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NEOTECTONICS OF THE MBEYA AREA, SW TANZANIA

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Abstract. - The Mbeya area is part of the western branch of the East African Rift System and lies on the intersection of the NW-SE trending South Rukwa-North Malawi segment and the NE-SW trending Ruaha-Usangu depression. The area was already tectonically active during earlier riftings periods (Permo-Triassic and Mesozoic), but underwent a major rift development during Cenozoic times. The neotectonic period, discussed in this work, corresponds to this last first-order geodynamic mechanism. In the Mbeya area this mechanism is characterized since the middle Pleistocene by a dominant strike-slip stress regime.

A neotectonic map of the Mbeya area was compiled from Quaternary structural elements and volcanic centres, active hot springs and earthquake epicentres recorded by a regional seismic network. An additional morphostructural map, highlighting active faulting and basin tilting in the northern extremity of Lake Malawi, was drawn using a LANDSAT-TM scene and data from a study on recent sediment distribution in that part of the lake. The depth distribution of earthquakes obtained from a network of five digital three-components seismometers provides new information about the rheology and the geometry of active faults down to the lower crust.

Résumé. - La région de Mbeya est située à l'intersection de la branche ouest du rift est-africain (bassins de Sud Rukwa et de Nord Malawi), orientée NO-SE, avec la dépression NE-SO de Ruaha-Usangu. Cette région déjà active durant de précédents épisodes de formation du rift (Permo-Triasique et Mésozoïque), a connu une nouvelle importante phase de riftogenèse durant le Cénozoïque. La période néotectonique considérée dans la présente synthèse correspond à la durée du dernier mécanisme géodynamique de premier ordre. Dans la région de Mbeya, ce mécanisme est caractérisé, depuis le Pléistocène moyen, par un régime de contrainte de type strike-slip.

Une carte néotectonique a été élaborée sur base d'une compilation des éléments structuraux et centres volcaniques quaternaires, des sources chaudes active et de la position des épicentres de tremblements de terre enregistrés à partir d'un réseau sismique local. La fracturation active et les basculements de blocs à l'extrémité nord du lac Malawi sont mis en évidence par une carte morphostructurale réalisée à partir d'une scène Landsat-TM et d'une étude de l'évolution de la sédimentation récente dans cette partie du lac. La distribution des tremblements de terre en fonction de la profondeur, obtenue à l'aide d'un réseau de cinq séismomètres digitaux à trois composants, fournit de nouvelles informations sur la rhéologie et la géométrie des failles actives en profondeur, jusqu'à la base croûte.

Samenvatting. - De streek van Mbeya is gelegen op de intersectie van de Westerlijke tak van de Oost-Afrikaanse rift (bekkens van Zuid-Rukwa en Noord-Malawi meren), volgens een NW-ZO richting, met de depressie, NO-ZW gericht van Ruaha-Usanga. Deze streek, reeds tectonisch aktief gedurende vorige riftperiodes (Permo-Trias en Mesozoïcum) heeft een nieuwe belangrijke fase van riftontwikkeling gekend tijdens het Cenozoïcum. De neotectonische periode zoals gebruikt in de huidige synthese stemt overeen met de duur van het laatste geodynamisch mechanisme van eerste orde. In de streek van Mbeya is dit mechanisme sinds het Midden-Pleistoceen gekenmerkt door een strike-slip spannings regime.

Een neotectonische kaart werd opgemaakt op basis van kwartaire structurele gegevens, de localisatie van recente vulcanische centra, thermale bronnen en epicentra van aardschokken, geregistreerd door een lokaal seismisch net. De actieve breuken en blokkantelingen op het uiterste noorden van het Malawi meer werden in het licht gesteld door een morphopstructurele kaart. Deze werd gerealiseerd op basis van een Landsat TM-beeld en een studie van de verdeling van de jongste sedimenten in dat deel van het meer. De verdeling van de aardschokken, rekening houdend met hun diepte, bekomen bij middel van een net van vijf digitale drie-componenten-seismometers, levert nieuwe informatie over de rheologische en de geometrische karakteristieken van de actieve breuken en dit tot op de basis van de korst.

1. INTRODUCTION

The Mbeya area is situated on the accommodation zone between the South Rukwa and the North Malawi Rift Basins, belonging to the western branch of the East African Rift System (EARS). It corresponds to the intersection of this NW-SE rift valley with the NE-SW trending Ruaha-Usangu depression. The latter being one of the southward prolongations of the eastern branch of the EARS (Kenya Rift). The Rungwe volcanic province developed at the intersection of these two rift directions. The area is known to be seismically active, with volcanic eruptions occurring till historial times and hot springs activity is still noticeable. Uplift, erosion and sedimentation are also important active processes.

The Mbeya area being at the intersection of three rift basins is a key area in investigating the structural evolution of the rift system. Good exposures allow direct observation of the accommodation processes between the rift segments. The rift basins are filled with a wide variety of deposits including fluvio-lacustrine volcanoclastic sediments, volcanic rocks and travertines. A detailed stratigraphy can easily be stated, allowing to define a precise chronology of the neotectonic processes.

