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Interactions between Great Lakes Level Change, Tectonics and Volcanism in the Rungwe Volcanic Province, SW Highlands of Tanzania*

by

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KEYWORDS. — Southwestern Tanzania; East African Rift; Active Tectonics; Volcanism; Palaeoclimate; Lake Level Fluctuation.

SUMMARY. — The Rungwe Volcanic Province extends between the Rukwa and Nyasa (Malawi) rift lakes, which both experienced marked water level fluctuations during the last 40 ka. The infilling of water reservoirs, whether artificial or natural, is known to be able to trigger earthquakes and volcanism. In the southwestern Highlands of Tanzania and especially in the Rungwe Volcanic Province, where the western and eastern branches of the East African Rift System meet, a similar link is highlighted. Compilation of available data supplemented by new observations allows investigating the time relations between (1) climatically-induced, rapid water level fluctuations in the surrounding rift lakes, (2) tectonic activation of the fault systems that extend from the lacustrine depressions to the volcanic area, and (3) deposition of *tephra* layers in soils and sediments. The latter are considered to reflect the frequency and/or magnitude of explosive eruptions in the Rungwe massif. According to these data, a connexion is suggested between the great lakes level change, tectonics, and volcanic activity for the last glacial-interglacial transition (14-11.5 cal. ka BP), and possibly also during the Holocene.

MOTS-CLES. — Sud-ouest de la Tanzanie; Rift est-africain; Tectonique active; Volcanisme; Paléoclimat; Fluctuation du niveau lacustre.

RESUME. — *Interactions entre les variations du niveau des grands lacs, la tectonique et le volcanisme dans la province volcanique du Rungwe, Highlands du SO de la Tanzanie.* — La Province volcanique du Rungwe s'étend entre les bassins de rift des lacs Rukwa et Nyasa (Malawi), tous deux marqués par des fluctuations considérables de leur plan d'eau au cours du dernier cycle glaciaire-interglaciaire (40 ka). Le remplissage de réservoirs d'eau, artificiels ou naturels, est connu pour stimuler l'apparition de tremblements de terre ainsi que le volcanisme. Dans les Highands du sud-ouest de la Tanzanie, en particulier dans la Province volcanique du Rungwe où les branches occidentales et orientales du

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Système du Rift est-africain se rejoignent, un lien similaire est mis en évidence. La compilation des données disponibles, complétées par de nouvelles observations, permet d'étudier les relations temporelles entre (1) les variations rapides du niveau d'eau, causées par le climat, dans les lacs de rift avoisinants, (2) l'activation tectonique de systèmes de failles, présents sous les dépressions lacustres et se prolongeant jusque dans la région volcanique, et (3) l'enregistrement d'événements volcaniques (dépôts de *tephra*) dans les sols et sédiments. Ces derniers sont considérés comme reflétant la fréquence et/ou la magnitude des éruptions explosives dans le massif du Rungwe. Sur la base des données disponibles, une relation causale semble exister entre les fluctuations du niveau des grands lacs, la tectonique et le volcanisme pendant la dernière transition glaciaire-interglaciaire (14-11,5 cal. ka BP) et probablement aussi pendant l'Holocène moyen.

TREFWOORDEN. — Zuidwest Tanzanië; Oost-Afrikaanse Rift; Actieve tektoniek; Vulkanisme; Paleoklimaat; Fluctuatie van het peil van meren.

SAMENVATTING. — *Interacties tussen schommelingen van het peil van grote meren, tektoniek en vulkanisme in de Rungwe Vulkanische Provincie, zuidwestelijk Hoogland van Tanzanië.* — De Rungwe Vulkanische Provincie is gelegen tussen de Rukwa en Nyassa (Malawi) riftmeren, die beide beduidende fluctuaties van hun waterpeil gekend hebben in de laatste glaciale-interglaciale cyclus (40 Ka). Het is bekend dat het artificieel of natuurlijk vollopen van waterreservoirs tot aardbevingen en vulkanisme kan leiden. In het zuidwestelijk Hoogland van Tanzanië, waar de westelijke en oostelijke takken van het Oost-Afrikaanse Riftsysteem samenkomen, wordt getracht om in het geval van de Rungwe Vulkanische Provincie een mogelijk gelijkaardig verband aan te tonen. De compilatie van nieuwe waarnemingen laat toe de tijdsrelaties te onderzoeken tussen (1) klimaatgebonden snelle fluctuaties in het waterpeil van de omgevende meren, (2) de tektonische activatie van het breuksysteem in de regio's van de lacustriene depressies tot en met de vulkanen, en (3) de waarneming van gedateerde vulkanische asprojecties (*tephra*laag), tussengelaagd in de bodems en de sedimenten. Deze laatste kunnen gezien worden als indicatoren van de frequentie en de magnitude van vulkanische erupties in het Rungwemassief. Op basis van de beschikbare gegevens lijkt er een causaal verband te bestaan tussen variaties van het waterpeil van de grote meren, tektoniek en vulkanisme in de tijdsperiode van de laatste glaciaal-interglaciale transitie (14-11,5 cal. Ka BP) en mogelijk ook tijdens het Midden-Holoceen.

1. Introduction

The occurrence of moderate to large earthquakes (Ms 5 to 6.5) triggered by the rapid level fluctuations in large artificial reservoirs (particularly during their infilling) has been observed in several dam sites for decades (AMBRASEYS & SARMA 1968). In particular, the Koyma water reservoir in India, which regularly triggers earthquakes, is one of the best known sites (GUPTA 2002, PANDAY & CHADHA 2003, SINGH *et al.* 2008). At the boundary between Zimbabwe and Zambia, the Kariba Dam also regularly triggers Ms $\geq$ 5.0 earthquakes since the Ms 6.1 earthquake of 1963, the largest recorded so far in Zimbabwe (MAPANI *et* *al.* 2006). The common characteristic of these sites is that they are located in areas affected by major fault systems but which were considered as seismically quiescent before filling the water reservoir. At the Koyma site in India, detailed investigations have demonstrated a causal relation between the water level fluctuation in the reservoir and the occurrence of earthquakes. It is explained by a diffusion process along faults and fractures rather than by the loading effect of the reservoir (Panday & Chadha 2003, Singh *et al.* 2008). This diffusion effect occurs particularly along vertical strike-slip faults. In terms of fault mechanics, an elevated fluid pressure in a fractured medium promotes lubrication of fault surfaces, reducing normal stress and the associated mechanical friction.

In nature and on a larger scale, it has also been suggested that changes in climatic precession that coincided with climate and sea-level change (Paterne *et al.* 1990) and/or rapid sea-level changes during the last 100,000 years (McGuire *et al.* 1997) possibly triggered explosive volcanism, as observed from the Mediterranean region during the Late Quaternary. In particular, McGuire *et al.* (1997) showed that the last low sea-level period around 22 cal. ka BP corresponds to a more quiescent volcanic phase than the period of rapid sea-level rise between 15 and 8 cal. ka BP.

