CENOZOIC PALEOSTRESS AND KINEMATIC EVOLUTION OF THE RUKWA – NORTH MALAWI RIFT VALLEY (EAST AFRICAN RIFT SYSTEM)

Damien DELVAUX, Kirill LEVI, Rugaibuhamu KAJARA and Julius SAROTA

DELVAUX, D., LEVI, K., KAJARA, R. & SAROTA, J. (1992). – Cenozoic paleostress and kinematic evolution of the Rukwa – North Malawi rift valley (East African Rift System). – *Bull. Centres Rech. Explor.-Prod. Elf Aquitaine,* **16**, 2, 383-406, 13 fig., 2 tab.; Boussens, December 24, 1992. – ISSN : 0396-2687. CODEN : BCREDP.

L'évolution cinématique du secteur Tanganyika – Rukwa – Malawi de la branche occidentale du rift est-africain est encore relativement mal connue. Le rôle respectif des mouvements verticaux ou horizontaux le long des failles liées au développement des bassins du rift est toujours l'objet de discussions contradictoires, ainsi que l'estimation de la direction d'extension principale.

Afin d'éclaircir ces problèmes, 976 failles mineures provenant de 29 sites différents ont été mesurées dans l'ouest de la Tanzanie, le long de la partie nord de la dépression du lac Malawi et de sa jonction triple avec le rift de Rukwa et la dépression transversale d'Usangu. Ces mesures ont été effectuées le long des failles majeures ainsi que dans les sédiments et volcanites du rift. Les données de faille avec stries de glissement ont été analysées en termes de paléotenseurs de contraintes.

D'après les données de terrain et ainsi qu'il a été montré par d'autres, il est clair que la direction NW-SE majeure des failles du rift Rukwa – Nord Malawi a été fortement influencée par les directions structurales précambriennes. D'autre part, elles sont également largement héritées de la phase de rifting Karoo (permo-triassique).

Les données discutées ici ne concernent que la période de riftogenèse crétacée, pour laquelle deux principales phases de paléocontraintes ont été mises en évidence :

I : un premier système en extension multidirectionnelle (compression majeure verticale, magnitude de la contrainte intermédiaire proche de celle de la contrainte minimale), avec deux directions d'extension dominantes (ENE-WSW et NW-SE) qui ont provoqué la genèse ou la réactivation de failles limitant les semi-grabens, avec mouvement vertical dominant;

II : un système en décrochement (contrainte intermédiaire verticale) avec une compression horizontale selon une direction N-S dominante, qui provoque principalement la réactivation des failles bordières du rift par coulissements latéraux.

Les relations stratigraphiques avec des coulées volcaniques d'âge connu fixent l'inversion de contraintes du régime extensif au régime décrochant au Pléistocène moyen, entre 0,55 et 0,42 Ma.

La phase I représente l'évolution cinématique du Miocène supérieur au Pléistocène, auquel sont liés la majeure partie du développement des bassins cénozoïques (réactivation des bassins du Nord-Malawi et de Rukwa et néoformation du bassin d'Usangu) ainsi que les deux premières pulsations magmatiques dans la province volcanique de Rungwe. La seconde phase débute au Pléistocène moyen suite à une inversion des contraintes due à la permutation des axes compressifs et intermédiaires. Ce nouveau régime évolue rapidement par rotations horaires successives de la direction de compression principale, depuis le NNW-SSE, tout d'abord vers le N-S (régime dominant), et ensuite vers le NNE-SSW (dernier régime de paléocontraintes reconnu).

La phase II a provoqué la réactivation latérale dextre des failles normales majeures du rift, orientées NW-SE, et la réactivation latérale sénestre d'un système de joints subverticaux d'orientation NE-SW, dont l'origine remonte à la période anté-Karoo.

La comparaison avec les mécanismes au foyer des tremblements de terre de l'Afrique de l'Est montre que les directions des contraintes horizontales compressive et extensive actuelles sont similaires à celles du dernier état de paléocontrainte reconnu.

0396-2687/92/0016-0383 $ 4.80

Cette évolution cinématique est similaire à celle déduite d'observations faites par d'autres équipes dans le rift central du Kenya et le long de la côte ouest du lac Malawi. Ce parallélisme indique qu'il s'agit d'un phénomène au moins de dimension régionale et dont les causes doivent être recherchées aux limites de la plaque lithosphérique africaine.

Damien Delvaux, Royal Museum for Central Africa, Department of Geology, B-3080 Tervuren, Belgium; Kirill Levi, Institute of the Earth Crust, Russian Academy of Sciences, Siberian branch, Irkutsk, Russia; Rugaibuhamu Kajara and Julius Sarota, Madini, box 903 Dodoma, Tanzania. – August 20, 1992.

Mots-clefs : Contrainte (Paléocontrainte), Cinématique, Rift, Cénozoïque, Faille, Faille décrochement, Faille effondrement, Tanzanie, Rift Est Africain (Rift Rukwa – Malawi).

ABSTRACT

The kinematic evolution of the Tanganyika – Rukwa – Malawi rift zone of the western branch of the East African Rift System has been intensely debated, but there is still a major controversy about the role of dip-slip versus strike-slip faulting in rift development, as well as about the principal extension direction.

A detailed field survey was carried out in Western Tanzania, along the northern part of the Lake Malawi rift valley, and at its triple junction with the Rukwa rift valley and the transversal Usangu trough. Paleostress tensors have been determined from fault-slip data, for a total of 976 minor faults on 29 sites distributed along major border faults and in rift sediments and volcanics.

From field data, and as evidenced by previous works, it is clear that the general NW-SE fault trend of the Rukwa-North Malawi rift segment is strongly influenced by the Precambrian structural trend, and partly inherited from a Karoo (Permo-Triassic) rifting phase.

This work focuses on the Cenozoic rifting period, demonstrating two major stages of paleostress state :

I : an initial near-radial extensive stress regime (principal compression vertical, magnitude of intermediate stress close to magnitude of minimum stress), with two dominant extension directions (ENE-WSW and NW-SE), which generated or reactivated major rift border faults with a dominant dip-slip component;

II : a subsequent strike-slip stress regime (intermediate compression vertical), with dominantly N-S principal compression, which mainly caused strike-slip reactivation of major rift border faults.

Stratigraphic constraints, provided by dated lava flows, fix the stress inversion from radial extensive to strike-slip regime in the Middle Pleistocene, between 0.55 My and 0.42 My.

Phase I represents the kinematic evolution from Late-Miocene to Pleistocene. It could also account for the major part of basin development during the Cenozoic (reactivation of the North-Malawi and Rukwa rift basins and neoformation of the Usangu basin) and it is associated with two magmatic pulses in the Rungwe Volcanic Province. The second kinematic phase started in Middle Pleistocene following a stress inversion caused by the permutation of the compressive and intermediate stress axis, leading to a strike-slip regime. Once established, this new regime evolved rapidly by successive clockwise rotations of the NNW-SSE maximum compression, first to N-S (dominant regime), and then to NNE-SSW (last paleostress regime recognized).The stress inversion is also marked by the onset of a third magmatic pulse in the Rungwe Volcanic Province. Phase II caused dextral strike-slip reactivation of the major NW-SE trending normal rift faults, and sinistral strike-slip reactivation of a system of NE-SW subvertical joints of pre-Karoo origin.

A comparison with earthquake focal mechanisms in the area indicates that the present stress conditions of its horizontal compressive and extensive axes show similarities to the last recorded paleostress state.

This kinematic evolution appears to be at least on a regional scale, as indicated by similar observations made by other teams in the Central Kenya Rift and along the western coast of Lake Malawi. The causes for this paleostress evolution have not yet been established, but it could be related to modifications in the kinematics of the African lithospheric plate.

Key words : Stress (Paleostress), Kinematics, Rift zones, Cenozoic, Faults, Strike-slip faults, Dip-slip faults, Tanzania, East African Rift (Rukwa – Malawi Rift).

CONTENTS

INTRODUCTION

It has been demonstrated that Cenozoic rifting in East Africa started in Mid-Upper Miocene, and that the major sedimentary basins evolved as a series of tectonically-controlled half-grabens (McConnell, 1972; Crossley & Crow, 1980; Tiercelin *et al.*, 1980; Ebinger, 1989; Morley, 1989; Sander & Rosendahl, 1989; Specht & Rosendahl, 1989).

Despite a wide variety of kinematic models based on field geology, seismic profiling, remote sensing, and limited microstructural field arguments, a major controversy subsists on the principal extension direction for the rift basin development, as well as for the role of dip-slip versus strike-slip movements over the whole western branch of the East African Rift System.

Results from a detailed paleostress analysis performed on about a thousand of minor faults are used here to outline the Cenozoic kinematic evolution of a segment of the Western Rift Valley, covering the northern part of Lake Malawi, and its junction near Mbeya with the Rukwa rift valley and the transversal Usangu trough.

1. — GEOLOGICAL CONTEXT

The East African Rift System extends over a wide area, mainly located in ancient Proterozoic mobile belts surrounding the Tanzanian craton (McConnell, 1972). It is broadly subdivided into an eastern branch (Kenya or Gregory rift) and a western branch, including lakes Tanganyika, Rukwa, and Malawi (Fig. 1). These two branches link at the Mbeya rift triple junction, where the Rungwe Volcanic Province developed.

1.1. GEOLOGICAL AND TECTONIC EVOLUTION OF THE RUKWA - MALAWI RIFT SEGMENT

In the Rukwa-Malawi area, rift-related sedimentary basins are known to belong to three distinct rifting episodes : the Permo-Triassic, the Cretaceous and the Cenozoic rift systems (Daly *et al.*, 1989; Fairhead & Green, 1989; Lambiase, 1989). The corresponding stratigraphic units are traditionally said to be the Karoo Supergroup, the Red Sandstone Group and the Lake Beds (Quennell *et al.*, 1956).

As a bibliographical review of the geological and tectonic evolution of the western branch of the East African Rift System from Paleozoic times to the Present has been presented elsewhere (Delvaux, 1991), only a summary of the most relevant aspects will be discussed here.

1.1.1. Geological context

The western branch of the East African Rift System consists of a series of deep sedimentary basins partly occupied by lakes, and disposed in a sigmoidal shape around the western side of the Tanzanian craton (Fig.1). The central part has a general NW-SE orientation (South Tanganyika, Rukwa and North Malawi rift valleys, hereafter referred to as TRM zone) and both the northern and southern extremities have a N-S trend. In addition, several shallow and immature basins develop over a wide area, along a NE-SW trend : the Usangu flats, the Lakes Bangweulu and Mweru and the Mweru-Wantipa trough system (Chorowicz *et al.*, 1987; Mondeguer *et al.*, 1989). Reactivation of NE-SW trending Karoo rift basins also occurred in Cenozoic times, as in the Luangwa valley in Zambia (Utting, 1976) and the Ruhuhu basin (Tanzania, this article).

1.1.2. Rift architecture

In the Mbeya area (Fig. 2), the major NW-SE rift trend is shown by the Rukwa – North Malawi alignment of half-grabens (Rukwa, Songwe and Livingstone basins) which developed along major border faults (Lupa, Mbeya and Livingstone faults). The Usangu basin developed at a right angle to the latter, and is bordered by the Usangu fault. The triple junction is occupied by the Rungwe Volcanic Province (Harkin, 1960). The internal structure of the Tanganyika, Rukwa and Malawi rift basins has been interpreted as a succession of half-grabens, alternately facing opposite directions and linked by accommodation zones (Chorowicz, 1983; Tiercelin *et al.*, 1988; Ebinger, 1989; Mondeguer *et al.*, 1989; Morley, 1989; Sanders & Rosendahl, 1989; Specht & Rosendahl, 1989; Morley *et al.*, 1992).