During the kinematic rifting history, several successive phases occurred, due to the partial superimposing of the Cenozoic rift system on older Permo-Triassic and Mesozoic rift structures. The Cenozoic period itself is clearly marked by two first-order geodynamic processes, separated by a period of tectonic rest at the Plio-Pleistocene boundary. The upper Miocene-Pliocene period is characterised by dominant normal faulting, under a semi-radial extensive stress regime, leading to an important deepening of the sedimentary basins by reactivation of the NW-SE trending South Rukwa - North Malawi basins and neoformation of the NE-SW trending Usangu basin. During the middle Pleistocene, a new first-order geodynamic regime iniated, with the onset of a dominantly strike-slip stress field, a new volcanic pulse and a renewed sedimentation. Quaternary second-order variations in the geodynamic system occurred as a consequence of a clockwise rotation of horizontal stress axes.

A detailed knowledge of this neotectonic activity in the area is not only important for scientific purposes but is also a critical element in the economic and human development of the region. The highly productive volcanic soils, together with good rainfall, attract many people and several important cities developed, such as Mbeya, Tukuyu and Kyela. The population growth combined with tectonic instability, increases the risks for natural hazards (Ebinger, 1993, this volume). The region is also considered to be a case study for paleoclimatic reconstructions based on lake sediments analysis and lake level fluctuations. Tectonic instabilities are important parametres to be taken into account in these studies.

2. GEOLOGICAL SETTING

The western branch of the EARS (fig. 1) developed in a sigmoidal shape on the Proterozoic mobile belts which surround the Tanzanian Archean craton (McConnell, 1972; Delvaux, 1991). The central part of the western branch has a general NW-SE orientation and is occupied by the Tanganyika, Rukwa and Malawi (Nyasa) rift valleys, along which Cenozoic basins and major faults are partly superimposed on an older Permo-Triassic (Karoo) rift system (Dypvik *et al.*, 1990; Morley *et al.*, 1992).

The Mbeya area is supposed to be an accomodation or transfer zone between the South Rukwa, North Malawi (Livingstone / Karonga) and Usangu rift segments (Ebinger *et al.*, 1989; Morley *et al.*, 1990). However, the term accommodation or transfer zone is not fully adequate, since it generally refers to the geometry that develops as a consequence of linking only two rift segments.

The present area can better be described as a triple junction between two diachronous rift trends. The North Rukwa-South Malawi NW-SE trend already developed in Permo-Triassic times and was first rejuvenated during the Mesozoic. This is indicated by the occurrence of Karoo (Permo-Trias) and Red Sandstones (Jurassic-Cretaceous ?), in scarce outcrops along the western side of the Rukwa basin and the North Malawi basins (Grantham *et al.*, 1958; Harkin and Harpum, 1957). The NE-SW trending Usangu basin developed solely during the Cenozoic rift period, together with a second reactivation of the North Rukwa-South Malawi rift trend and the onset of volcanism in the Rungwe Province (Ebinger *et al.*, 1989; Delvaux *et al.*, 1992). The junction between the eastern and the western branches of the EARS was in his period (fig. 1).

The southern Rukwa basin and the northernpart of the Lake Malawi rift (Livingstone or Karongo basin) form a striking alignment, and both are bordered by SW dipping faults (respectively the Lupa and the Livingstone faults). These two faults fade out progressively towards each other, in the centre of the Rungwe volcanic province. They are relayed by the also SW dipping Mbeya Range - Mbaka fault zone, also dipping SW, which isolates a narrow elongated basin occupied by the Songwe (Rukwa) and Kiwira rivers (the Songwe-Kiwira basin, not to be confused with the Songwe-Kiwira coal field). The south Rukwa and Livingstone basins are thus linked trough a narrowing