One of the best geological features where this interplay between climatic, tectonic and volcanic processes can be observed are the tectonically active continental rift areas, and especially where large lacustrine depressions border active or dormant volcanic areas. Cyclic sedimentation is frequently observed in these lacustrine basins (just like in marine and oceanic systems) and it has been shown that this can be caused by water level fluctuations, eustatic, climatic and tectonic factors (Morley *et al.* 2000).

In East Africa, the Great Lakes' region of western Tanzania and neighbouring countries is particularly sensitive to environmental changes (Cohen *et al.* 1993, Bergonzini 1998, Branchu *et al.* 2005). These lakes occupy rift depressions where erosional and depositional processes are naturally controlled by long-term relations between topography, geodynamics and climatic variations. So far, research on the Great Lakes of East Africa has laid emphasis on paleolimnological changes and the consequences of past climate changes. This was especially the case for the International Decades for the East African Lakes — IDEAL project (Scholz & Rosendahl 1988, Rosendahl *et al.* 1992, Cohen *et al.* 1997) or oil exploration projects (Sander & Rosendahl 1989, Morley *et al.* 1992). However, the coupling between surface geodynamic processes and hydrological changes has rarely been considered.

These geodynamic processes are particularly active in the region between Lakes Tanganyika, Rukwa and Nyasa (Malawi [1]*), extending over western Tanzania, northeastern Zambia and northern Malawi (fig. 1). In fact, this region

* Numbers in brackets [ ] refer to the notes, p. 595.

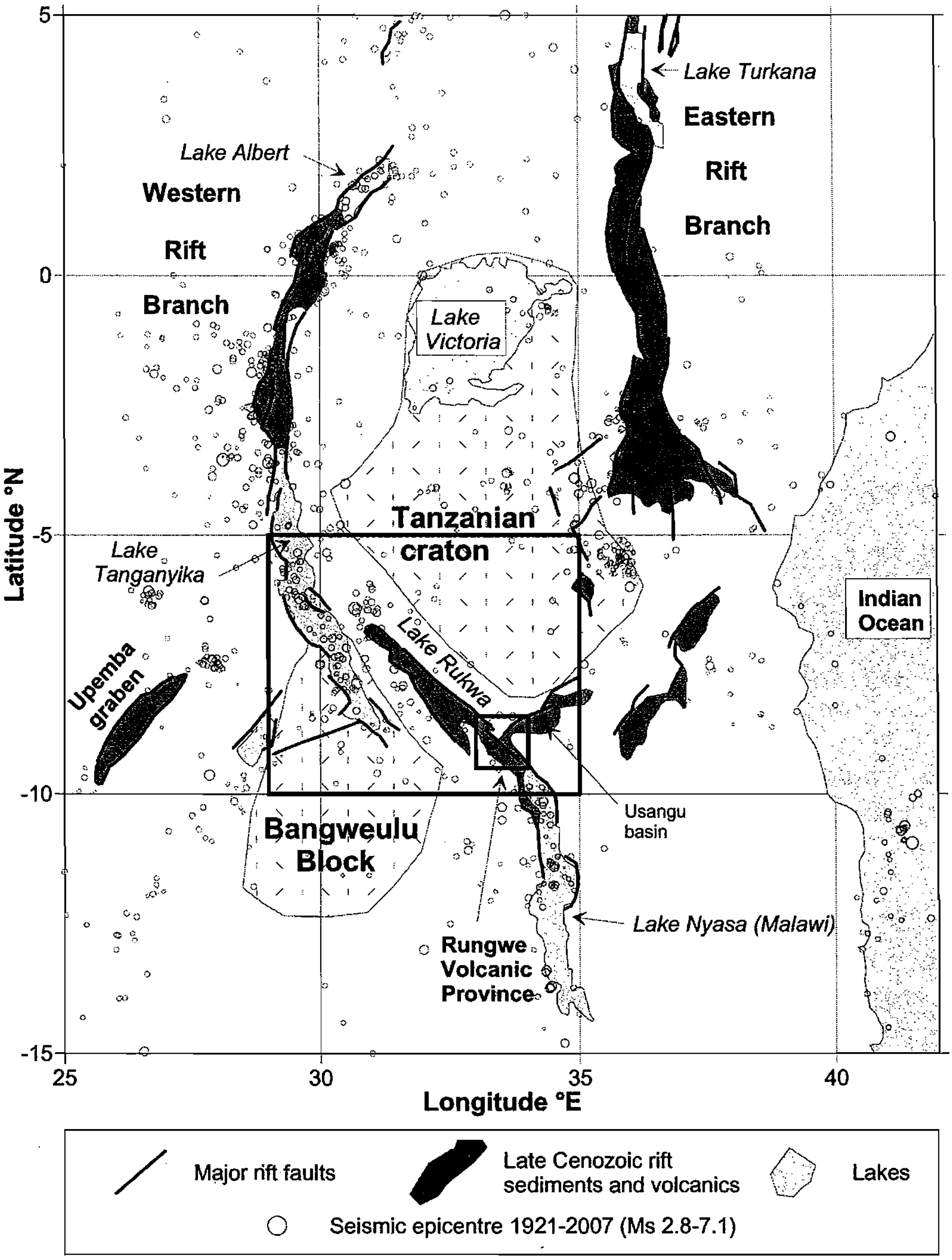

Fig. 1. — Schematic tectonic map of the East African Rift System showing the Rungwe Volcanic Province at the Mbeya Triple Junction between the eastern and western branches of the East African Rift System (adapted from Delvaux 1991 and Macheyeki *et al.* 2008). Seismic epicentres from 1921 to 2007 are derived from the Earthquake Database for Eastern and Southern Africa compiled by Turyomurugyendo (1996) and used as input for the Global Seismic Hazard Assessment Program (GSHAP). Magnitudes are homogenized to Ms and dependent events were removed. Data are considered as complete for Ms Larger than 5. This includes also the data of Ambraseys (1991) and Ambraseys & Adams (1992). It has been completed by data from the USGS NEIC Earthquake Data Base and from the Harvard Centroid Moment Tensor catalogue (magnitudes Mw) for the largest magnitude (Mw > 6.0). The symbol size is proportional to the magnitude Ms (Mw for the largest magnitude). Large rectangle corresponds to figure 2, small rectangle to the Rungwe Volcanic Province.

is characterized by rift-type extensional tectonics and volcanism, resulting in important vertical relative movements between tectonic blocks. They occur as slow continuous or long-period geological processes involving instantaneous episodic events that are important in terms of risks and hazards like earthquakes and volcanic eruptions (DELVAUX *et al.* 1998, MORLEY *et al.* 2000).