1.1.3. Stratigraphy and volcanism

In the Rukwa – North Malawi valley, rift basins are filled with a complex succession of sedimentary formations and volcanics (Fig. 3). The oldest sedimentary sequence is the Late Carboniferous-Triassic Karoo Formation. Incomplete Karoo sequences outcrop as isolated patches along the shoaling side of the Rukwa and Livingstone half-grabens. Under the southern part of the Rukwa basin, a maximum thickness of 3 to 3.5 km of Karoo has been proved by seismic profiles and borehole data (Morley *et al.*, 1992). The Karoo is unconformably overlain by the Red Sandstone Group, of controversial age. A Late Jurassic to Early Cretaceous age for this Red Sandstone Group is proposed by McConnell (1950), Brants (*in* Smirnov *et al.*, 1974) and Jakobs *et al.* (1989), but an Upper Miocene age is deduced by Wescott *et al.* (1991) from microfaunal assemblages, and was adopted by Morley *et al.* (1992). However, the question of the age of the Red Sandstone Group is still far from resolved (Dypvik, in press). The sediments of the Red Sandstone Group have a maximum thickness of 2 km in the Rukwa seismic profiles, and are unconformably overlain by Neogene sediments of the Late-Miocene to Recent age. Together, they have a maximum thickness of 7 to 7.5 km in the Rukwa seismic profiles (Morley *et al.*, 1992).

Not taking into account the work of Wescott *et al.* (1991), the oldest known Cenozoic deposits are lacustrine series (Chiwondo beds) of the Upper Miocene to Pliocene age (Crossley & Crow, 1980; Kaufulu & White, 1981; Wescott *et al.*, 1991). The oldest volcanic activity recorded in the Rungwe Volcanic Province is a phonolite which gave 8.36 ± 0.09 My and 8.6 ± 0.01 My (Ebinger *et al.*, submitted).

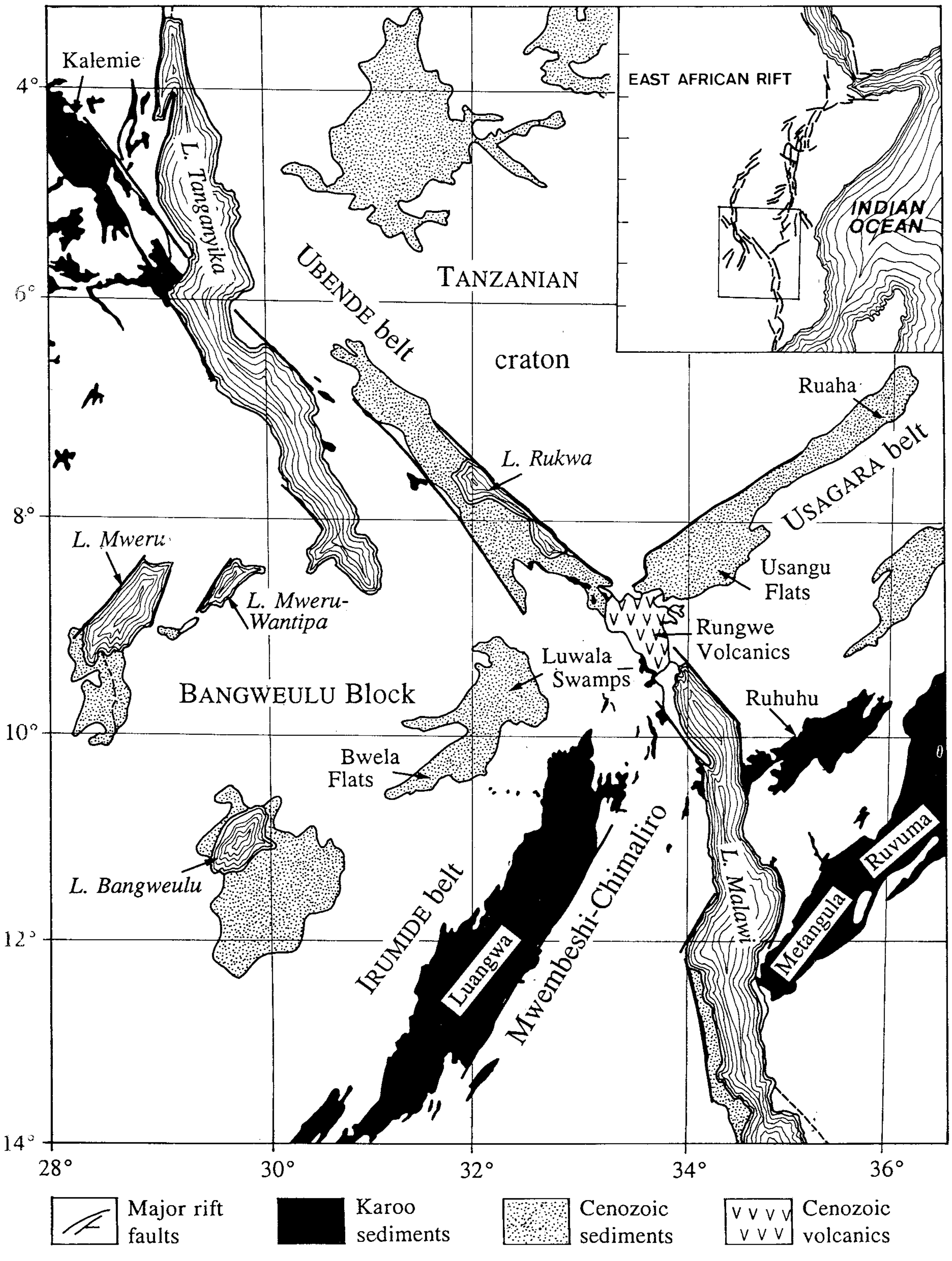

FIGURE 1

The western branch of the East African Rift System, with Permo-Triassic basins (Karoo) and Cenozoic basins located in Proterozoic mobile belts surrounding the Tanzanian craton (modified after DELVAUX, 1990).

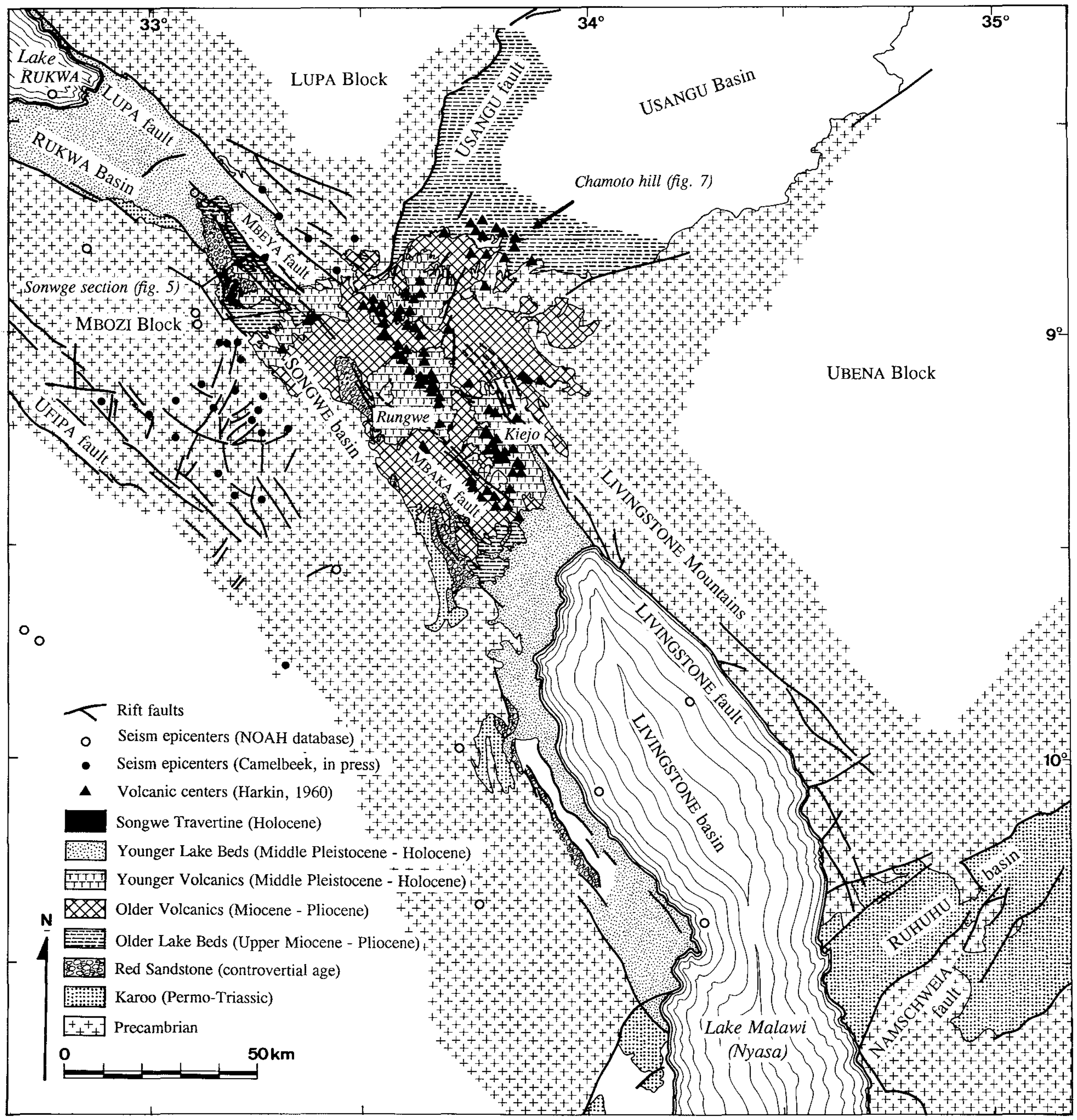

FIGURE 2
Structural setting of the Rukwa - North Malawi rift valley.

In the Songwe basin near Mbeya, the Neogene is composed of a lower member of mixed tuffaceous – detritical sediments, known as Older Lake Beds and Fluviatile Deposits which dip gently to the NE, and of an upper member of flat-lying Quaternary lake sediments referred to as Younger Lake Beds (GRANTHAM *et al.*, 1958). Along the Songwe valley (Fig. 5), the Older Lake Beds and Fluviatile Deposits are directly overlain by a lava flow dated at 0.55 ± 0.01 My (EBINGER *et al.*, 1989), with little or no unconformity. Travertine related to hot spring activity was deposited unconformably over the 0.55 My lava flow, the Older Lake Beds and the Red Sandstone Group in the Songwe valley (Songwe Travertine, GRANTHAM *et al.*, 1958). Much of the Songwe plain is covered by a thin layer of recent volcanic ash.

The Usangu basin is filled with an estimated maximum of 2 km of sediments, as deduced from gravity data (PEIRCE & LIPKOV, 1988). They are probably entirely of Cenozoic origin,with an upper layer of pumaceous sediments and water-deposited tuffs, accumulated between 2.2 and 0.57 My (EBINGER *et al.*, 1989). The lack of Karoo outcrops in the Usangu Flats suggests that there was no rifting in this area, at least not before the deposition of the Red Sandstone Group (DYPVIK *et al.*, 1990). However, deposition of limited Karoo sediments in shallow depressions cannot be excluded.

		Sedimentation	Volcanism
HOLO. / PLEISTO.	Younger Lake Beds (Chitimwe)	travertine & lake sediments	Rungwe pulse 3
PLIOCENE / U.MIO.	Older Lake Beds (Chiwondo)	mixed tuffaceous - detritical sediments	Rungwe pulse 2 Rungwe pulse 1
JUR.-CRET.	Red Sandstone Group	red sandst. shales & marls	Mbeya carbonatitic volcanism
TRIAS	Karoo System	K8 K7	
PERMIAN		K6 K5 K4 K3 K2	
CARB.		K1	

FIGURE 3

Stratigraphic succession in the Rukwa – North Malawi area with special reference to the Songwe plain.

Carbonatitic volcanism has been reported near Mbeya, with a Late Jurassic to Cretaceous age (PENTEL'KOV & VORONOVSKIY, 1977). In the triple junction between the North Malawi, South Rukwa and Usangu rifts, the Rungwe Volcanic Province (HARKIN, 1960) recorded three major pulses (Fig. 4); in Miocene (8.6 – 5.4 My), Pliocene (2.4 – 1.7 My) and Middle Pleistocene to Holocene (0.57 My – historical times), as shown by K-Ar and Ar-Ar dating (EBINGER *et al.*, 1989; EBINGER *et al.*, submitted).

