the same type of material can be observed at the same level. The sand morphoscopy evidenced a dominance of angular shapes. This pleads for a short transport and the domination of lateral sedimentary supply.

CONCLUSIONS

The study of the characteristics of Holocene deposits, fossilised by the emplacement of tufas at the confluence

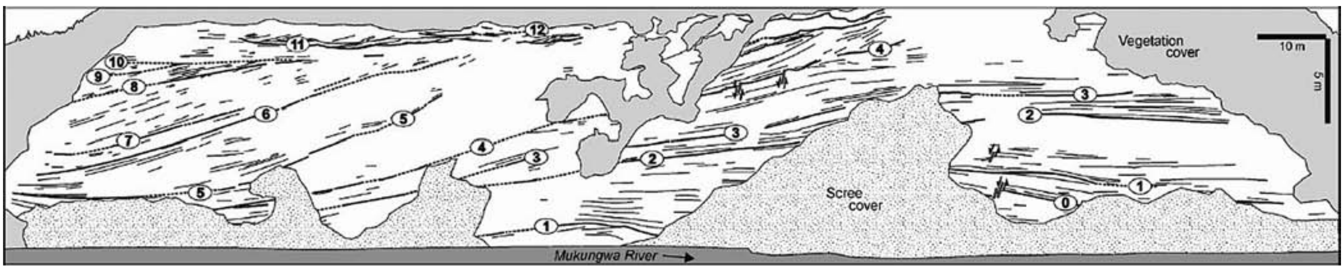

FIG. 8 - Ngaru-Amasangano, the main outcrop oriented N320-N140 (left-right) displaying sedimentary structures. The numbers correspond to the different traced/interpolated set boundaries (from Holtzförster & Schmidt, 2007).

TABLE 1 - Synthetic table of Africa Quaternary environments in the Great Lakes Region

AGE BP	BURUNDI 1987	TANGANYIKA 1989	RWANDA 1985	RWANDA 1982	RWA-BURUNDI 1991	TANGANYIKA 1993	RWANDA 1983-1987	AGE BP
	Kashiru peat-bog Altitude 2014 m	**Drilling core** Lake altitude 782 m	**Rugezi Swamp** Altitude 2055 m	**Kamiranzovu swamp** Altitude 1950 m	**Congo-Nile Crest** Sedimentological, morphological and palynological synthesis	**Drilling core** Lake altitude 782 m	**Amasangano** Formation 1400 m	
	Bonnefille (1987)	**Vincens** (1989)	**Roche & van Gründerbeek** (1985)	**Hamilton** (1982)	**Roche** (1991)	**Vincens** (1993)	**Wassmer &** ***alii*** (this paper)	
1000					More warm & more humid			1000
2000		Degradation of the tree cover	Forest expansion		1600-1500 Dryer			2000
2500		Grassland dominates	Maximum of the cold		Humid pulsation			2500
3000	Receding from 4350		and dry pulsation	Forest expansion				3000
4000	Climate more arid	Accentuated humid phase	Forest receding and		Dryer			4000
5000		Maximum extension of the	savannah extension	Gap	Large extension			5000
6000	Maximum extension	Zambezian clear forest	Extension of the mountain	probably related to	of the forest		Tufa formation	6000
7000	of mountain rain forest	Rainfall increases drastically	forest and receding	a flooding of	Max extension	Maximum extension	Human settling	7000
8000		from 10,000	of the open formations	the swamp	of the mountain	of the Zambesian	Climate more humid	8000
9000		Progressive T° increasing		linked to a	rain forest	clear forest	Forest expansion	9000
10,000	Re-installation	Installation of the clear forest		rainfal	Momentary receding		Terraces formation	10,000
11,000	of the forest formations			increasing	Forest expansion	Forest reconquest		11,000
12,000		Clear forest reduced				Expansion of clear forest		12,000
13,000		Grass domination		Forest expansion	Momentary receding	on the lake littoral		13,000
14,000	From 13,500	Mean annual temperature		more humid and	Forest expansion	T° and/or P increasing		14,000
15,000	regression	drops of about 5 to 6 °C		more warm	Savannah receding			15,000
16,000	of all	Vegetation belts drop of 1000 m			Reconquest by heliophyle	Colder and dryer	Phase of alluvial	16,000
17,000	forest types			Cold and dry climate	taxa from heterogenous	(temperature drops	high sedimentation	17,000
18,000				grassland expansion	secondary formations	~4 °C) Dominance of	Flows seasonally	18,000
19,000	Climate dryer and colder				22,000 - 18,000	mountain elements	contrasted	19,000
20,000	(-2,5 to 3 °C				Arid context	Receding of Zambesian	Slopes covered by	20,000
25,000				Forest, $^{+}$warm $^{+}$humid	Grass extension	clear forest	sparse vegetation	25,000
30,000				Forest receding	Mixed forest $^{+}$dry $^{+}$cool			30,000
35,000				Climate colder & dryer				35,000
40,000				Mountain forest				40,000

between the Nyabarongo (Upper Nile River) and the Mukungwa River, to the North of Rwanda, show that the depositional environment has varied during the late Quaternary period. The sedimentary data is completed by the discovery of mammal remains providing environmental markers, especially two species characterised with strong ecologic valence. The lack of collagen in the bones has not allowed for absolute dating. Therefore, we related the stratigraphic units in the terraces with palynological data from regional peatbog, and with sediment studies in Lake Tanganika.

The authors have compiled all these data into a single synthesis table (tab. 1). The dataset suggests that the valleys obstructed by lateral fans corresponding to seasonally contrasted flows and sparsely vegetated slopes, which in a cooler climatic context than the present one might have been extended between 30,000 and 14,000 BP. One must keep in mind that the progressive damming of the northbound Nyabarongo palaeo-Valley by the uplift of the eastern shoulder of the African Rift's western branch have contributed (i) to reduce the sediment transfers in the river and (ii) to favour high sedimentation rates. By then, the relative part of the climatic and/or tectonic effects on the sedimentation in the valley is impossible to determine. The period of terrace construction was triggered by the development of a humid and warm climate, which allowed slope stabilisation through the extension of dense rainforest. The incision of the hydrographical network in the valley alluvium has probably been helped, at least during its latter stages, by the lowering of the Mutenderi threshold when the Nyabarongo drainage system poured into the Rubuvu-Akagera Basin. Fossilisation of alluvial sequences by hydrothermal tufa is post-human settlement, as the osteodontokeratic culture attests to. The emplacement of tufa deposits has to be related to the important hydrothermal activity that started in the basin of Lake Kivu between 7000 and 6000 BP.

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