In addition to geodynamic controls, strong climatic variations also largely affect the region. The transition from the Last Glacial Maximum (LGM) to the Holocene in East Africa resulted in major environmental changes. In the Lake Rukwa area, the relatively cool, dry and windy climate of the LGM (*ca.* 23-19 ka BP) changed to a warmer and wetter climate during the deglaciation and until the Early Holocene Optimum, between *ca.* 14 and 8 ka BP. The last 40 ka period encompasses a late glacial aridity period (from 40 ka up to ~14 ka), the Early Holocene climate optimum (14-8 ka) and relatively drier conditions during the mid- and Late Holocene (BARKER *et al.* 2002, 2003; GIBERT *et al.* 2002; THEVENON *et al.* 2002; GARCIN *et al.* 2006a). Lake Rukwa responded dramatically to this climatic forcing, with rapid lake-level fluctuations up to 200 m in amplitude and intermittent connections with the Lake Tanganyika drainage system (DELVAUX *et al.* 1998).

In this study, we present a possible coupling between climatically-induced lake-level changes, volcanic eruptions and seismo-tectonic activation in the Rukwa-Rungwe-Malawi rift segment of SW Tanzania. After presenting briefly the major active fault systems in the region, we review the available data on recent (Late Pleistocene – Holocene) volcanic eruptions in the Rungwe region itself, in drill cores from the surrounding lakes and from surface observations up to 300 km away from the Rungwe Province. We synthesize the present knowledge on the Rukwa and Nyasa lake-level changes for the same period. For the last 40,000 years, episodes of rapid lake-level changes in Lakes Rukwa and Nyasa and episodes of strengthened volcanic activity in the Rungwe Volcanic Province appear to coincide. Seismo-tectonic activation of the regional fault network is proposed as a possible mechanism linking the two processes.

2. Morphostructural Setting

The present-day physical environment (landscape) of the southwestern Highlands of Tanzania (figs. 1, 2) is the result of a long-term geological and morphological evolution of the western branch of the East African Rift System (MCCONNELL 1972, TIERCELIN *et al.* 1988, EBINGER 1989, DELVAUX 1991, DELVAUX *et al.* 1998). It is characterized by important topographical contrasts between rift depressions and surrounding high plateaus and volcanic mountains. Some of these depressions contain large and deep long-lived rift lakes (Lakes Tanganyika and Nyasa). Others are filled by intermittent shallow lakes (Lake Rukwa) or by seasonal swamps (Usangu depression). Their internal structure has been investigated by geophysical methods but is still incompletely known (DELVAUX 1991, Morley *et al.* 1992, Rosendahl *et al.* 1992). These basins are bounded by major fault zones, which were active during different periods of geological history (Delvaux 2001). Most of the topographical heights that are adjacent to the deep tectonic basins are related to the same process of rift faulting that created the basins, forming the so-called “rift shoulders”.

In the region of Mbeya, the western and eastern branches of the East African Rift System (EARS) intersect, forming a triple junction between the three rift depressions (North-Malawi, South-Rukwa and Usangu rift depressions) (fig. 2). At this particular spot, the crust is extended in two orthogonal directions, creating a zone of weakness that favoured the emplacement of volcanic rocks. Several volcanoes developed in this area, starting 8-9 Ma years ago (Ebinger *et al.* 1989).

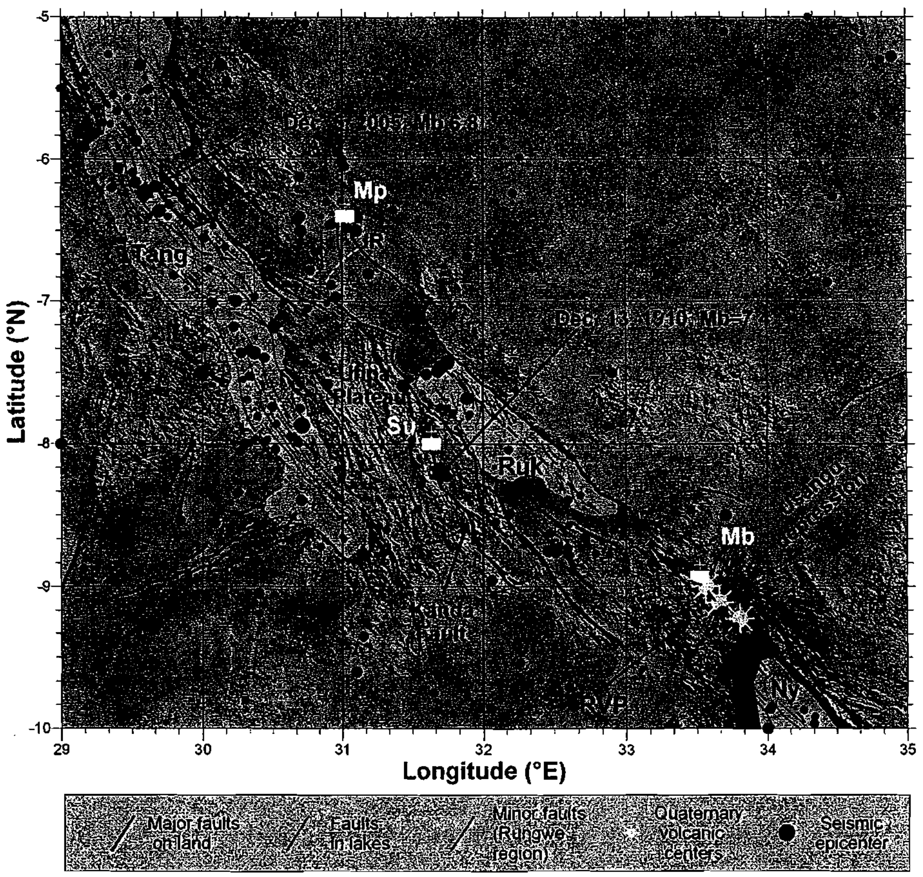

Fig. 2. — Neotectonic structure of the Tanganyika – Rukwa – Malawi Rift segment with the Rungwe Volcanic Province (RVP) located at the junction between the NW-trending Rukwa and Malawi rift basins and the NE-trending Usangu depression (fig. 1). Background: colour-coded SRTM-Digital Topography (90 m resolution) with artificial shading, seismic epicentres (same source and representation as in fig. 1), the Kanda fault system cutting longitudinally the Ufipa plateau and recent faults in the lakes from Morley (1988), Specht & Rosendahl (1989), Morley *et al.* (1992, 2000). Lakes and corresponding rift depressions: Tang (Tanganyika), Ruk (Rukwa), Ny (Lake Nyasa, Malawi Rift Basin). Major cities: Mp (Mpanda), Su (Sumbawanga), Mb (Mbeya). Palaeoshoreline: IL (Ilyandi Ridge). The December 13, 1910 Ms 7.4 earthquake in the Ufipa plateau (data from Ambraseys 1991) and the December 5, 2005 Mw 6.8 earthquake within Lake Tanganyika (data from the Harvard Centroid Moment Tensor catalogue) are shown as large solid black stars.