In accordance with DYPVICK *et al.* (1990), it appears that the NW-SE trending rift basins in the Rukwa – Malawi area initiated as early as in Lower Permian by faulting and half-graben formation, with the deposition of thick series of Karoo in the Rukwa basin and Karoo series of more limited extension in the Songwe and Livingstone basins. The seismic profile of Amoco in the South Rukwa basin (MORLEY *et al.*, 1992) shows the Karoo sediments to thicken towards the eastern border fault (Lupa fault), indicating faulting during Karoo sedimentation. The same rift segment underwent limited reactivation in Late Jurassic – Cretaceous times (alkaline volcanism and possible deposition of the Red Sandstone Group, if Mesozoic in age), and more important reactivation in the Cenozoic age (Rungwe Volcanics, Lake Beds and rift lakes). As a consequence, the present Rukwa – North Malawi rift segment is mainly the product of the successive reactivation of earlier rift structures of Permo-Triassic origin.

Repeated rifting also occurred in Permo-Triassic and Cenozoic times, along a NE-SW trend perpendicular to the Rukwa – North Malawi trend, in the Ruhuhu basin and in the Usangu Flats. However, the Ruhuhu basin was mainly active during the Karoo period, with very limited reactivation during the Cenozoic age (KREUSER & MARKWORT, 1989), while the Usangu basin developed mainly during the Pliocene-Pleistocene age (EBINGER *et al.*, 1989).

1.1.4. Precambrian inheritance

The Rukwa – North Malawi rift valley is superimposed on the meridional extremity of the NW-striking Ubende belt. This belt is characterized by high-grade gneisses with metabasic and metasedimentary sequences, affected by intense mylonitic shear zones in apparent conformity with the surrounding gneisses (MCCONNELL, 1950, 1972). During the Early Proterozoic age, it underwent an important Pan-African reactivation, as revealed by U-Pb geochronology on zircon samples from the Livingstone Mountains (THEUNISSEN *et al.*, 1992). In this area, a thick sequence of intensely-sheared rocks evolved in a sinistral strike-slip regime under a retrograde greenschists to lower amphibolitite facies, between 814 ± 120 My and 724 ± 6 My (THEUNISSEN *et al.*, 1992). The mylonitic shear zones and the surrounding gneisses exhibit a tectonic foliation consistently striking NW and generally dipping SW, steeply to moderately (DELVAUX *et al.*, in press). This trend seems to control the development of major rift faults to a great extent.

Cross cutting the NW-striking precambrian gneisses and mylonites, a regional system of NE-striking trending subvertical joints developed (DELVAUX, 1990). These are older than

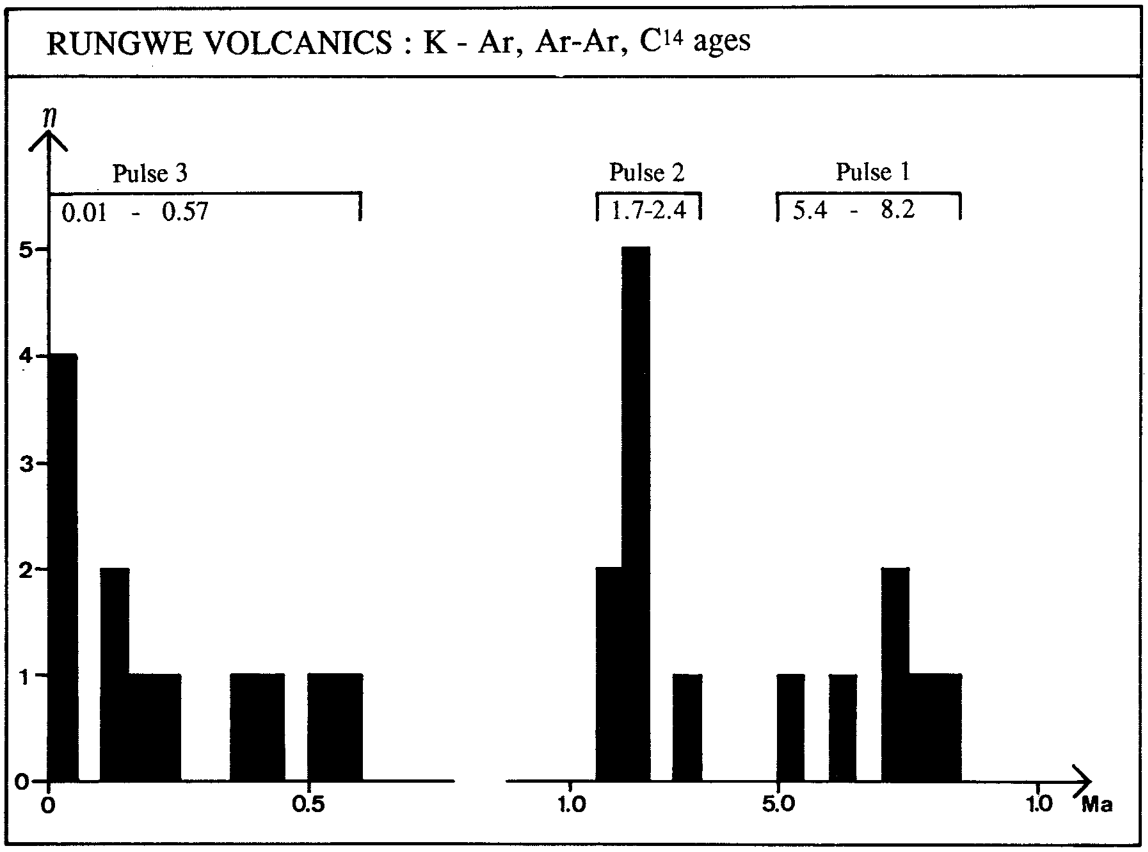

FIGURE 4

Distribution of the geochronologic ages obtained by EBINGER *et al.* (1989) and EBINGER & DEINO (1990), for the Rungwe Volcanic Province.

the Karoo rift basins and constitute a pervasive network of regularly-spaced planar joints reactivated during Cenozoic rifting, but only during the second kinematic phase (see below).

Also of NE-SW trend, the Mwembeschi-Chimaliro dislocation zone is shown by DALY *et al.* (1989) to affect the Precambrian basement, west of Lake Malawi, in Malawi and Zambia. It is of Late Paleozoic origin and is supposed to be of continental scale.

1.1.5. Permo-Triassic inheritance

Before studying the kinematics of Cenozoic rifting, it is important to emphasize that, in the Tanganyika-Rukwa-Malawi (TRM) zone, the Western branch of the Cenozoic East African Rift System is largely superimposed on an older Permo-Trisassic (Karoo) rift system. The Karoo sedimentation was started in the Late Carboniferous age by the deposition of glacial and periglacial deposits on a glacial type of relief. It is then followed by the depostion of fluvio-lacustrine beds in tectonically-controlled basins during the Permian and Early Triassic, as a result of intra-cratonic rift basin development (WOPFNER, 1991 and WOPFNER & KAAYA, in press). The major Karoo depocenters are located along two orthogonal trends (Fig. 1). The NW-SE trend follows the general Precambrian trend, with the Kalemie basin and the Rukwa basin as known major depocenters (CAHEN & LEPERSONNE, 1978; DYPVIK *et al.*, 1990, MORLEY *et al.*, 1992). The NE-SW trend is characterized by large, elongated rift basins with half-graben structures : the Luangwa rift in Zambia (UTTING, 1976), the Ruhuhu and Ruvuma basins in Tanzania (KREUSER & MARKWORT, 1989; WOPFNER, 1991); and the Metangula-Maniamba basin in Mozambique (VERNIERS *et al.*, 1989). Their development may be influenced by the existence of the Late Paleozoic Mwembeshi-Chimaliro dislocations zone (DALY *et al.*, 1989) and it is thought to be the result of a Late Paleozoic distant collision at the southern margin of Gondwana (DALY *et al.*, 1991).

1.2. REVIEW OF KINEMATIC MODELS

The TRM zone is usually considered as a major transcurrent wrench fault zone involved in the SE drift of the East African (or Somalian) lithospheric plate away from the African plate (CHOROWICZ & MUKONKI, 1980; CHOROWICZ *et al.*, 1987; TIERCELIN *et al.*, 1988; DALY *et al.*, 1989). From fault and slip line analysis, CHOROWICZ *et al.* (1983, 1987) concluded that dextral strike-slip movements occurred along NW-striking inherited fractures along the TRM lineament, with a principal NW-SE direction of extension. MONDEGUER *et al.* (1989) confirm this NW-SE extension for the Quaternary evolution of the Mweru-Mweru-Wantipa trough system at the southern extremity of Lake Tanganyika. WHEELER & KARSON

(1989) interpret the Livingstone basin, at the northern extremity of Lake Malawi, as a pull-apart related to right-lateral, oblique-slip movement along the Livingstone fault.

Present kinematics, expressed by earthquake focal mechanisms, give a great variety of extension directions : ENE-WSW, E-W and WNW-ESE (FAIRHEAD & GIRDLER, 1972; FAIRHEAD & STUART, 1982; SHUDOVSKY, 1985), but most of them are compatible with a NW-SE to WNW-ESE extension (CHOROWICZ, 1983).

However, according to fault geometry and rift architecture, SANDER & ROSENDAHL (1989), MORLEY (1989) and MORLEY *et al.* (1992) suggest an E-W principal extension for the whole western branch of the East African Rift, and EBINGER (1989) suggests a more NE-SW extension. In addition, the presence of several sets of slip lines superimposed on minor fault planes are frequently reported along the major NW-striking faults, the majority of them indicating strike-slip movements and the rest indicating normal dip-slip movements (TIERCELIN *et al.*, 1988; WHEELER & KARSON, 1989). Also, PEIRCE & LIPKOV (1988) emphasize that the strike-slip activity for the major rift faults refers only to the current stage of rifting, and that the total tectonic activity may be more complex.

According to these previous studies, it also appears that different interpretations can be proposed for the kinematic evolution of the TRM zone. In this analysis, it appears that the kinematics is probably more complicated that any single phase model usually proposes. The great diversity of extension directions already proposed for the opening of the rift basins reflects a major controversy about the principal extension direction and the role of dip-slip versus strike-slip movements during rift development.

2. — PALEOSTRESS ANALYSIS

A database consisting of 976 fault plane and slip line measurements from 29 sites along the major rift border faults and in rift sediments was used to obtain the four parameters of reduced stress tensors, defined by ANGELIER (1989) : the orientation of the principal stress axes $\sigma1$ (maximum compression), $\sigma2$ (intermediate compression) and $\sigma3$ (minimum compression) and the ratio of stress magnitudes R ($\sigma2$-$\sigma3$/$\sigma1$-$\sigma3$). This new database forms the core around which further discussion is developed.

2.1. METHODOLOGY

The method used for stress tensor determination, and for the separation of raw fault populations into homogeneous sets, includes the interactive use of kinematic discrimination of individual faults, the estimation of stress axes using the improved Right Dihedron method of ANGELIER & MECHLER (1977), and a precise determination of the reduced stress tensor by a minimization of the angle between observed slip line and computed shear, together with a maximization of the friction coefficient for each fault, in a manner similar to ANGELIER (1991) (computer program developed by D. DELVAUX).

The classification of various types of deformation according to the deviatoric stress tensors and their representation as map symbols is made according to GUIRAUD *et al.*(1989). The three principal tectonic regimes are the extensive, strike-slip and compressive ones, and, in function of the stress ratio R, they are further classified into :

— radial / pure / strike-slip extension (R=0/.5/1, $\sigma1$ vertical);

— extensive / pure / compressive strike-slip (R=1/.5/0, $\sigma2$ vertical);

— strike-slip / pure / radial compression (R=0/.5/1, $\sigma2$ vertical).