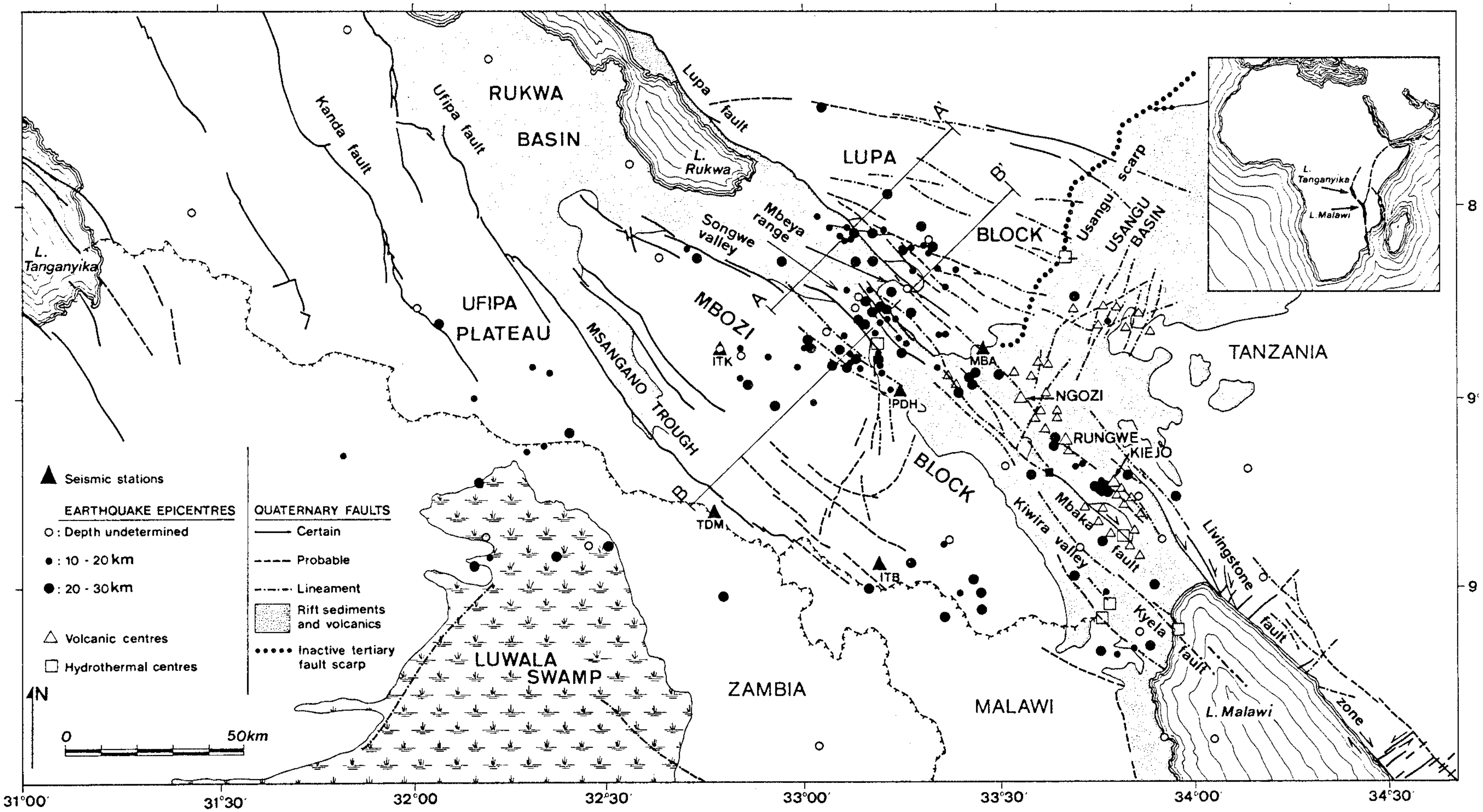


Fig. 1. - Neotectonic map from the South Rukwa - North Malawi area. Reported neotectoic elements are described and discussed in the text.

of the sedimentary basins, with the development of two overlapping synthetic transfer zones (as defined in Morley *et al.,* 1990), between the Lupa and Mbeya faults and between the Mbaka and the Livingstone faults. This structural pattern apparently established as early as in the Karoo times, was rejuvenated during the Mesozoic, concurrently with the deposition of the Jurassic - Cretaceous Red Sandstone formation (Dypvik, 1990).

3. CENOZOIC GEOLOGICAL HISTORY

3.1. Tertiary

In the Mbeya triple junction area, Cenozoic rifting started in upper Miocene, by normal faulting which leading to block tilting and basin subsidence. The age of the Red Sandstone formation is still controversial; however, numerous evidences point to Jurassic - Cretaceous age (Dypvik and Nesteby, 1992), rather than to an early Miocene age (Wescott *et al.,* 1991). Therefore, the oldest Cenozoic deposits are Mio-Pliocene fluvial sands, phonolitic tuffs dated 8.6 Ma in Malawi) Crossley and Crow, 1980; Kaufulu and White. 1981; Ring and Betzler, in press) and fluvio-deltaic sands and lacustrine muds from the Rukwa basin (Wescott *et al.,* 1991). Increased subsidence in Pliocene times allowed the accumulation of water-deposited volcanoclastic sediments in the NW-SE trending Rukwa, Songwe-Kiwira and Livingstone basins as well as in the transverse Usangu basin (Older Lake Beds in Tanzania and lower part of the Chiwondo Beds in Malawi). Sedimentation occurred contemporaneously with the first two volcanic pulses in the Rungwe volcanic province, between 8.6 and 1.7 Ma (Ebinger *et al.,* 1989 and submitted, Betzler and Ring, submitted). Paleostress analysis of minor faults in relation to well dated sediments and volcanics shows that the structural evolution of rift basins and related sedimentation and volcanism occurred in a tectonic context dominated by normal faulting, under a semi-radial extensive stress field (Delvaux *et al.,* 1992; Ring *et al.,* 1992).

3.2. Upper Pliocene - lower Pleistocene

From the upper Pliocene to the lower Pleistocene, a period of tectonic rest is marked by a low lake level and intense weathering and erosion. Neither sediments nor volcanics were deposited during this period which corresponds to the development of the late Tertiary morphological surface, covered by lateritic soil (African Two geomorphological surface of King, 1963). It caused an erosional and structural unconformity of Plio-Pleistocene age, over which Quaternary lake beds were deposited (Ebinger *et al.,* submitted; Ring and Betzler, in press).

3.3. Middle Pleistocene

During middel Pleistocene, probably between 0.57 and 0.42 Ma, a new kinematic regime established, together with a new pulse of volcanic activity and renewed sedimentation (Delvaux *et al.,* 1992). This second regime is characterized by horizontal principal compression and extension axes, typical for a strike-slip regime with a dominant N-S horizontal compression and an E-W principal extension.