The Late Quaternary volcanic activity is related to three major volcanic centres (from north to south: Ngozi, Rungwe and Kiejo) of which Mount Rungwe (2,962 m) is the highest. This volcanic area is one of the most humid and fertile regions of Tanzania (Delvaux & Hanon 1993).

The Rukwa rift basin is now a closed hydrogeological depression containing a shallow lake (max. 20 m water depth) with its surface at an altitude around 802 m a.s.l. It is surrounded by rising tectonic blocks and characterized by a particularly high seismicity (Camelbeeck & Iranga 1996). Several active fault zones affect the lake floor and the surrounding plateaus (Vittori *et al.* 1997, Morley *et al.* 2000). Lacustrine terraces and palaeoshorelines are known up to 980 m a.s.l., an altitude at which the overflow sill to Lake Tanganyika is reached (Delvaux *et al.* 1998). Both Lakes Tanganyika and Nyasa are now overflowing into respectively Lukuga and Shire rivers, but they have been disconnected from their outlet in recent historical times (Bergonzini 1998).

Separating the Rukwa depression from the Tanganyika basin, the Ufipa plateau is a tilted block (horst) rising progressively from Lake Tanganyika (800 m a.s.l.) to an altitude of 1,800 m a.s.l. on its northeastern side, where it is sharply cut by an important fault system (fig. 2). The Ufipa plateau itself is dissected longitudinally by several NW-SE trending fault systems.

The sediments deposited in the Rukwa and Nyasa basins recorded both slow, multimillennial long-term processes as well as rapid, "catastrophic" hydrological changes (less than a few decades in duration). Their detailed investigation allows discriminating the effects of local climate change, tectonic evolution and volcanic activity, yielding a chronological time frame for such environmental changes.

3. Late Quaternary Tectonic Activity

3.1. Distribution of Seismic Epicentres

The East African Rift is still poorly covered by permanent seismic stations, but knowledge of its seismicity is improving constantly thanks to the establishment of local seismic networks and also to the recording of teleseismic earthquakes (with magnitudes Ms $\geq$ = 4.0) by the world seismic network (Fairhead & Stuart 1982, Iranga 1992). Figure 1 shows the seismic epicentres recorded instrumentally since 1921. Before 1950, the density of the network only allowed recording of the strongest events and before 1920, the epicentres were poorly constrained by a few seismic stations located exclusively outside Africa. The catalogue used is based on the compilation of Turyomurugyendo (1996) with the magnitudes homogenized to *surface magnitudes* Ms. It has been completed by data from the USGS NEIC Earthquake Data Base and from the Harvard Centroid Moment Tensor catalogue using *moment magnitudes* Mw for the largest magnitude (Mw > 5.0).

Along the western branch of the East African Rift System, seismic epicentres are centred along a broad zone corresponding to the Tanganyika, Rukwa and Nyasa rift lakes (fig. 2). Two strong earthquakes were recorded with their accompanying fore- or aftershocks, at almost 100 years interval. The strongest earthquake ever recorded instrumentally in the entire East African Rift System is the December 13, 1910 Ms 7.4 earthquake near Sumbawanga town (AMBRASEYS 1991). It occurred along the Kanda fault, described hereafter. More recently, the December 5, 2005 Mw 6.8 earthquake occurred within Lake Tanganyika along the Tanzanian shore, close to the unpopulated Mahali Mountain natural reserve. It caused destructions and several casualties in Kalemie, the nearest town on the Congolese side. A small tsunami was also reported to have been caused by this event (courtesy of the Geological Survey of Tanzania).

The Rungwe Volcanic Province appears seismically active in the alignment of the Rukwa and Malawi rift valley, but the orthogonal Usangu depression does not show much seismicity. This is supported not only by teleseismic data (fig. 2), but also by the results of a local seismic network established in the area between 1991 and 1993 (DELVAUX & HANON 1993, CAMELBEECK & IRANGA 1996).

3.2. ACTIVE FAULTING IN THE UFIPA PLATEAU AND ON THE FLOOR OF THE RUKWA DEPRESSION

The architecture of the Rukwa-Rungwe-Malawi rift segment is controlled by a series of fault systems inherited from earlier rift stages. In the Late Quaternary, most of these faults were reactivated in addition to the development of new fault systems. Of particular interest are the active normal fault systems in the Ufipa plateau (Kanda fault) and on the floor of Lake Rukwa, and the conjugated strike-slip faults that crosscut the Rungwe massif and control the recent eruptive centres.

3.2.1. Ufipa Plateau

Cutting the Ufipa plateau longitudinally in its centre, the Kanda normal fault system is the most prominent active fault system for the whole region (figs. 2, 3). As mentioned earlier, it was the presumed fault activated by the December 13, 1910 Ms 7.4 Sumbawanga earthquake. Preliminary palaeoseismic investigation of the Kanda fault revealed Holocene vertical slip-rate of at least 2 mm/yr, making this fault a potential candidate for a Ms $\geq$ 7.0 earthquake in the future (VITTORI *et al.* 1997). Recent detailed studies (DELVAUX *et al.* 2007) have shown that significant vertical movement occurred along that fault segment during the last 10,000 years, after a long period of quietness.

3.2.2. Rukwa Lake Floor

High-resolution seismic profiles carried out in the southern part of Lake Rukwa in the summer of 1994 by Ghent University highlighted a NW-trending underwater active fault system, superposed on a deeper fault system that was

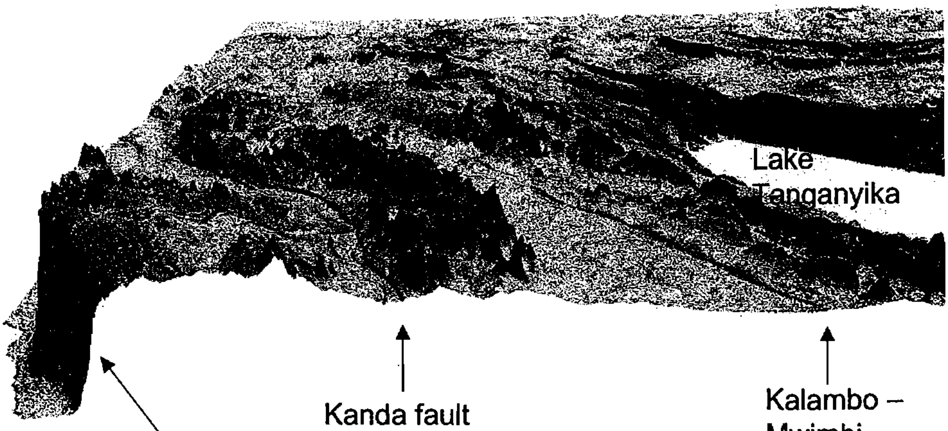

Fig. 3. — Morphostructure of the Ufipa plateau, between the Tanganyika and Rukwa rift basins. 3D oblique view (from north to south) of the SRTM-Digital topography (3 arc-seconds, ± 90 m resolution) with artificial shading (from north to south). The Ufipa plateau appears as a tilted horst separated from the Rukwa basin by the 1,000 m high Ufipa fault scarp and decreases progressively in altitude towards the Tanganyika basin. It is affected longitudinally by the Kalambo-Mwimbi and the Kanda fault systems. Only the latter is still active. Data processed using the Fledermaus programme in the Renard Centre of Marine Geology, Ghent University.