2.2. PALEOSTRESS TENSOR DETERMINATION

For most of the sites studied, two, three or even four subsets of faults were separated, each characterized by a different stress tensor. The relative chronology was established using cross-cutting faults, superposition of slip lines, and spatial relations of minor faults relative to the major fault trace. Most fault data were collected in basement rocks. Measurements in rift sediments were used to constrain the evolution of the major kinematic phases in time, by stratigraphic relations between faulting, sediments and dated lava flows.

2.2.1. Songwe plain

In the Songwe plain, a condensed but complete stratigraphical section can be observed along the Songwe and Ifisi rivers, and in the travertine quarry exploited by the Mbeya Cement Factory. The stratigraphic relations observed are schematized in Figure 5, with an unconformable succession of Karoo, Red Sandstones and Older Lake Beds. The Lake Beds are partly overlain by a flat-lying basaltic lava flow, dated at 0.55 ± 0.01 My by EBINGER *et al.* (1989). The Songwe Travertine and Limestone deposit, related to hot spring activity in a lacustrine environment, lies partly above the 0.55 My lava flow and partly on the Lake Beds, as indicated by exploratory drilling (information provided gratefully by the Mbeya Cement Company).

Minor faults were observed in the Red Sandstones along the Songwe river, in the Older Lake Beds along the Ifisi river and in the Songwe Travertine in the Mbeya Cement Company quarry (Fig. 6). The Karoo was not investigated.

In the Red Sandstones of the Songwe river, conjugated normal faults are well expressed. They do not extend into the overlying Lake Beds. They all trend NNW-SSE, and the conjugated sets dip ENE and WSW. The obtained tensors show a radial extensive paleostress regime ($\sigma1$ axis vertical and multidirectional extension), which acted prior to the deposition of the Lake Beds. It may correspond to a Mesozoic phase of rifting (GUIRAUD & MAURIN, 1991) or to a Miocene phase, depending on the age of the Red Sandstones.

In the Lake Beds along the Ifisi river, only one set of normal faults was observed. As a result, the tensor is not well constrained, but is still compatible with a near-radial extensive regime. The minor faults in the Lake Beds have a similar trend and dip as the ones observed in the Red Sandstones, so faulting in the Lake Beds may be controlled by the existing fault pattern in the Red Sandstones.

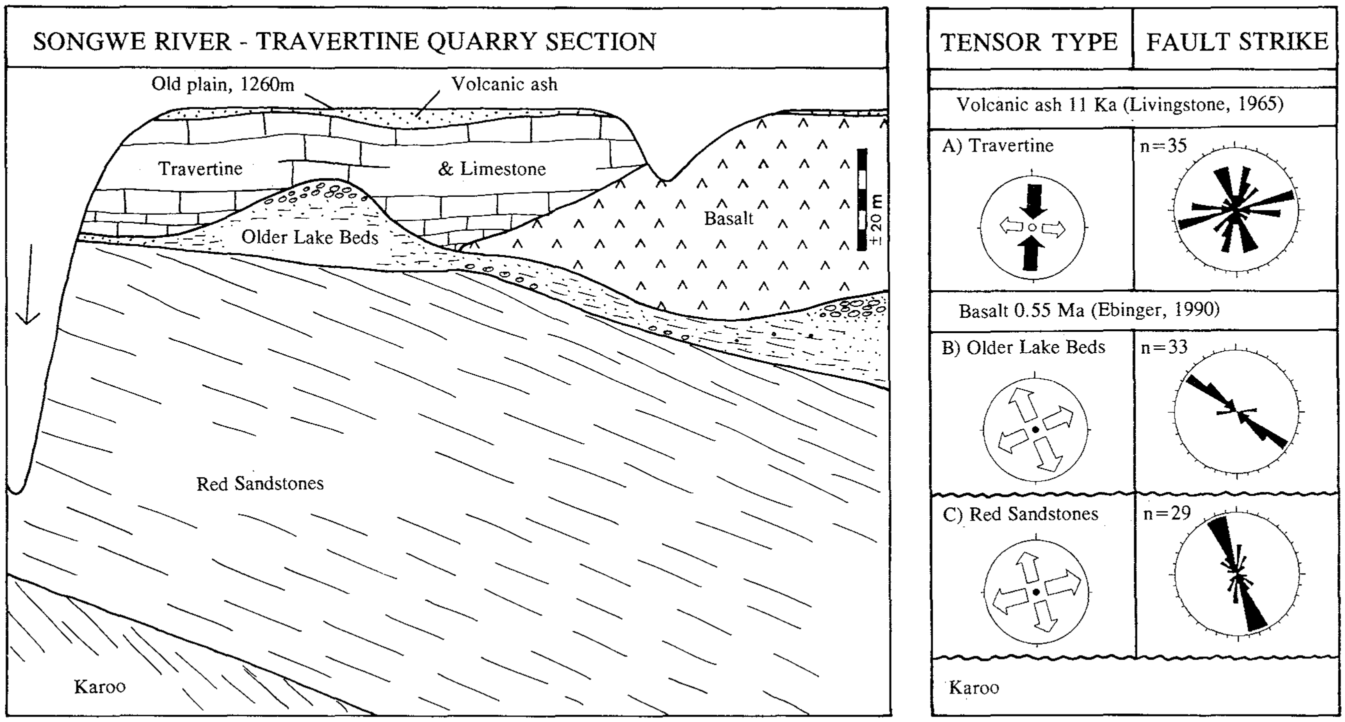

FIGURE 5

Type section of the Songwe plain including observations from the Songwe river, Ifisi river and the Mbeya Cement Company exploratory wells. Tensor types with arrows showing directions of the horizontal stress axes (length according to stress ratio R) and small central circle referring to vertical stress axis. White is for extensional axes and black for compressional axes. A : strike-slip type, with both horizontal maximum compression (σ1 axis) and intermediate compression (σ2 axis, which is extensive). B & C : radial extensive type, with both σ3 and σ2 axis horizontal and extensive. Rose diagrams indicate the strike of minor faults observed (more detail in Figure 6).

In the travertine levels of the quarry, faults which are subvertical and bear dominantly subhorizontal slip lines developed along new trends. The computed tensor is of the pure strike-slip type (σ2 axis vertical), with subhorizontal N-S principal compression. The presence of mud gauges as thick as 20 cm in the fault planes attests that they were formed close to the topographical surface.

In this case, the neoformed minor faults were not inherited from underlying fault trends, probably due to the important differences, both in the material involved and in the stress regime.

The travertine of the quarry, lying above the 0.55 My lava flow, is only affected by faults related to the strike-slip regime, so a major change in the kinematic regime occurred after the deposition of the Older Lake Beds. Since the basaltic lava flow is not displaced by normal faults of the NW-SE trend, the upper limit for the end of the radial extensive regime is 0.55 My. Also, because strike-slip faults were recorded in the travertine deposits overlying this lava flow, the onset of the strike-slip regime should be younger than 0.55 My.

It can be concluded from this section that the kinematic evolution in the Songwe basin is polyphased, with two pulses of radial extension. The first one after the deposition of the Red Beds; the other during or after the deposition of the Lake Beds. A major change in the kinematic regime occurred after 0.55 My, with the onset of a pure strike-slip regime having a N-S principal compression direction.

2.2.2. Usangu Flats

At the southern border of the Usangu basin, the Chamoto hill is composed of silicified argillaceous deposits overlain by water-deposited tuffs, which are affected by conjugated normal faults (Fig. 7). These are assumed to be lake beds of Cenozoic age (HORNE *in* TEALE *et al.*, 1962). A paleostress tensor of extensive type was obtained (σ1 axis vertical), with a well-defined extension direction (R ratio is 0.18) at a high angle to the axial valley of the Usangu basin. One set of these minor normal faults was reactivated by a subhorizontal sinistral slip, compatible with a pure strike-slip system (σ2 axis vertical) with subvertical NNW-SSE principal compression.

In this case, superimposition of strike-slip movements on existing minor normal faults also evidenced the succession of paleostress phases, with an earlier extensive regime and a later strike-slip regime. The estimated age for the deposition of the Lake Beds in the Usangu basin is between 2.2 My and 0.57 My (EBINGER *et al.*, 1989), but the timing of the stress inversion cannot be constrained more precisely. However, both normal and strike-slip movements seem to be post-sedimentary.

2.2.3. Mbaka fault

The Mbaka fault offers another opportunity to establish a relative chronology of paleostress regimes and to constrain the age of the stress inversion. The NW-striking

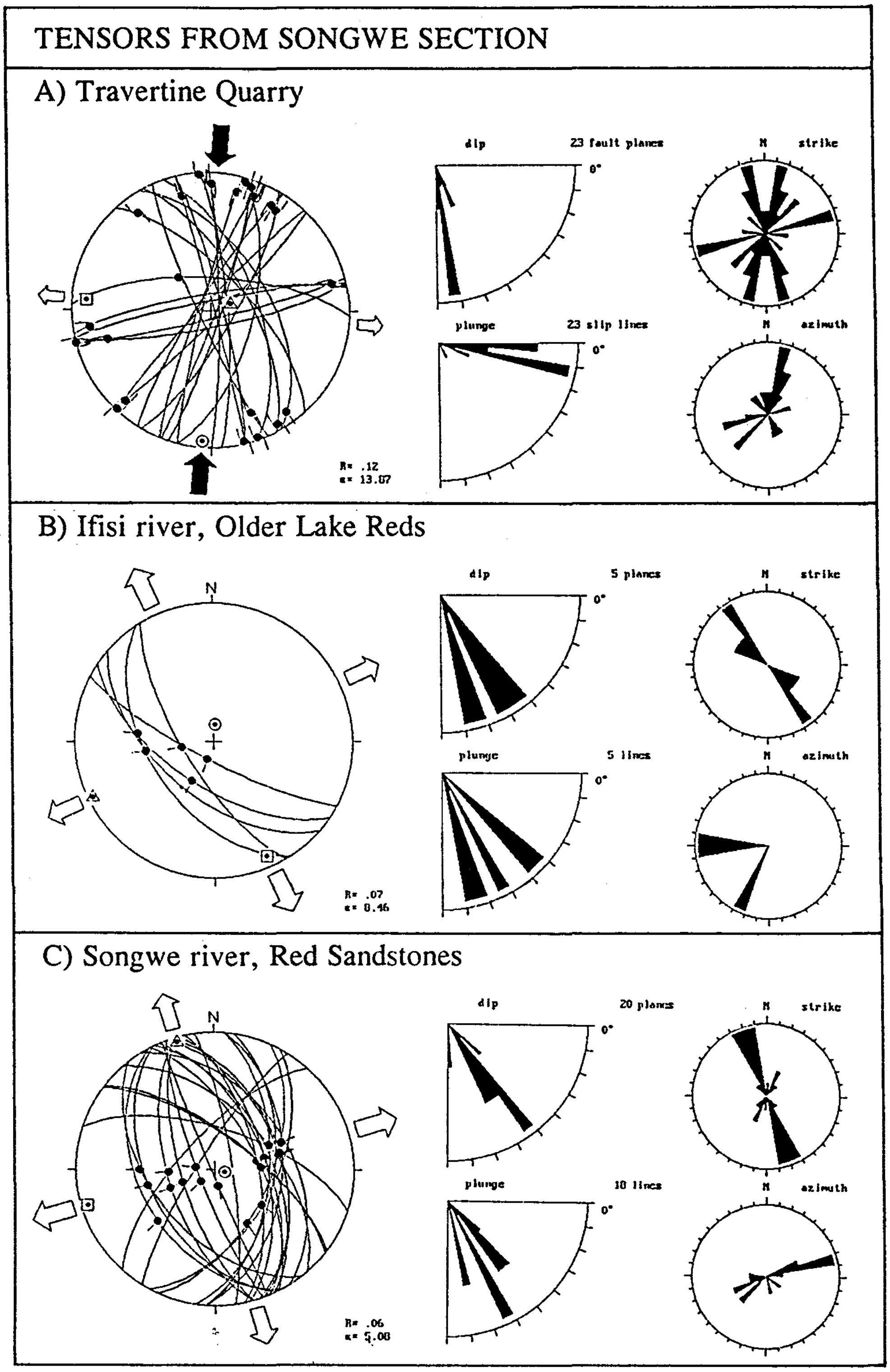

FIGURE 6

Fault data and stress tensors for different stratigraphic horizons of the Songwe section of Figure 5. Schmidt projections, lower hemisphere. Small circle : σ1 axes, triangles : σ2 axes, squares : σ3 axes, R : stress ratio σ2-σ3/σ1-σ3, α : mean angular deviation between observed slip lines and computed shears on fault planes. Stress symbols as in Figure 5.