The first Quaternary lava flows are the North Porotos trachyandesites and basalts, and the basalts of the Songwe basin, dated respectively at 0.57 and 0.55 Ma (Ebinger *et al.,* 1989). In the Songwe basin, fossil travertines, due to large-scale, diffuse hot spring activity, were deposited at the edge of the older Rukwa lake. These deposits overlie a 0.55 Ma basaltic flow and are now dissected by recent erosion. Carbonate was brought by ascending mineralised hydrothermal waters trough a network of extension fissures, in a transtensive context. The main tectonic movements are dextral strike-slips along reactivated NW-SE faults, expressing the effect of the N-S principal compression. Strike-slip faults also affect the travertine deposits in the Songwe basin. The Usangu fault scarp was not reactivated during the Quaternary but was affected instead by cross-faulting of a WNW-ESE trend.

3.4. Late middle Pleistocene - Holocene

The middle Pleistocene period of tectonic activity ends by the development between 0.42 and 0.25 Ma of young-looking volcanic cones and related lava flows of trachytic, phonolitic and basaltic composition, in the Ngozi, Rungwe and Kiejo areas and in the Usangu basin (Ebinger *et al.,* 1989).

These volcanics partly submerged the Mbaka fault zone and its related morphologic scarp. The northern extremity of the Mbaka fault is covered by lavas from the Rungwe volcanics, the southern end is concealed under lava erupted from the Kiejo volcanic centre. Small valleys dissecting the fault scarp itself are occupied by 0.42 Ma basalts which flew down an existing scarp, and which are apparently not affected by more recent faulting.

Paleostress analysis shows that the stress regime evolved by clockwise rotation of the horizontal stress axis at about 0.42 Ma, bringing the horizontal principal compression in a NNE-SSW direction and the horizontal principal extension in a WNW-SSE direction (Delvaux *et al.,* 1992).

The late middle Pleistocene corresponds also to the onset of a stepwise domal uplift centred on the Rungwe - Ngozi area. This caused the regression of Lakes Rukwa and Malawi away from the Rungwe area and the dissection of the Songwe plain by the Songwe river and its tributaries. The stepwise character of the uplift is shown by the profiles of the valleys cross-cutting the Songwe plain.

The domal uplift caused the renewal, on a new stratigraphic unconformity of sedimentation of reworked material from the Rungwe area. The resulting sediments are the Chitimwe alluvial fan deposits in Malawi and the Younger Lake Beds in Tanzania (Quaternary alluvia), deposited at the margin of the uplifted Rungwe-Songwe area in the lower parts of Rukwa, Livingstone and Usangu basins. The lower part of the Chitimwe alluvial deposits is dated at 20 Ka (Stokes, *in* Ring and Betzler, submitted) and a calcitic episode is dated at 10 to 6 Ka (Finney and Johnson, 1991).

An intense explosive volcanic phase occurred in upper Pleistocene, along a NW-SE alignment, and is expressed by abundant explosive craters of the Ngozi and Rungwe volcanoes, and along the Mbaka fault scarp. An explosive crater along the Mbaka fault zone is dated at 0.12 Ma, by Ebinger *et al.* (1989). The last explosive eruption of the Rungwe volcano is dated at 11 Ka and covered the whole area with up to one metre of volcanic ashes (Livingstone, 1965).

3.5. Present day activity

The recent tectonic activity of the Mbeya area is characterized by historical eruptions, hot springs activity, active faulting, high seismicity, vertical movements and the continuation of sedimentation in the rift depressions.

Recent activity of the Rungwe volcano built subsidiary cones at its summit from which flows of phonolitic trachytes, pumices and ashes were erupted. Recent basaltic lava, scoria and pumice were also erupted from the Kiejo caldera, and several centres of lava emission are known near the Mbaka fault scarp. The last eruption of the Kiejo volcano happened in the late 1800's (Sarabwe Tephrite).

Vertical movements are expressed by the continuation of the regional domal uplift centred on the Rungwe - Ngozi volcanic area, causing mass transfer through erosion and sedimentation. In addition to the domal uplift, block tilting is evidenced in the Kyela plain, at the northern extremity of Lake Malawi (see below).

An active fault, locally associated with hydrothermal activity and gas emissions (CO_2, CH_4), displaces the Younger Lake Beds in the Kyela plain. Aligned active hot springs and related travertine deposits are additional indications of present fault activity in the Songwe basin, along the Mbaka fault scarp and at the foot of the Usangu scarp.

The most recent paleostress regime, deduced from fault measurements and from the present stress field, as deduced from teleseism focal mechanisms, indicates a consistent NW-SE extension direction (Delvaux *et al.*, 1992). The regional Quaternary stress change in the Rukwa-Malawi-Usangu rift zone is similar to that observed in the Kenya rift (Strecker *et al.*, 1990) and can be integrated in the stress pattern of the whole East African rift zone (Bothworth *et al.*, 1992; Delvaux, 1993).

4. NEOTECTONIC GEODYNAMICS

4.1. Definition of neotectonic period

Different opinions exist on the definition of the term «neotectonic period», refering to more or less arbitrary chronostratigraphic subdivisions. In this work, following Angelier (1989), it is defined as the period under tectonic control of the last geodynamic mechanism, and still prevailing at the present time.