evidenced by oil exploration (Morley *et al.* 1992, fig. 2). Interpretation of the high-resolution profiles points to a high-frequency cyclic fault activity with a periodicity of 1,000 to 10,000 years (Morley *et al.* 2000) and an average fault displacement rate of 0.7 mm/yr, with a maximum up to 1.6 mm/yr (Kjennerud *et al.* 2001). According to these authors the sedimentary cycles are controlled by the cyclic fault activity, causing changes in the rate of subsidence, and by climatic events. Episodic mass influx of volcanic material as a result of intense activity of the Rungwe Volcanic Province at the southeastern extremity of the Rukwa depression must be added to these factors.

This active deformation zone continues on-land towards the southeast on the floor of the Rukwa depression and at the foot of Mbeya Range (Delvaux *et al.* 1998). It continues further south to the northern extremity of the Malawi rift depression, crossing the Rungwe Volcanic Province in its middle where it is punctuated by a series of young volcanoes with known historical eruptions (Harkin 1960, Gibert *et al.* 2002, Barker *et al.* 2003, Fontijn *et al.* 2007).

At the northern extremity of the Rukwa depression a large sandy ridge (Ilyandi Ridge, IR on fig. 2) culminating at an altitude of 998 m a.s.l. marks the highest possible level of Lake Rukwa, the level at which it overflows into Lake

Tanganyika. This link towards Lake Tanganyika is tectonically controlled (Fernandez-Alonso *et al.* 2001). Deposits marking the last high level recorded at the foot of the Ilyandi Ridge have been dated as Early Holocene and those are displaced by a recent fault with a dominant normal faulting component (Kervyn *et al.* 2006).

3.2.3. The Rungwe Volcanic Province

Recent investigations in the Rungwe Volcanic Province (fig. 2.) have confirmed the importance of the recent tectonic architecture in controlling the location of Quaternary volcanic eruptive centres (De Craene 2005, Fontijn *et al.* 2007, Delvaux *et al.* 2008). The present-day tectonic regime in the area started *ca.* 1.5-1 Ma ago, as constrained stratigraphically by dated volcanics and sediments from the Rungwe massif, defining the Neotectonic period (Delvaux *et al.* 1992). Deformation is localized mainly along high-angle faults that cross-cut the whole volcanic massif and along which significant strike-slip movements occur. These faults often reactivate older basement structures and/or normal fault systems within the rift sediments and volcanics that are related to the first phase of late Cainozoic rifting (9-2 Ma, Delvaux *et al.* 1992). Field observations show that at least two of the three largest volcanic centres, *i.e.* Ngozi and Rungwe — which are together with Kyejo aligned along a NW-SE trend — are controlled by two sets of subvertical faults, trending respectively NNE-SSW and ENE-WSW (Fontijn *et al.* 2007). Recent field evidence shows that they control the location of the Late Quaternary (both major and minor) volcanic vents and also the discharge of many hydrothermal springs (thermal springs and CO_2 gas vents).

4. Lake-level Changes

In addition to geodynamic controls, lake-level fluctuations strongly depend on the hydrological balance between precipitation (*P*) and evapotranspiration (*E*). This balance is controlled by a series of climate-driven processes including albedo, temperature, wind and sun exposure (Bergonzini 1998). The Late Quaternary climate of Africa was strongly controlled by high-latitude glacial or interglacial conditions together with low latitude insolation changes (Gasse *et al.* 2008). Both controls resulted in contrasted interhemispheric temperature gradients and monsoon circulation patterns, which affected dramatically the regional hydrology. East African lakes responded remarkably to this global forcing, as illustrated by considerable changes in lake level such as those reported for Lakes Tanganyika and Rukwa. Low lake stands are inferred regionally for the last glacial period, especially between *ca.* 25 and 14.5 ka BP: the Lake Tanganyika level was at least 180 m below the modern lake level (Tiercelin *et al.* 1988, Williamson *et al.* 1991, Gasse *et al.* 2008, Cohen *et al.* 1997), while Lake Rukwa was a very shallow lake (Barker *et al.* 2003, Thevenon *et al.* 2002). From *ca.*

14.5 ka BP, *i.e.* during the first major deglaciation meltwater pulse — and sea-level rise — of the Bölling-Alleröd, the levels of lake Tanganyika (WILLIAMSON *et al.* 1992, GASSE *et al.* 2008) and Rukwa (DELVAUX et *al.* 1998) rose rapidly by more than one hundred metres in less than three thousand years.

South of the Rungwe province, aridity probably started to resume from the end of the Younger Dryas (11.5 ka BP), when the intertropical convergence zone (ITCZ) shifted northward (TALBOT *et al.* 2007, GARCIN *et al.* 2006a, VINCENS *et al.* 2007). Dry conditions, however, had not affected significantly the Lake Rukwa and Tanganyika basins until the interval 8-4 ka BP (BARKER *et al.* 2002, THEVENON *et al.* 2002). The development of an open vegetation around Lake Rukwa during the last 5 ka BP (VINCENS *et al.* 2007) as well as the salinity proxy record (BARKER *et al.* 2002) indicate that dry conditions probably strengthened through the Late Holocene, although the sedimentological data point to short duration (< 10^2 yr) wet spells in the last 3 ka BP (THEVENON *et al.* 2002).

The respective impacts of climate and tectonics on lake level are still matter of debate as it is difficult to evaluate quantitatively the contributions of different origins. However, in the case of Lake Rukwa, climatically-induced lake-level changes of more than 100 metres did occur at submillennial scale, this inferring rates of 10-100 $m.ka^{-1}$. This clearly exceeds the potential effect of episodic movements of the active faults on the rift floor (0.7-1.6 $m.ka^{-1}$, KJENNERUD *et al.* 2001) or the magmatic doming at the southern extremity of the lake which does not exceed ~0.5 m. ka^{-1} (DELVAUX *et al.* 1998). Moreover, in closed depressions, the tectonic forcing might slightly modify lake level, but the volume of water and the properties depending on it such as water salinity would basically remain unchanged. Therefore, in the case of Lake Rukwa and at submillennial scale, the tectonic control on lake level must be considered as minor compared to climate unlike MORLEY *et al.* (2000) and KJENNERUD *et al.* (2001) assumptions.