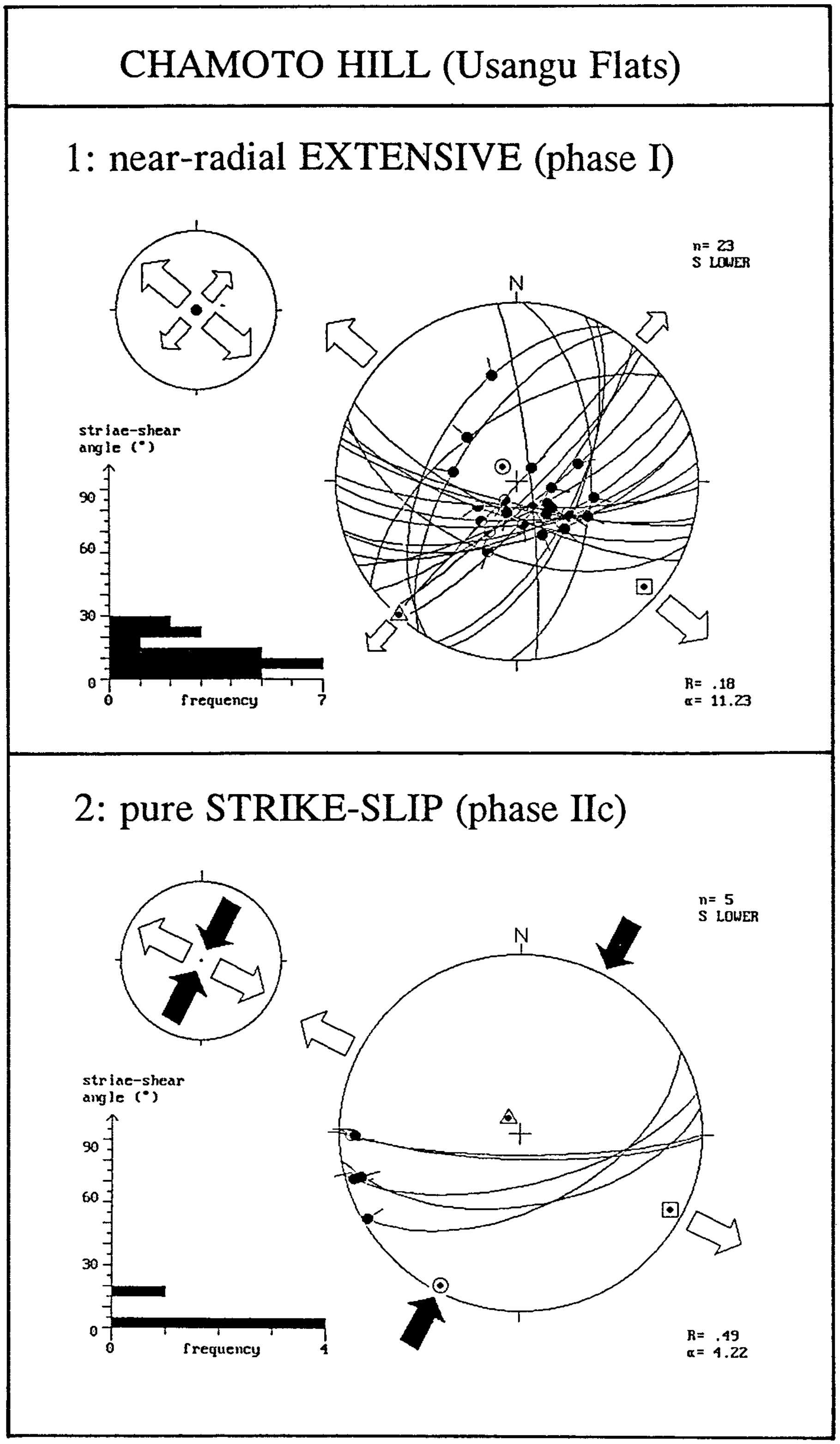

FIGURE 7

Superimposition of minor faults and stress tensors for the Lake beds at Chamoto hill in the Usangu basin. Schmidt projections, lower hemisphere (phase number according to regional synthesis). Small circle : σ1 axes, triangles : σ2 axes, squares : σ3 axes, R : stress ratio σ2-σ3/σ1-σ3, α : mean angular deviation between observed slip lines and computed shears on fault planes. Stress symbols as in Figure 5.

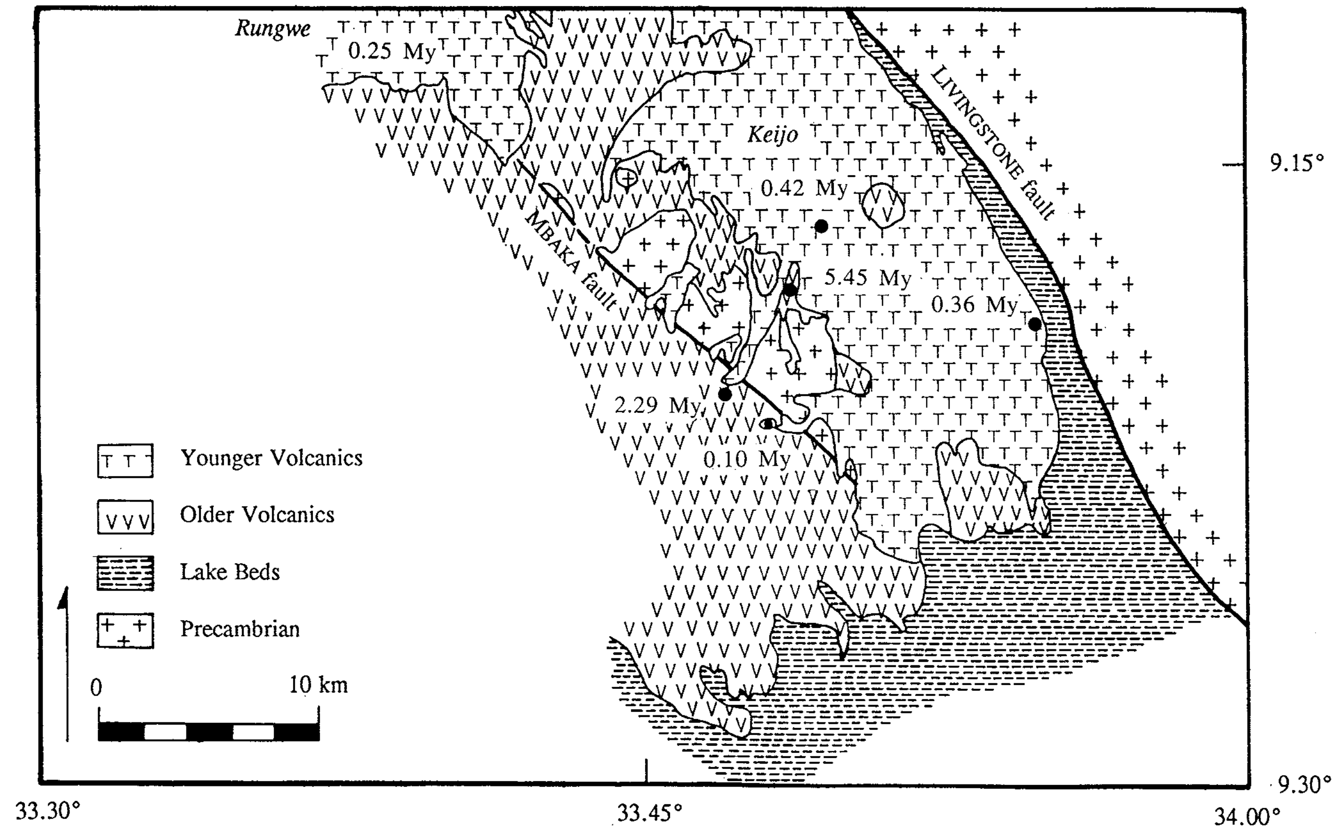

FIGURE 8

Geological map (HARKIN, 1960) and ages of lava flows (EBINGER, 1989) of the Mbaka fault zone in the Rungwe Volcanic Province.

Mbaka fault exposes the Precambrian basement, directly overlain by the volcanics of the Kiejo complex. The Mbaka fault has an important vertical throw component, and separates the northern part of the Livingstone basin into two longitudinal segments (Fig. 8). It was mainly active during the Pliocene age (EBINGER *et al.*, 1989), affecting lava flows dated at 5.45 ± 0.21 My and 2.29 ± 0.05 My. It's SE extremity is buried under 0.36 ± 0.03 My phonolitic lava from the Kiejo volcanic center, and its NW continuation is obscured by 0.25 ± 0.01 My lava from the Rungwe complex. Small valleys dissecting the fault scarp are occupied by a 0.42 ± 0.03 My lava flow also coming from the Kiejo center, in which no clear indications of faulting were found. At the footwall of the Mbaka fault, tephra cones and craters are dated at 0.10 ± 0.11 My and 0.12 ± 0.10 My (EBINGER *et al.*, 1989; EBINGER *et al.*, submitted).

Along a transverse section across the Mbaka fault zone (Fig. 8), most of the minor faults exposed in the hanging wall indicate that earlier movements have been normal dip-slip, while concentrations of subhorizontal slip-lines at the base of the fault escarpment indicate that younger movements were strike-slip to oblique-slip. Separation of the total fault population and paleostress analysis reveal the existence of three successive paleostress states, respectively extensive ($\sigma 1$ vertical) with a NE-SW extension, pure strike-slip ($\sigma 2$ vertical) with a NNE-SSW principal compression and compressive ($\sigma 3$ vertical) with a NE-SW principal compression (Fig. 9). The relative succession is well constrained by cross-cutting slip lines in fault planes.

On the basis of the 0.42 My lava which flowed from the Kiejo down an existing escarpment above the Mbaka fault, and in which no clear faulting evidence has been found, it can be concluded that most of the faulting activity along the Mbaka fault occurred prior to 0.42 My. The presence of an important fault scarp over which the lava flowed indicates that most of the vertical displacement took place before 0.42 My. The occurrence of strike-slip minor faults at the base of the scarp, and their apparent exclusion in the lava flow also indicates that the strike-slip phase predates 0.42 My. Consequently, the Mbaka fault evidence shows that the stress inversion from extensive regime to strike-slip regime is also older than 0.42 My. Both extremities of the Mbaka fault are entirely covered by more recent lava flows from the Rungwe and Kiejo volcanic centers, but limited movements apparently continued later, as noted by EBINGER (1989).

The Mbaka fault is also a good example of the successive reactivation of the earliest fracture planes, during the succession of paleostress phases. In the extensive regime, dip-slip movements occurred not only along NW-striking, SW-dipping minor faults parallel to the Mbaka fault trace, but also along fractures of two other dominant trends, NE-SW and E-W. The pure strike-slip phase reactivates the NW-striking normal faults in a dextral manner. NNW-striking subvertical joints of pre-rift origin were reactivated in a sinistral manner. The last compressive phase caused inverse reactivation of the NW-striking, SW-dipping faults and subsequent reactivation of the NNW-striking subvertical joints.