As a consequence, the time span of the neotectonic period depends on the onset age of the present mechanism, supposed to be continuous and homogeneous. Generally, only first-order geodynamic systems are taken into account, since significant rotation of paleostress trajectories is frequent, as showing in the East African Rift.

The paleostress results obtained from the analysis of brittle, small-scale structures in Tanzania (Delvaux *et al.*, 1992) allow to determine the onset of the first-order neotectonic regime at 0.57 Ma (middle Pleistocene), at the beginning of the Quaternary volcanic pulse in the Rungwe volcanic province. In this neotectonic period, the second-order events, such as the clockwise rotation of horizontal stress axes at the end of the middle Pleistocene are not differenciated (although the geodynamic regime can locally be subdivided in several second-orders stages). Therefore, the present-day tectonic, volcanic and sedimentary activity does not necessarily reflect the geodynamic mechanisms of the whole neotectonic period. As a result, some features caracterising the earlier stages of the neotectonic period may be inactive in the present-day geodynamic situation. On the other hand, neotectonic mapping based only on the last second-order geodynamic mechanism could only be realised in restricted areas where fine stratigraphical subdivisions were made. Thus, in order to produce an homogeneous document at a regional scale, only the first-order geodynamic regime must be considered in defining the neotectonic period.

4.2. Neotectonic map

The neotectonic map of the Mbeya area (fig. 1) was originally based on the compilation of published geological information (maps, catalogues and papers). This information was imported in a Geographic Information System, allowing easy update while the map has to be considered as an evolutive document, liable to be permanently improved. In its present version the earlier information was updated with the results of recent field work realised in this area over the last five years, with Landsat TM image interpretation and with data coming from a local seismic network installed in 1992.

a. Quaternary faults

A first set of Quaternary faults was identified by a critical compilation of the 1/125.000 geological maps published by the Geological Survey of Tanzania, the 1/100.000 geological maps of Malawi and 1/1.000.000 map of Zambia. This compilation was completed with Landsat TM satellite image interpretations where several lineaments show evidences of recent movement and with the data collected during field work in Tanzania.

Fault lines are classified as :

- faults with known Quaternary movements;
- faults with probable Quaternary movements;
- lineaments possibly corresponding to Quaternary faults.

The now inactive Usangu fault scarp is also shown, as it forms the major border fault of the Usangu basin.

b. Hydrothermal centres

Hydrothermal activity is rather frequent in the Mbeya area. It is clearly controlled by faults and is considered to be a good indicator for their present activity.

The most important centres of hot spring activity are generally mentioned on geological maps, and also in the work of Harkin (1960). The centres in the Songwe valley, in the Usangu basin and near Kyela were precisely located using a hand held Sony GPS. The most spectacular hydrothermal centre is the Malonde hot spring area (Songwe valley), building travertine deposits and directly related to an active fault scarp (Spurr, 1953). The hot springs in the Usangu basin, near the Indindiro farm, are aligned along a WNW-ESE fault that intersects the inactive Usangu fault scarp. Two hot springs are located along the Mbaka fault zone, at the foot of the fault scarp (Mulagura and Kalambo). the Kiejo volcano is known for its gas emissions (mainly CO_2) collected for industrial purposes. In the Kyela plain, near the northern extremity of Lake Malawi, two on-land hot springs are known (Mapulo and Kasimulo), and a series of underwater gas vents aligned along a NW-SE trend were recently discovered in the lake near the mouth of the Kiwira river (Klerkx, pers. comm.). In addition, local people report that hot springs may exist along the Livingstone fault scarp.

c. Volcanic centres

The location of major Quaternary volcanic centres was compiled from Harkin (1960). The age estimation is based on the relative chronology established by the authors, and on recently published K-Ar and Ar-Ar ages (Ebinger *et al.,* 1989 and submitted).

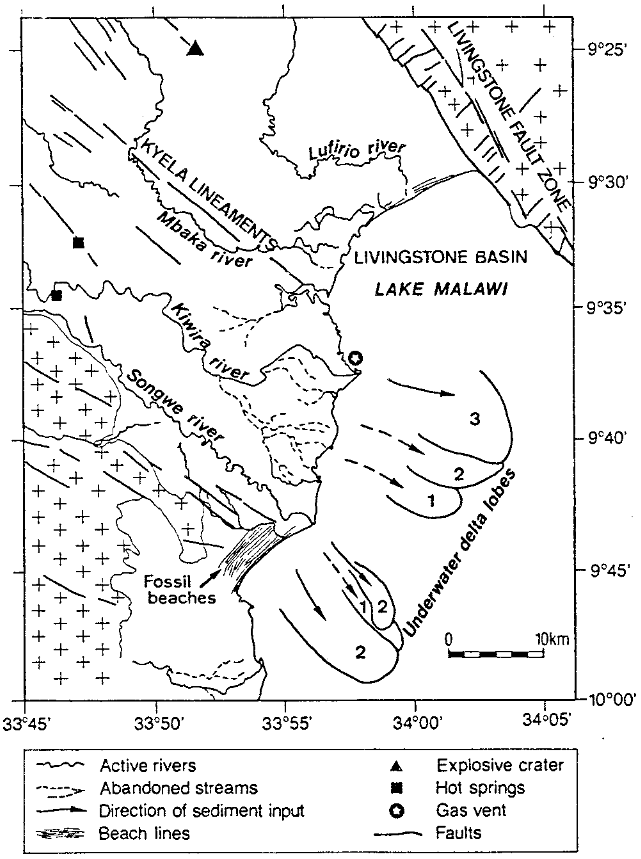
Four distinct volcanic episodes can be distinguished. The Quaternary volcanic activity started in middle Pleistocene with trachyandesitic and basaltic eruptions on the northern side of the Ngozi volcano and in the Songwe valley (0.57-0.55 Ma). It was followed in the late middle Pleistocene, by the development of phonolitic domes in the Usangu basin, and by the eruption of large quantities of lava from the Kiejo volcanic centre and from the Rungwe volcano (0.42-0.25 Ma).