The Rungwe massif lies between two rift lakes that may show contrasting lake-level fluctuations in response to climate forcing. This can be understood by examining an elevation profile combining land altimetry and lake bathymetry in a longitudinal section from the central part of Lake Tanganyika to the northern extremity of Lake Nyasa and passing through Lake Rukwa and the Rungwe-Ngozi volcanic field (fig. 4). Lake Rukwa is currently a shallow (max. water depth ~20 m) and closed lake within a mature depression containing at least 3-4 km of sediments, but with a flat bottom and no outlet. In contrast, Lake Nyasa is a deep (max. water depth ~700 m) lake within a relatively young rift depression. It has an axial drainage on the rift floor and is now outflowing (DELVAUX 1991, 1995).

Due to such basin morphologies, similar climate changes would induce contrasted effects on the water-table of both lakes. In the case of a positive and higher than today [*P-E*] balance, no significant lake-level change is expected in Lake Nyasa as the latter is limited by the outflow level. In fact, a drop in lake level might even occur, considering that a stronger outflow might strengthen erosion in

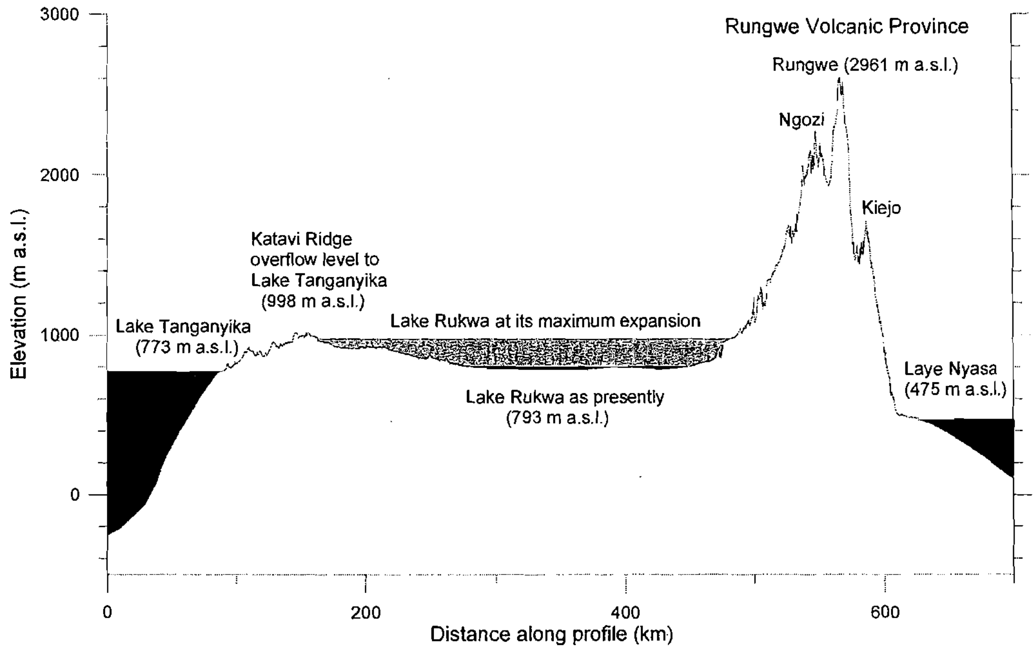

Fig. 4. — Longitudinal topographic/bathymetric section along the Tanganyika – Rukwa – Malawi rift segment, from the central part of Lake Tanganyika to the northern extremity of Lake Nyasa, passing through Lake Rukwa and the Ngozi and Rungwe volcanoes, and showing the maximum possible water level fluctuations. Topography has been extracted from the SRTM-DTM, bathymetry from the available bathymetric and topographic maps.

the outlet area. In contrast, the level of Lake Rukwa would rise markedly, filling progressively the Rukwa depression until the altitude of the outflow towards Lake Tanganyika at 980 m a.s.l., *i.e.* 180 m above the present-day water level. In the case of a negative [*P-E*] balance, Lake Nyasa would be disconnected from its outflow and its level would drop markedly. As suggested by Finney *et al.* (1996), Johnson *et al.* (2002) and Branchu *et al.* (2005), the Nyasa level has probably dropped by as much as 100-200 m in the Late Quaternary. At the same time, Lake Rukwa would shrink to a seasonal swamp, as it occurred at the dawn of the 20th century (Nicholson 1999). Compared to the present day, its level would be lowered by a maximum of 20 m (Talbot & Livingstone 1989, Delvaux *et al.* 1998, Nicholson 1999).

Consequently, the climatically-controlled lake level might swing from a higher Lake Rukwa and an almost stable Lake Nyasa during positive water budget periods, to a slightly lower Lake Rukwa but markedly lower Lake Nyasa during less favourable periods. This would occur assuming homogeneous climatic forcing over the entire region. In addition, regional climate contrasts must be taken into account as the equatorial "rainfall belt" defined by the InterTropical Convergence Zone (ITCZ) probably shifted southwards during the LGM and the

Younger Dryas (GARCIN *et al.* 2006a), resulting most likely in out-of-phase changes of the Rukwa and Nyasa water tables.

In general, from the LGM onwards, Lake Rukwa behaved in phase with Lake Tanganyika (COHEN *et al.* 1997, BARKER *et al.* 2002). The first studies (HABEYRAN 1987, TALBOT & LIVINGSTONE 1989) showed that Lake Rukwa was a deep freshwater lake from 15.6 to 5.0 ka. This was further confirmed by the dating of charcoal (10,740 cal. yr BP, DELVAUX *et al.* 1998) and mollusc shells (10,960 cal. yr BP, CLARK *et al.* 1970) from shorelines at 930-940 m a.s.l., *i.e.* 130-140 m above the present lake level. The LGM lake level is still matter of debate. BARKER *et al.* (2002) argued that it might have been relatively low, but sedimentological evidence (THEVENON *et al.* 2002) as well as observations in Lake Beds' sections along the Songwe and Ipwizi rivers in the southeastern extremity of the Rukwa depression (unpublished data) suggest that the lake did not dry out and had a much larger extension between 19 and 15 cal. ka BP than at present. As this area of the basin has probably been affected by tectonics, it is too early to give a more accurate estimation of lake level during that period. This is in line with the work of WILLIAMS *et al.* (2006) that provides evidence of an abrupt return to warmer and wetter conditions in intertropical Africa, particularly in the White Nile valley and Lake Albert ~14.5 ka ago. The sediment core from Lake Rukwa studied by THEVENON *et al.* (2002) and BARKER *et al.* (2002) shows that the lake became probably shallow, fragmented and saline after *ca.* 21 ka. However, a major rise in lake level probably occurred after 16 ka BP, most especially after *ca.* 13.6 ka, with freshwater conditions that prevailed until the Mid-Holocene.