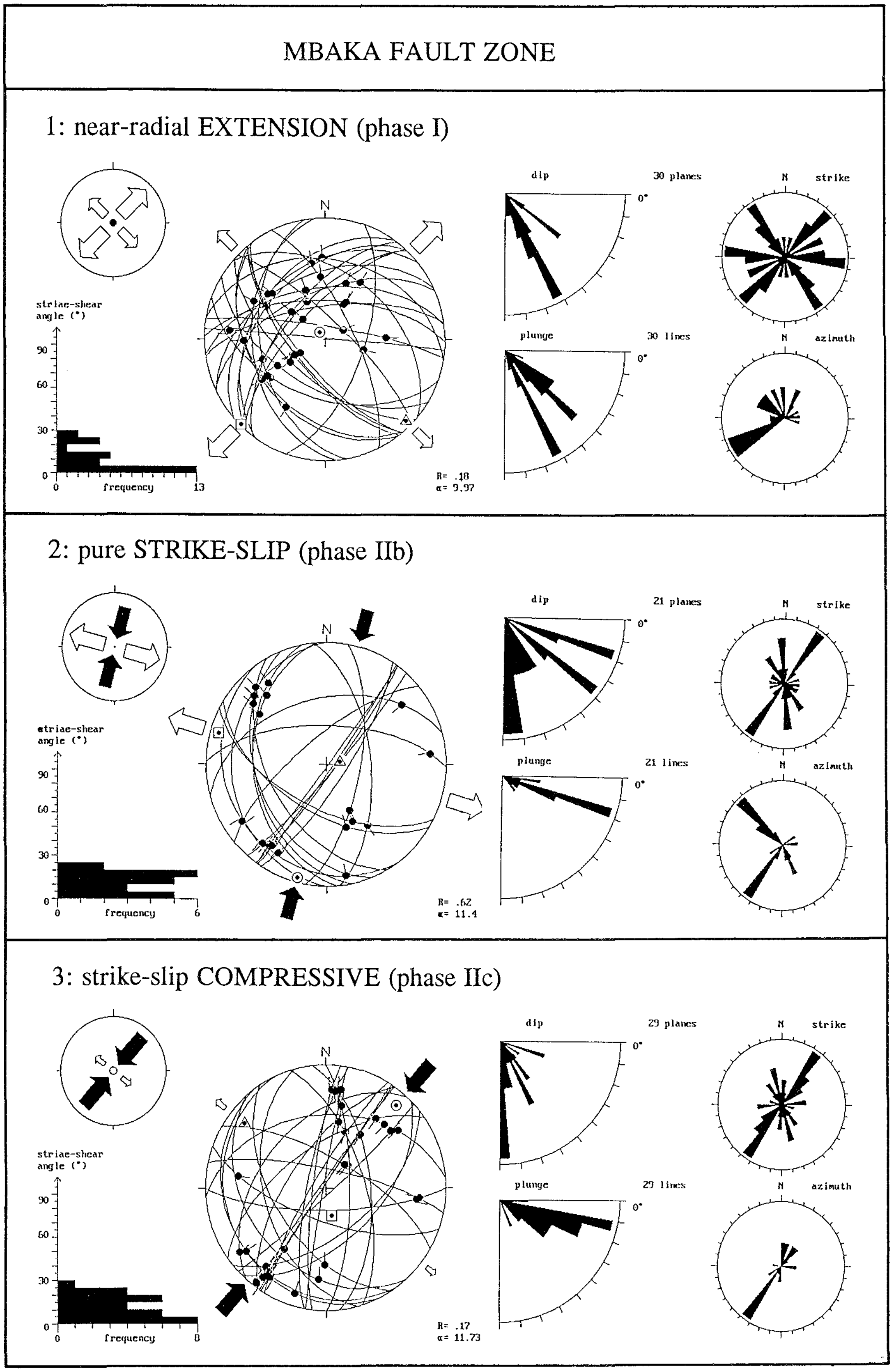

FIGURE 9

Superimposition of fault data and stress tensors for the Mbaka fault zone in the Livingstone basin (phase number according to regional synthesis). Schmidt projections, lower hemisphere. Small circle : σ1 axes, triangles : σ2 axes, squares : σ3 axes, R : stress ratio σ2-σ3/σ1-σ3, α : mean angular deviation between observed slip lines and computed shears on fault planes. Stress symbols as in Figure 5.

2.3. REGIONAL SYNTHESIS

47 tensors were obtained for the whole investigated area and assembled into four groups according to their kinematic type and stress axis orientation (Tab. I and II). These four groups belong to two major phases, separated by a marked change in kinematic regimes (Fig. 10) :

— phase I (18 tensors, 327 faults) : characterized by near-radial extension (σ1 vertical, low R ratio) and a bi-modal distribution of the principal directions of extension (σ3 axis) with two equally-defined maxima, in ENE-WSW (N 065° E) and NW-SE (N 325° E) directions.

— phase II, (29 tensors, 649 faults) : characterized by strike-slip tensors (σ2 axis vertical) with subhorizontal compression (σ1 axis), grouped along three dominant directions : NNW-SSE (N 145° E, set a), N-S (N 004° E, set b) and NNE-SSW (N 037° E, set c).

TABLE I

Paleostress tensors of the kinematic phase I (Late Miocene to Early Pleistocene)
σ1, σ2, σ3 : maximum, intermediate and minimum compressive stress axes (plunge angle / azimuth, from N to E);
R : ratio of principal stress magnitute differences (σ2-σ3)/(σ1-σ3);
α : mean angle between observed slip striae and computed shears on fault planes;
n : number of fault-slip data.

Site	Area	Latitude	Longitude	σ1 axis	σ2 axis	σ3 axis	R	α	n
311	Songwe basin, Ifisi river	-8.91833°	33.29516°	80/005	04/245	09/156	0.07	8.4	5
304	Mbeya scarp, Mshewe river	-8.84392°	33.28330°	72/264	15/119	10/026	0.10	13.4	16
303	Mbeya scarp, Kumbi river	-8.87432°	33.31113°	80/139	01/232	10/322	0.14	16.4	25
300	Usangu flats, Chamoto Hill			81/317	01/221	09/130	0.18	11.2	23
301	Usangu scarp	-8.68750°	33.61293°	85/113	02/228	04/318	0.39	13.0	23
321b	Mbaka fault, Itende	-9.33168°	33.78916°	84/324	06/135	01/225	0.18	10.0	30
				57/072	33/246	10/148	0.84	8.8	9
319	Mbaka fault, road	-9.35920°	33.82104°	87/007	04/245	06/155	0.02	10.4	19
334	Livingstone fault, Lufirio river	-9.38809°	33.96129°	87/200	02/321	02/061	0.58	9.7	23
335	Livingstone fault, Matema	-9.48192°	34.32331°	78/073	04/182	12/273	0.02	12.5	31
358	Livingstone fault, Matema	-9.49503°	34.45537°	83/007	06/155	04/245	0.01	9.8	18
359	Livingstone fault, Ikombe	-9.51679°	34.72669°	76/303	13/151	06/060	0.26	14.6	38
338-40	Livingstone fault, Lupingu	-10.03125°	34.55220°	86/345	02/227	10/317	0.10	6.6	6
341-45	Luika fault, Lupingu	-10.06590°	34.55220°	75/103	04/206	15/297	0.52	6.3	14
				53/212	31/070	18/329	0.39	5.1	8
347-49	Ilombe river, Lupingu	-10.07042°	34.55746°	81/246	04/358	08/088	0.12	12.1	12
350-57	Lupingu-Cape Kaiser	-10.09488°	34.53709°	84/040	04/175	04/265	0.11	8.3	14
270	Namschweia fault, Mhulasi riv	-10.52627°	34.74954°	75/187	07/070	13/338	0.32	6.5	13

TABLE II

Paleostress tensors of the kinematic phase II (Late Pleistocene - Holocene)
σ1, σ2, σ3 : maximum, intermediate and minimum compressive stress axes (plunge angle / azimuth);
R : ratio of principal stress magnitute differences (σ2-σ3)/(σ1-σ3);
α : mean angle between observed slip striae and computed shears on fault planes;
n : number of fault-slip data.

TABLE II: Phase II (Late Pleistocene)

Site	Area	Latitude	Longitude	σ1 axis	σ2 axis	σ3 axis	R	α	n
				Set A					
309-10	Ufipa fault	-9.31352°	32.80931°	11/328	79/141	01/238	.05	7.9	53
301	Usangu Scarp	-8.68750°	33.61293°	06/107	70/002	19/199	0.66	10.9	20
223	Mchuchuma basin	-10.29031°	34.65917°	01/132	71/224	19/042	.48	17	17
287	Namschweia fault	-10.61730°	34.68555°	06/329	68/074	21/237	.52	7.5	10
280	Ruhuhu basin	-10.63043°	34.66590°	18/338	11/244	69/124	0.92	8.7	15
				fold axis: 08/235					
273-5	Namschweia fault	-10.70063°	34.65402°	19/186	70/022	05/277	0.30	14.0	8
329-33	Songwe-Kiwira basin	-9.48369°	33.66241°	01/313	58/221	32/044	.05	10.4	16
				Set B					
316	Songwe basin, Travertine	-8.91802°	33.22445°	05/184	78/069	11/274	.12	13.9	23
303	Mbeya scarp, Kumbir	-8.87432°	33.31113°	16/005	29/265	55/120	.35	9.8	11
321Bis	Mbaka fault	-9.33168°	33.78916°	04/195	81/081	08/286	0.62	11.4	21
319-21	Mbaka fault	-9.35920°	33.82104°	01/173	79/078	11/263	0.28	10.8	28
334	Livingstone fault , Matema	-9.38809°	33.96129°	18/198	72/005	04/106	0.92	6.4	16
335	Livingstone fault , Matema	-9.48192°	34.32331°	21/357	62/221	18/095	0.32	8.6	14
358	Livingstone fault , Matema	-9.49503°	34.45537°	01/173	79/078	11/263	0.28	10.8	28
359	Livingstone fault , Matema	-9.51679°	34.72669°	21/194	68/350	09/101	0.81	10.3	20
336-7	Livingstone fault , Lupingu	-10.02152°	34.51328°	07/010	76/130	12/279	.45	13.6	37
				17/345	73/147	06/256	.72	12.6	15
338-40	Livingstone fault , Lupingu	-10.03125°	34.51694°	03/356	84/219	04/076	.26	9.8	54
				04/226	68/123	21/318	.55	13.3	14
341-45	Luika fault, Lupingu	-10.06453°	34.55746°	08/007	79/142	08/276	.33	8.8	22
347-49	Ilombe river, Lupingu	-10.07042°	34.55746°	81/246	04/358	08/088	0.12	12.1	12
350-57	Lupingu-Cape Kaiser	-10.10440°	34.52930°	24/017	66/188	03/286	.91	7.5	20
355	Ukenju Bay	-10.20153°	34.56548°	01/350	54/259	36/082	.66	10.6	36
				11/192	71/317	16//099	.15	11.6	10
				Set C					
304	Mbeya scarp, Mshewe r.	-8.84392°	33.28330°	08/030	75/151	12/298	0.56	10.2	7
300	Usangu flats, Chamoto			04/207	81/324	08/117	.49	4.2	5
301	Usangu scarp	-8.68750°	33.78916°	04/040	27/309	63/137	0.73	10.3	14
321Bis	Mbaka fault, Itende	-9.33168°	33.78916°	12/041	15/308	71/170	0.17	11.7	29
338-40	Livingstone fault , Upingu	-10.03125°	34.51694°	04/226	68/123	21/318	.55	13.3	14
356	Msimbaji Bay	-10.23958°	34.57097°	13/037	77/212	01/307	.61	9.8	24