An upper-Pleistocene explosive phase created calderas along a NW-SE line (Ngozi, Rungwe, Kiejo). Very recent (Holocene - Historical) eruptions occurred at the Rungwe and Kiejo central cones. The last eruption (Sarabwe tephrite) occurred at the Kiejo, in the 1800's.

d. Earthquake epicentres

During two months in 1991, the seismic activity of the Mbeya area was recorded by a single, three component seismic station installed at Panda Hill (PDH, fig. 1). Its aim was to evaluate the usefulness of a small seismic network in this area. During these two months, 80 earthquakes were recorded for which the epicentres of 32 with a magnitude between 1.0 and 4.1 could be defined (Camelbeek, 1992).

Since June 1992, a network of five three-components digital seismic stations is installed, with stations at Panda Hill (PDH), Mbeya (MBA), Itaka (ITK), Tunduma (TDM) and Itumba (ITB). Until November 1992, more than 1500 local and regional earthquakes with magnitudes ranging from 1.0 to 5.2 have been recorded (Camelbeek and Iranga, 1993a, b). about 160



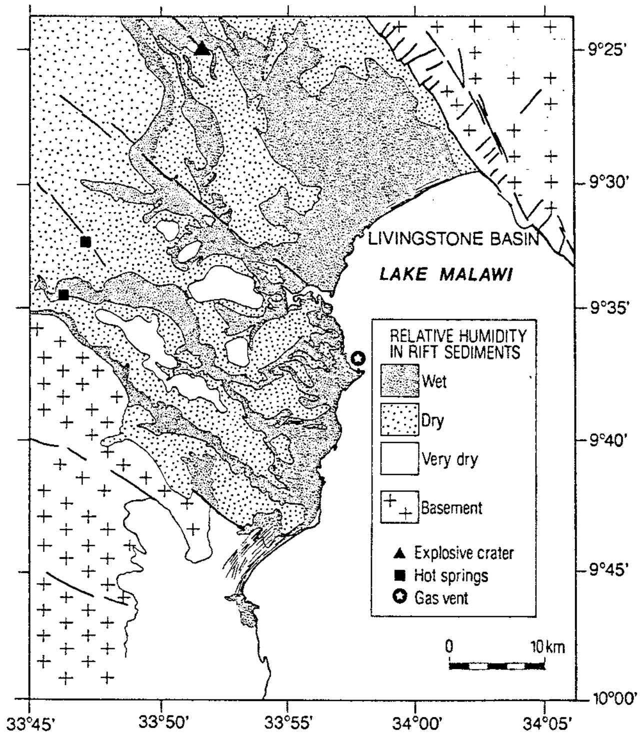


Fig. 2. - Morphostructural map of the Kyela plain at the northern extremity of Lake Malawi, drawn from Landsat-TM interpretation and results of high resolution seismic profiling (Versteeg *et al.,* 1993).

a. systematic northwestward migration of river streams, migration of underwater delta lobes and uplift of fossil beaches.

b. relative humidity in rift sediments based on type of vegetation coverage.

of them have been recorded by at least three different seismic stations, and their horizontal coordinates were precisely determined. The 30 to 50 km spacing between each station allowed precise depth determinations for 97 earthquakes inside or at the vicinity of the network.

4.3. Vertical movements

A morpho- and hydrostructural map of the Kyela plain at the northern end of Lake Malawi was drawn using the interpretation of Landsat-TM satellite imagery (fig. 2a, b).

A careful examination of the present-day and past riverbeds (fig. 2a) evidences a systematic northeastward migration of the rivers close to Lake Malawi, suggesting a general tilting of the Kyela plain to the northeast. This is visible for the Lufiro and the Mbaka rivers, but the best example is the northward migration of the active delta system of the Kiwira river. On land, the southern branch of the Kiwira river delta system is inactive, but it is still well expressed. In the lake itself, high-resolution seismic profiling demonstrates the successive northeastward migration of three delta lobes in the upper part of the sedimentary section (Versteeg *et al.,* 1993). The southern one is the older and the northern one is the younger, and is still developing.

Along the Mbaka river, an abandoned section of the river is exactly located on a well defined lineament that affects the superficial sediments (the Kyela lineament). The prolongation of this lineament in the lake is marked by the gas vent observed near the mouth of the Kiwira river (Klerkx, pers. comm.), and by a small active fault scarp detected on the seismic profiles, downthrowing a southern block (Versteeg *et al.,* 1993).