Interpretation of cores and seismic profiles from Lake Nyasa suggests low stand conditions during the LGM (BARRY *et al.* 2002), with a ~ 250 m lake-level drop between > 40 and 28 ka (SCHOLZ & FINNEY 1994). Between 15 Ka to the beginning of the generally dry 12.8-11.5 ka Younger Dryas event, there is a general rise in the level of East African tropical lakes. During this time interval, Lakes Rukwa and Nyasa evolved in phase (GASSE *et al.* 2008). Lake Nyasa was probably overflowing before 12.8 ka, with a water level close to that of the present day (FINNEY & JOHNSON 1991, CASTANEDA *et al.* 2007). The Early Holocene was dry (RICKETTS & JOHNSON 1996). Between 10 and 6 ka, the level probably dropped by 100-150 m. A mid- to Late Holocene high stand probably occurred after 6 ka BP (JOHNSON 1996) and peak wet conditions occurred at 4.9 ka (CASTANEDA *et al.* 2007). In contrast, Lake Rukwa was high until at least 6.7 cal. ka BP. Its level dropped sharply after 5 ka BP and remained relatively low until recently (BARKER *et al.* 2002, THEVENON *et al.* 2002, and our observations).

5. Rates of Explosive Volcanic Activity

There is a good record of Late Pleistocene – Holocene explosive volcanic eruptions in the Rungwe massif and its surroundings. Ash layers have been found in cores drilled within the Masoko Crater Lake (Williamson *et al.* 1999, Barker *et al.* 2003, Thevenon *et al.* 2003, Garcin *et al.* 2006b) and the surrounding rift lakes, up to 300 km away from the eruptive centres (Mondeguer *et al.* 1989, Williams *et al.* 1993, Barry *et al.* 2002). Ash layers were also identified on-land in several outcrops and trenches (Clark *et al.* 1970, Haynes 1970, Crossley 1982). Their ages have been constrained by radiocarbon dating but no attempt for correlating the *tephra* layers between them has been made.

Similarly as McGuire *et al.* (1997) for the Mediterranean, we consider that the chronology of *tephra* deposition in the Rungwe area and surroundings reflect the explosive volcanic activity in the Rungwe massif itself. Over the last 46 cal. ka, we compiled a total of forty-eight dated occurrences of *tephras* (both volcanic glass and pumice lapilli). They were found in outcrops, in trenches and in lacustrine cores, from the flanks of the Ngozi and Rungwe volcanoes to the surrounding areas over a distance as far as 300 km away from the centre of the Rungwe Volcanic Province. Some of these occurrences may correspond to the same major eruption, but they are not yet firmly correlated. Major eruptions recorded by more than two occurrences were identified at the following cal. ka ages BP: 12.93 ± 0.48 (nine occurrences, regional marker), 11.87 ± 0.25 (two occurrences), 8.68 ± 0.39 (four occurrences), 6.53 ± 0.04 (two occurrences), 4.46 ± 0.30 (three occurrences, ~1 m thick in Masoko core and ~30 cm thick layer in Lake Nyasa core M98), 3.75 ± 0.19 (two occurrences) and 1.30 ± 0.15 (two occurrences, ~15 cm in Lake Masoko core).

Within the 46 ka continuous deposits of Lake Masoko, up to sixty-three prominent *tephra* layers have been successively identified by Barker *et al.* (2003) and Garcin *et al.* (2006b) using a progressively improved depth-age model. New *tephra* layers as revealed using a finer analysis of the Masoko core (Williamson & Fontijn, work in progress). However, using only the data of Barker *et al.* (2003) in a cumulative plot of ordered dated *tephra* layer occurrences *versus* time (fig. 5a), the dashed line shows that the return period (time to next event) is lower than 2.2 ka (0.46 events per ka).

When including all the *tephra* observations from the Rungwe region and surroundings, we face the problem of correlation between different records of the same major event. Our current knowledge does not allow to relate the *tephra* layers to particular eruptions. However, the database of dated *tephra* occurrences indirectly constrains the size of the eruption, as small eruptions are observed locally (only 1-2 dated occurrences for the same eruption) while the more powerful eruptions do throw thick ashes over a larger surface and are more easily and frequently observed (several dated occurrences for the same eruption). Assuming randomly distributed observation points, the *tephra* originating from a single powerful eruption will statistically be observed more often than from a small eruption (the latter might even remain unrecorded). Although our database is still fragmentary, the cumulative plot of all dated *tephra* occurrences in the Rungwe region versus time (fig. 5b) shows marked changes in *tephra* frequency with time.

The rate of *tephra* observation times is assumed to be an indirect indicator of the volcanic activity. This is specially the case for the last 14 ka BP where the regional sedimentary record is well documented and where biases introduced by the occurrence of sedimentary hiatuses are eluded, most especially in cored sequences from the regional Lakes Tanganyika, Nyasa, Rukwa, Masoko. We therefore consider here that the larger amount of dated *tephra* observations per fixed period of time reflects either more frequent volcanic eruptions or more explosive volcanic activity or both.

6. Relation between Lake-level Change and Imprints of Explosive Volcanism

Combining the water-level fluctuation curves with the observation times of *tephra* layers on a same diagram (fig. 6) shows that the marked increase in observation times of *tephra* dated between 14 and 12 cal. ka BP corresponds to a period during which both Lakes Rukwa and Nyasa went through rapid and high-amplitude lake-level rise. A second period of increased observation times is seen for *tephra* dated 5 and 3 cal. ka BP, during an interval of sharp out-of-phase variations (relatively high Lake Nyasa and relatively low Lake Rukwa). For this time interval, the lake-level variations are not well constrained but a simultaneity between lake-level fluctuations and the increased *tephra* observation cannot be excluded. The well-expressed 14-12 ka BP interval of increased *tephra* observation (fig. 5b) corresponds to a unique interval when the level of both lakes rose rapidly and simultaneously.

As shown in the introduction, moderate to large earthquakes (Ms 5 to 6.5) can be triggered by rapid level fluctuations in large artificial reservoirs, particularly during their infilling (Ambraseys & Sarma 1968). These sites are all located in areas affected by major fault systems which were seismically quiescent before the filling of the water reservoir. Panday & Chadha (2003) and Singh *et al.* (2008) explained the causal relation between the water-level fluctuation in the reservoir and the occurrence of earthquakes by a diffusion process along faults and fractures, especially along vertical strike-slip faults.

In the Rungwe area, it is known that a network of active high-angle strike-slip faults is controlling both hydrothermal water circulation (Delvaux *et al.* 2008) and the location of recent volcanic vents (Fontijn *et al.* 2007). Moreover, these fault systems extend from the volcanic area up to the floor of the adjacent basins. They are particularly well expressed in the Usangu depression and in the Songwe Valley, towards the Rukwa depression. It is therefore proposed that a causal relation may exist here between climatically-induced, rapid water-level fluctuations in the rift lakes and the frequency and/or magnitude of volcanic eruptions in the Rungwe area.