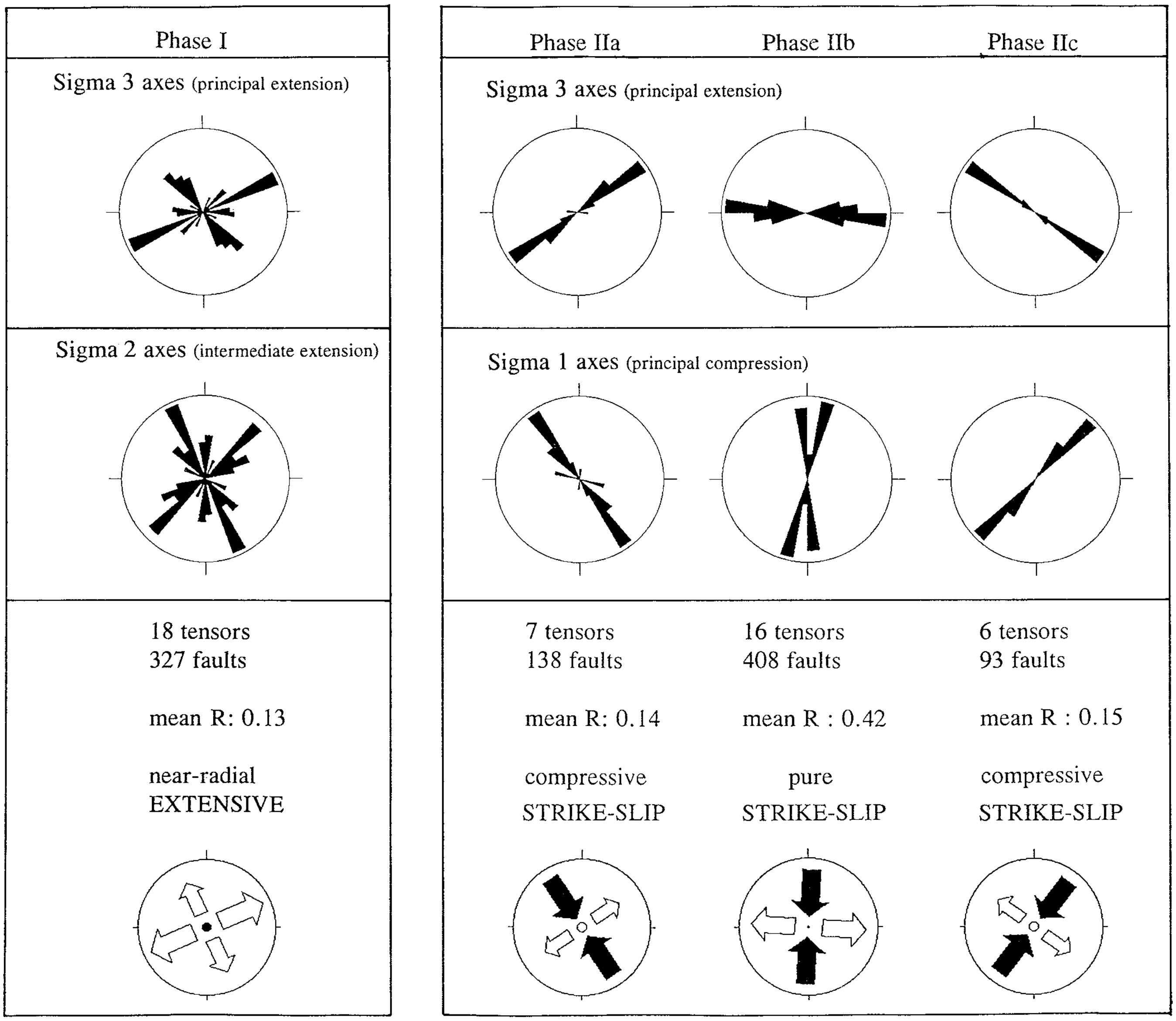

FIGURE 10

Regional synthesis of stress tensors. Roses of horizontal projections of stress axes. Tensor types with arrows showing directions of the horizontal stress axes (length according to stress ratio R) and the small central circles referring to vertical stress axis (symbols from GUIRAUD *et al.*, 1989). White is for extensional axes, and black for compressional axes. R : stress ratio (σ2-σ3)/(σ1-σ3).
Phase I : Near-radial extensive type, with both σ3 and σ2 axes horizontal and extensive.
Phase II : Strike-slip type, with horizontal maximum compression (σ1 axis) and intermediate compression (σ2 axis).

2.3.1. Spatial relations

The spatial distribution of the stress tensors for phase I (Fig. 11) shows no systematic distribution of tensor types in relation to the well-organized regional structure. Instead, both radial extension (multidirectional) and pure extension (unidirectional) were encountered independently of geological situation, with both ENE-WSW and NW-SE principal extension directions.

For phase II, the three subsets of tensors were recognized (Fig. 12) :

— set A (7 tensors for 138 faults) was found only in the NW side of a line running from the Mbozi block to the Ruhuhu basin;

— set B (16 tensors for 408 faults) was found SE of the same line, and is well expressed in the Songwe basin (Mbeya fault), and along the SE side of the Livingstone basin, (Mbaka and Livingstone faults), but it was not found in the Usangu basin;

— set C (6 tensors for 93 faults) is superimposed on set B along the Mbeya, Mbaka and Livingstone faults and also occurs in the Usangu basin.

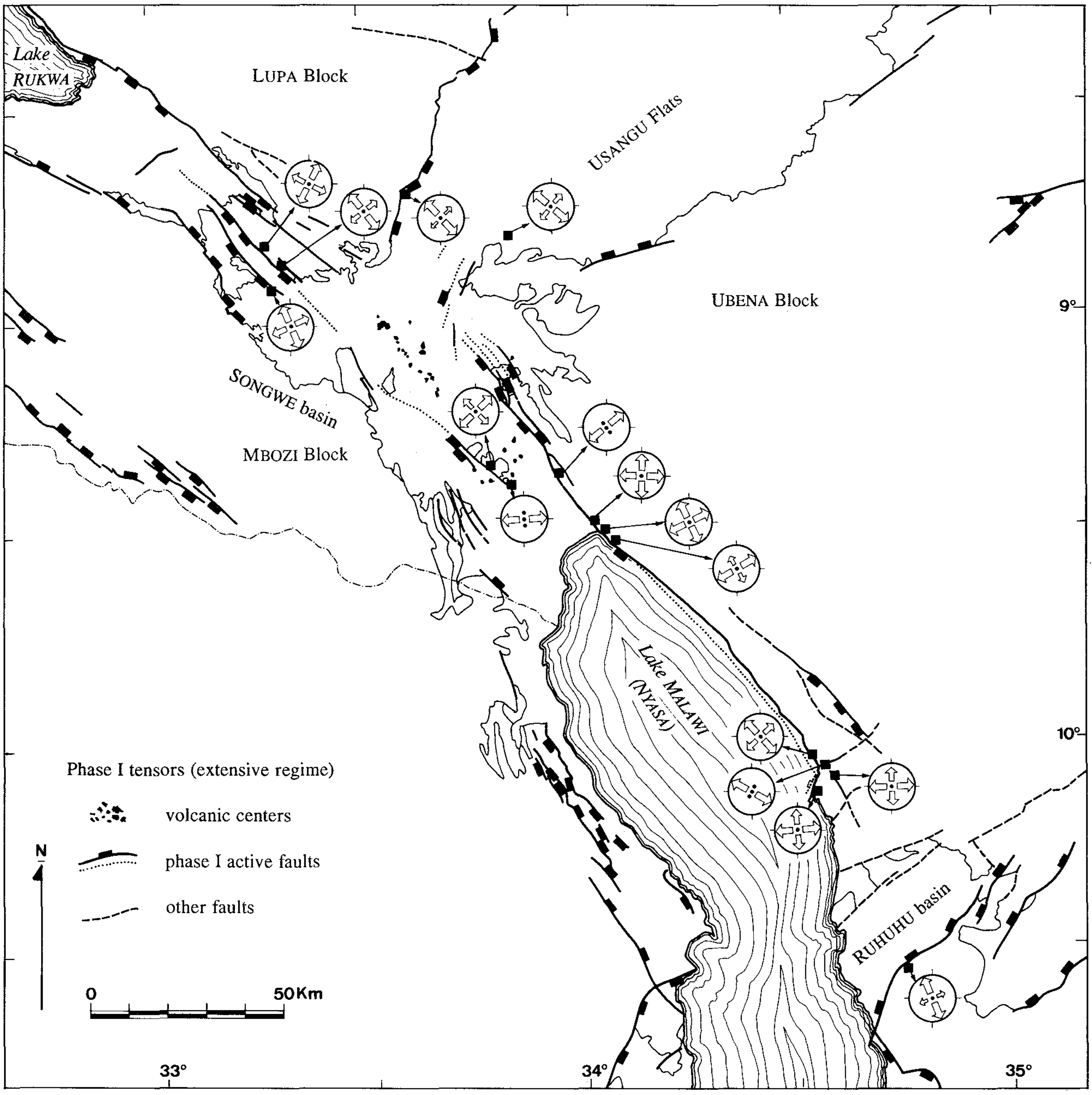

FIGURE 11
Regional distribution of stress tensors and active faults for kinematic phase I in the Rukwa - North Malawi area. Stress symbols as defined in Figure 10.

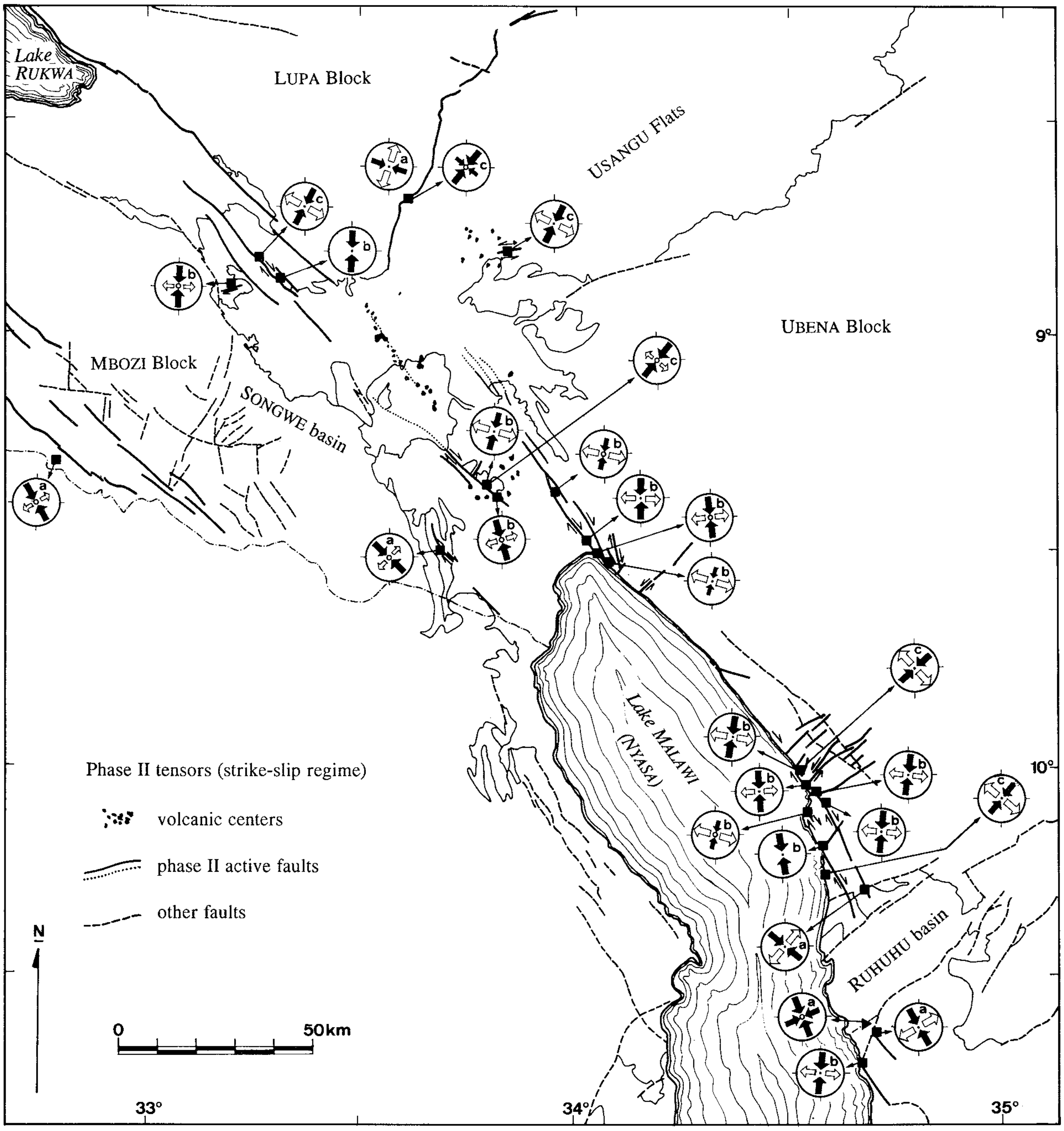

FIGURE 12
Regional distribution of stress tensors and active faults for kinematic phase II in the Rukwa – North Malawi area. Stress symbols as defined in Figure 10.