The relative humidity of the soil can be estimated using a channel 4.5 and 7 false-colour composite scenery of the Landsat-TM (fig. 2b). The wettest areas with an abundant vegetation of intense green colour, contrast with the dry areas covered by sun burned grass with yellowish colours. Mapping of the relative humidity gives an indication about the relative elevation of the plain. At the northern tip of Lake Malawi, a large wet area fringes the coast line and extends along the Lufirio river and tributaries. It is also the lowest part of the Kyela plain, so that it can be considered as being the most subsided area. This wet area is bordered to the south by a dryer area, between the Lufirio and the Mbaka rivers, which can be considered as uplifted relative to the area occupied by the Lufirio river. The Kyela lineament abruptly separates this dry area from the wet plain of the Mbaka river. This seems to indicate that the southern block of the Kyela lineament is downthrown relatively to the northern block. More southwards, the wet area is restricted to elongated strips along the Kiwira and the Songwe (Malawi) rivers, separated by very dry areas.

The presence of remnants of fossil beaches in Malawi, on the southern side of the Songwe (Malawi) river also indicates that this area was recently heightened relative to the lake level. The present altitude of the lake level is 474 m above the sea level and the fossil beaches are all above the 480 m contour line. As a contrast, beach lines observed near Matema, close to the Livingstone fault, are all restricted to the coast line and they all lie under the 480 M contour line.

As a conclusion, it can be stated that the Kyela plain is being tilted to the northeast, towards the deepest part of the Livingstone basin and its related border fault. It reacts as two independent blocks, separated by the NW-SE running Kyela lineament and causing apparent downthrow of the southern block.

5. DISCUSSION

5.1. Active structures

The major faults which controlled the development of the rift basins during the Tertiary geodynamic period (normal faulting, semi-radial extensive stress regime) are the Ufipa fault (bordering the western side of the Rukwa basin and the Msangano trough), the Lupa fault (bordering the eastern side of the Rukwa basin), the Mbeya - Mbaka fault line (isolating the long and narrow Songwe - Kiwira depression), the Livingstone fault zone (the major border fault of the Livingstone or Karonga basin), and the Usangu fault scarp (forming the northern limit of the Usangu basin). These Tertiary faults were largely reactivated during the neotectonic period, except for the Usangu rift scarp, which is morphologically degraded. The Lupa, Mbaka and Livingstone faults were reactivated by right-lateral horizontal to oblique-slip movements (Wheeler and Karson, 1989; Delvaux *et al.*, 1992).

The neotectonic map shows that the Lupa fault seem to continue southeastwards, as indicated by the alignment of the Quaternary volcanic centres of the Ngozi, Rungwe and Kiejo volcanoes, and by the location of micro-earthquake epicentres. The Lupa fault is then relayed by the Livingstone fault zone, which develops typical R and P shears, indicating right-lateral movements. Along the whole length of the Livingstone fault zone, older vertical NE-SW joints are reactivated in a sinistral manner, forming a conjugated set. The Mbaka fault is in the prolongation of the fault bordering the Mbeya Range, as also suggested by the alignment of Quaternary volcanic centres, hot springs and earthquakes epicentres.

A careful examination of the Landsat-TM imagery (fig. 2) shows that an active fault affects the Kyela plain (the Kyela fault). A gas vent in Lake Malawi, near the outlet of the Kiwira river is just aligned along the trace of this lineament. The southeastward prolongation of the Kyela fault in the lake is postulated from the results of a high resolution seismic reconnaissance survey carried out by Versteeg *et al.* (1993) in the northern part of the Livingstone basin.

In addition to the NW-SE trending reactivated faults, new faults appear in the Lupa Block, along a NW-SE to WNW-ESE direction, slightly oblique to the Lupa fault trend. They dissect the Lupa Block, generally considered as being part of the southern extremity of the Proterozoic Tanzanian craton in paleo-Proterozoic times. They intersect the now inactive Usangu fault scarp, and they extend locally into the Usangu Pliocene sediments. The hot springs near the Indindiro farm are aligned along such a WNW-ESE active fault.

NE-SW transverse faults controlled the intrusion of recent (but undated) phonolitic volcanic domes in the Usangu basin.

Monitoring of the seismic activity shows that the Mbozi Block is also seismically active. The Mbozi Block is a remnant of the paleo-Proterozoic Ubendian structure, surrounded by NW-SE neo-Proterozoic shear zones formed as a consequence of left-lateral movements. It lies in the southern continuation of the Rukwa Basin, forming a structural height between the Msangano trough and the Songwe-Kiwira elongated rift depression. The marginal parts of the Mbozi Block are affected by Precambrian left-lateral shear zones, which clearly controlled the location of rift border faults. The transition between the Mbozi Block and the Songwe depression is a typical example of a present-day reactivation of Precambrian dislocation zones. The transverse NE-SW faults that cut the central part of the Mbozi Block are also active, as shown by the seismic activity recorded at the Panda Hill seismic station.