Unlike the examples discussed by Ambraseys & Sarma (1968), which were seismically quiescent before the filling of the water reservoir, the Rungwe

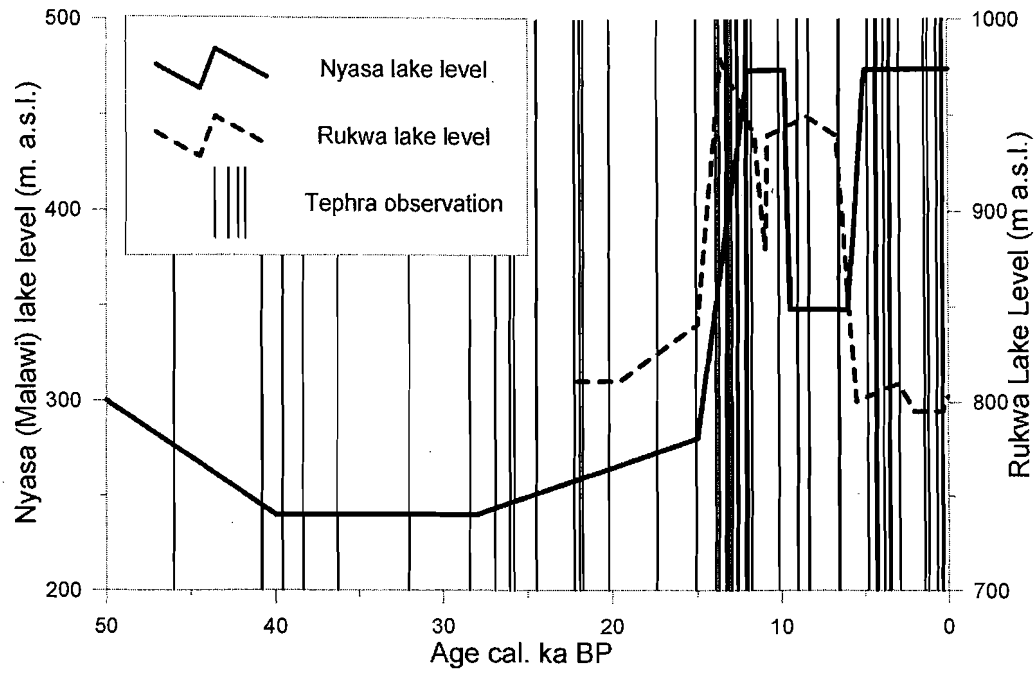

Fig. 6. — Relation between lake-level changes and explosive volcanic activity. Each vertical bar represents a single dated occurrence of an ash layer (*tephra* observation). Several evidences might correspond to the same event. In the case of closely spaced observation events, overlapping vertical bars appear as a single thick bar. Data compilation is detailed in the text.

Volcanic Province is located in an active rift system in which both seismogenic faulting and volcanic eruptions regularly occur, as shown by geological and historical records. Rifting is a long-term, slow process with occasional instantaneous events like earthquakes and volcanic eruptions. The relationship evidenced here would suggest that volcanic eruptions could be relatively more frequent during the short periods of rapid lake-level change (mainly rise) than during the longer periods of lake-level stability. As a result, such events would occur earlier than expected if the lakes did not exist or if their level was stable over long time intervals (several millennia).

The causal mechanism could involve an increase in fluid pressure and a diffusion process able to activate the high-angle fault systems that extend from the lacustrine depressions to the volcanic area, as shown by Panday & Chadha (2003) and Singh *et al.* (2008) for the Koyma reservoir in India. Higher fluid pressure in the fault zones would promote their activation by lowering the stress level necessary to initiate movement. As the faults do control the architecture of the Rungwe massif, the location of eruptive vents and the hydrothermal systems, such movements would probably also result in an addition of water to the magmatic system, triggering more frequent and/or more phreatomagmatic eruptions.

A direct observation of the relation between lake-level change and tectonic faulting or seismic activity could not be demonstrated at present for several reasons. The timespan of instrumental recording of seismicity is too short and does not cover significant lake-level changes (max. 5 m in amplitude for Lakes Rukwa and Nyasa; DELVAUX 1995, DELVAUX *et al.* 1998). Both lakes are known to fluctuate seasonally with an amplitude of about one metre (BERGONZINI 1998), but the scarcity of the seismic data available does not allow to investigate a possible link between the seasonal fluctuations and the seismicity. A semi-permanent dense network of seismometres surrounding the lakes would be necessary for studying such relation. A more realistic option is to examine the sedimentary record in both the lake floor and the basin shoulders with the aim to investigate evidence for palaeoseismic movements. Attempts in this direction are in progress and will be published elsewhere but this covers only the end of the last climatic cycle. Over a longer time interval (up to 100,000 years), high-resolution seismic stratigraphy in Lake Rukwa has revealed a high-frequency cyclic fault activity on the lake floor, with apparent periods of 10^3 to 10^4 years (MORLEY *et al.* 2000). However, improvements of the chronological frame are needed to relate such cycles to climatic forcing.

7. Conclusions

The Rungwe Volcanic Province lies at the triple junction between the western and eastern branches of the East African Rift System. Geodynamic processes occurring in this region are responsible for both tectonic and volcanic activities. A compilation of available data on Late Quaternary water level change in the rift lakes and of evidence for recent volcanic eruptions in sediments and soils (*tephra* layers) suggests that rapid lake-level changes in the large rift lakes (Rukwa and Nyasa) may trigger explosive volcanic eruptions in the Rungwe Volcanic Province. The record of such relationship in geological archives is suggested in both subaerial and lacustrine sediments deposited to the rift zone.

Such a causal relation has not yet been explored deeply in the case of the Rungwe Volcanic Province. However, the rapid and high amplitude hydrological variations of Lakes Rukwa and Nyasa on both sides of the Rungwe massif during the Holocene Optimum could have generated strong earthquakes in a similar way to the ones triggered by rapid water-level fluctuations in artificial water reservoirs. On the other hand, the tectonic architecture of the Rungwe massif is controlled since the Middle Pleistocene by a dense network of high-angle faults, some of which being still active. It is suggested here that climatically-driven, rapid and high-amplitude water-table fluctuations in rift lakes probably promoted tectonic fault activation and fluid circulation, triggering explosive volcanic eruptions in the Rungwe Volcanic Province, especially during periods of water-level rise.

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NOTE

[1] Lake Nyasa is the Tanzanian name for Lake Malawi. However, when speaking of rift segments, we use the term Malawi rift for the rift basin containing Lake Nyasa as in the international literature.

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