The Kanda fault affects the central part of the Ufipa plateau, an uplifted elongated block between the

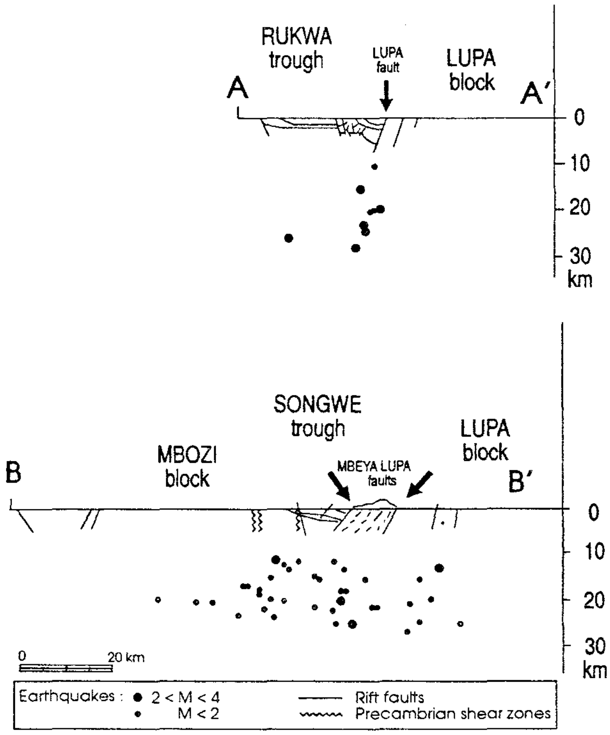


Fig. 3. - Structural seismic cross sections perpendicular to the main rift trend (location in figure 1). Earthquake epicentres determined by Camelbeek and Iranga (1993a).

Rukwa and the Tanganyika basins. The fault is up to 200 km long, and shows limited vertical displacement of no more than 30 m, althrough the fault mechanism is mainly normal. It displaces the pre-rift (Miocene) erosion surface covered by laterites, and it is part of a kilometric flexure that affects the Ufipa plateau. To the south, the Ufipa uplift merges gradually in a flat depression in Zambia (Luwala Swamp), also appearing to be seismically active.

In the Songwe (Rungwa) valley, the hot springs of the Malonde hydrothermal field are clearly aligned along two crossing active faults : a NW-SE normal fault with a scarp 10 to 20 m high, and a less defined E-W fault. This area is seismically very active and corresponds to the narrowing of the rift basin, due to the important uplift of the Mbeya Range.

5.2. Depth distribution of earthquakes

Camelbeek and Iranga (1993a, b) showed that the depth distribution of earthquakes during the period June 1992 to November 1992 ranges between 6 and 30 km. Most of the activity (78%) is concentrated between 14 and 24 km, with a maximum at 20 km.

This has important consequences on the crustal rheology. It indicates a continuous brittle behaviour of the crust, and particularly as a far down as its lower part. This confirms previous suggestions that the western rift exhibits considerable strengths down to lower crustal level (Sudofsky *et al.*, 1987; Ebinger *et al.*, 1991).

Two structural sections were drawn at right angle to the rift trend (fig. 3) across the southern extremity of the Rukwa basin (section A-A') and across the Songwe depression, from the Mbozi Block to the Lupa Block (section B-B'). They display the earthquake hypocentres determined by Camelbeek and Iranga (1993a), with less than 4.0 km depth errors. The superficial rift structures are drawn on profile A-A', according to the TVZ-1 seismic profile of Morley *et al.* (1992) and according to surface observations for the profile B-B'.

The A-A' profile shows that the earthquake epicentres are concentrated along two steeply inclined planes (60-70°). The western plane is situated in the direct prolongation of the Lupa fault trace as observed in the TVZ-1 seismic profile. The surface projection of the eastern plane coincides to an important fault that runs inside the Lupa Block, at a close distance from the Lupa fault. The depth distribution of earthquakes in the B-B' profile is much more scattered. No obvious concentration appears under the Mbeya and Lupa faults, but on the other hand, seismic activity seems to align along the prolongations of two faults belonging to the Lupa Block.

The earthquake epicentres data, together with the presented map of active, define an important high-angle planar zone of high seismic activity between 10 and 28 km depth, which can be correlated with a known fault zone affecting the Lupa Block, obliquely to the Lupa fault itself. In the A-A' profile, this fault zone corresponds partly to the Lupa fault, with which it seems to be connected. In the B-B' profile, this active fault zone dissociates from the Lupa and the Mbeya faults and enters directly into the Lupa Block. This fault possibly originated from the reactivation of the Lupa rift fault under the neotectonic stress field, and then extended independently eastwards, as a neoformed fault.

General conclusions on the rift structure and evolution cannot be drawn directly from these observations because this structural and seimic activity corresponds only to the neotectonic geodynamic regime. The latter mainly causes the reactivation of pre-existing structures developed under tensional stress field during the Tertiary and probably also during earlier rift stages. The paleostress data evidence a dominant strike-slip stress regime for the neotectonic period, therefore the occurrence of such a high-angle planar fault zone deeply penetrating into the crust is not an exceptional feature.

5.3. Vertical movements

The block tilting and active faulting of the Kyela plain is clearly evidenced from the hydromorpho-structural map of figure 2. The central part of the basin, at the vicinity of the major border fault, is subsiding with continued sedimentation. The shoaling side of the half graben is uplifted, causing erosion and reworking of recent sediments, and the internal part of the basin is affected by small-scale block faulting, synthetic with the major border fault.

These processes are typical for the development of a half graben type sedimentary basin. They indicate that the process of half graben deepening and tilting is still active in the Livingstone Basin.

These locally induced vertical movements are superimposed on the regional domal uplift of the Rungwe volcanic area.

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