The three sets of tensors related to phase II can be differentiated mainly by the preferred orientation of the $\sigma1$ and $\sigma3$ subhorizontal stress axes, and it is postulated that they represent subphases of the kinematic phase II.

2.3.2. Chronological relations

The relative chronology of minor faults systematically indicates that phase I is the oldest and phase II is the youngest. Since minor faults related to phase I were observed in the Older Lake Beds, the maximum age for this phase is Late-Miocene. Phase I remained active from Late-Miocene to Pleistocene, and is broadly contemporaneous with the first and second magmatic pulses.

The age constraints for the transition from phase I to phase II are given by dated lava flows. The maximum age is constrained by the occurrence of strike-slip faults in the Songwe travertine which overlies the 0.55 ± 0.01 My basaltic lava flow along the Songwe river. The minimum age is fixed by a 0.42 ± 0.03 My lava which flowed over the Mbaka fault.

The major stress inversion which led to the strike-slip setting of the kinematic phase II is not older than 0.55 My, but younger than 0.42 My. It probably also caused the third magmatic pulse. This new situation apparently continues until Recent times.

The areas affected by subphase IIa and subphase IIb tensors are juxtaposed, so no relative chronology between them could be established. On the contrary, the area affected by subphase IIb and subphase IIc are superimposed along the Mbaka and Livingstone faults (Fig. 12), deferring subphase IIc to be the youngest.

The relations between the last paleostress phase (IIc) with the present tectonic activity is unclear.

3. — CENOZOIC KINEMATICS

3.1. KINEMATIC EVOLUTION

The mean tectonic regime for phase I is near-radial extensive ($\sigma1$ compressive axis vertical, with a stress ratio $R = 0.13$). This means that the magnitude of the horizontal stress $\sigma2$ is close to the magnitude of $\sigma3$, and greatly differs from the magnitude of $\sigma1$ stress. During a single kinematic phase for a given area, it is well known that the permutation of $\sigma1$-$\sigma2$ or $\sigma2$-$\sigma3$ stress axes may occur several times (ANGELIER & BERGERAT, 1983). The present situation, with a low stress ratio R, is thus favorable for $\sigma2$-$\sigma3$ permutations in the same extensive regime. The two maxima of $\sigma3$ axis orientation shown in the rose diagram for phase I (Fig. 10) can thus be easily explained by $\sigma2$-$\sigma3$ permutations, with a relative stability of the orientation of the two major horizontal stress axes, regardless of their magnitude.

The transition from phase I to phase II corresponds to a stress inversion from normal dip-slip regime to strike-slip regime, by permutation of the compressional axis $\sigma1$ and intermediate axis $\sigma2$. This permutation is unique and definitive, and marks the emergence of a new stress regime with submeridian horizontal principal compression. The principal extension remains in a horizontal position, which implies that the new regime is of strike-slip type. This stress inversion occurred between 0.55 My and 0.42 My.

Due to the uncertainty of the relationship between the subphases IIa and IIb, a definite model for the kinematic evolution during phase II cannot be presented. The subphase IIc is clearly younger than subphase IIb, but different possibilites exist for the relations between subphase IIa and IIb.

If subphases IIa and IIb are contemporaneous, then they should represent spatial variations of the stress field of the same kinematic subphase. In this case, it would suggest an inhomogeneous stress field with spatial rotation of the horizontal $\sigma1$ and $\sigma3$ stress axes, possibly influenced by major heterogeneities of the Precambrian basement.

Alternatively, subphase IIa may be older than subphase IIb. In that case, the only differences between phase I and subphase IIa tensors are the inclination of the compressive $\sigma1$ and intermediate $\sigma2$ axes, while the extensive $\sigma3$ axis remains in an ENE-WSW direction. The stress regime of the subphase IIa could then be directly inherited from the extensive regime of phase I, simply by permutation of $\sigma2$ and $\sigma1$ stress axes, with relative stability of $\sigma3$ axes in a NE-SW direction. Further evolution towards stress states of subphases IIb and IIc occurred due to the progressive clockwise rotation of the two horizontal stress axes, $\sigma1$ and $\sigma3$. Subphase IIa acted here as a short-lived intermediary between major phases I and IIb.

An alternative could be that subphase IIa is younger than subphase IIb, but this is less probable, because it implies two inversions in the rotational direction of the horizontal stress axes, which is more difficult to explain mechanically.

3.2. RELATION WITH THE PRESENT STRESS STATE

Relations between the latest paleostress state (subphase IIc) and the present stress state are unclear, due to the lack of in situ stress measurements and earthquake focal mechanisms. Phase IIc apparently recorded the latest paleostress state expressed in the region, but it is not precisely known whether it corresponds to the present state.

Earthquake focal mechanisms of the southern half of the East African Rift System, including the Rukwa and Malawi rift valleys and the Luangwa Karoo basin in Zambia show a systematic WNW-ESE to NW-SE direction for the horizontal projection of the least compressive stress axes (SHUDOVSKY, 1985; SHUDOVSKY *et al.*, 1987; DOSER & YARWOOD, 1991), which is similar to the WNW-ESE extension direction of subphase IIc. In addition, DOSER & YARWOOD (1991) showed that in East Africa, about one third of the earthquakes have strike-slip mechanisms, the rest having normal or oblique-slip mechanisms, but no compressive mechanisms.

This is an apparent contradiction with the observation that the last recognized paleostress regime (IIc) is characterized by a strike-slip regime with a dominant compression ($R < 5$), having four strike-slip type tensors and two of inverse type.

From a reexamination of the 12 earthquake focal mechanisms computed by DOSER & YARWOOD (1991) for East Africa, a homogeneous stress tensor was obtained by superposition of compressional and extensional dihedra for 9 of the 12 published earthquake data (Fig. 13). This tensor is characterized by an extensive regime with a strong strike-slip component ($\sigma 1$ axis vertical and high stress ratio : R = 0.88), a WNW-ESE principal extension, $\sigma 3$ (N 118° E) and a NNW-SSE intermediate $\sigma 2$ axis (N 027° E). The stress regime deduced from these earthquake focal mechanisms is thus intermediate; between pure extensive and pure strike-slip.

Comparison with the paleostress tensor of subphase IIc indicates a good correspondence of the directions of horizontal stress (respectively $\sigma 1$ = N 067° E and $\sigma 3$ = N 128° E for subphase IIc and $\sigma 2$= N 027° E, $\sigma 3$ = N 118° E for the earthquake focal mechanisms). The main difference between the two tensors is the relative magnitude of the horizontal maximum stress, which is lower for earthquake focal mechanisms (= $\sigma 2$ axis) than for subphase IIc (= $\sigma 1$ axis).

However, this difference can simply be due to the fact that the depth of the earthquakes' focal mechanisms ranges from 7 to 29 km. It implies a substantial lithostatic load which causes vertical stress to exceed the horizontal stresses. At subsurface, where fault planes were measured, the lithostatic load is very weak. With the same magnitude of horizontal stresses, the stress tensor observed should be of strike-slip type, or even inverse type, while at a depth where the vertical load overcomes the horizontal stress, the stress tensor is extensive, with a strike-slip component.

3.3. KINEMATICS AND BASIN DEVELOPMENT

The kinematic phase I (Late Miocene to Early Pleistocene) accounts for the major development of Cenozoic basins along two orthogonal trends, with two magmatic pulses in the triple junction between them. The Older Lake Beds were deposited during this episode, mainly during the Pliocene – Early Pleistocene ages.

The NW-striking Rukwa, Songwe and Livingstone basins, which are partly inherited from older Karoo (and Mesozoic ?) rift structures (see above), were reactivated by normal faulting with dip-slip to oblique-slip movements along the major border faults, together with renewed tilting of the half-grabens. The Lupa, Mbeya and Livingstone border faults are nearly rectilinear, and follow the Precambrian trend precisely. This points to a strong structural control for the Lupa and Livingstone faults, where faulting occurred mainly by reactivation of Precambrian structural directions.

At a right angle to the Rukwa-Malawi axis, the Usangu basin developed with an estimated maximum sediment thickness of 2 km. The Usangu border fault has a broken trace in map view, which indicates a weaker structural control by the Precambrian basement. Its main activity is not older than 7 My and is most probably between 2.2 and 0.57 My (EBINGER *et al.*, 1989). So, the Usangu basin appears to be a relatively young feature originated mainly during the Cenozoic phase I, in response to the NW-SE extension direction of the near-radial extensive stress regime.

As shown by the displacement of the Mid Miocene peneplain, the Ruhuhu Permo-Triassic basin further south was also reactivated, with limited dip-slip faulting and renewed tilting along the major border faults, but without renewed sedimentation.

The tectonic inversion leading to kinematic phase II is linked with renewed magmatic activity in Upper Pleistocene (pulse 3) and a marked change in sedimentation history. Sedimentation of the Older Lake Beds stopped some time before the 0.55-0.57 My lava flows emplaced in the Songwe plain and in the Usangu Flats. The travertine deposits in the Songwe plain and the Younger Lake Beds in the Rukwa valley are the main sedimentary deposits of the Late Pleistocene – Holocene period. The last magmatic pulse is still active, as shown by the historic eruptions of the Kiejo volcano.

Subphase IIa is only expressed on the SW side of the Rukwa – North Malawi valley, with compressive strike-slip regime and NNW-SSE direction for $\sigma 1$ axis. It caused strike-slip reactivation of existing NW-striking rift faults.

Subphase IIb mainly caused a dextral strike-slip reactivation of the major NW-striking faults, with small dip-slip components depending on local conditions. Total slip related to this phase seems to have remained relatively modest regardless of the rift dimensions, with a 120 m horizontal component of dextral slip shown by river offsets along the Livingstone fault near Lupingu. A series of NE-striking subvertical joints of pre-Karoo origin were also sinistrally reactivated along the Mbeya, Mbaka and Livingstone faults.

Subphase IIc was evidenced along the Mbeya, Mbaka and Livingstone fault zones where it is generally expressed by superimposed reverse movements along SW-dipping major normal faults, and the strike-slip reactivation of NE-striking subvertical joints of pre-Karoo origin. It is also shown in the Usangu Flats by renewed strike-slip faulting (Usangu Scarp and Chamoto Hill, Fig. 7). The most recent volcanic eruptions in the Kiejo and Rungwe volcanoes and in the SW extremity of the Usangu Flats may also be related to this subphase.

The present tectonic activity is poorly known. However, a preliminary seismic survey (CAMELBEEK, in press) indicates that the Mbozi block is presently seismically active. The alignment of the Usangu Plain, the Holocene volcanic centers in the Rungwe Volcanic Province, and the seismically-active Mbozi block may correspond to a NE-striking belt of Recent to Actual tectonic activity.

3.4. REGIONAL EXTENSION DIRECTION

The recognition of the polyphase character of the Cenozoic kinematic evolution in the Rukwa–North Malawi area gives new elements to the controversy about the regional extension direction, and may explain why there are such a great number of conflicting theories, each based on different geological or geophysical data.

The earthquake focal mechanisms are characterized by a NW-SE extension with significant strike-slip components (SHUDOVSKY, 1985; DOSER & YARWOOD, 1991) and the major NW-striking rift faults frequently bear slip lines which display dextral oblique-slip (CHOROWICZ, 1983; WHEELER & KARSON, 1989). These two elements are compatible with the Recent

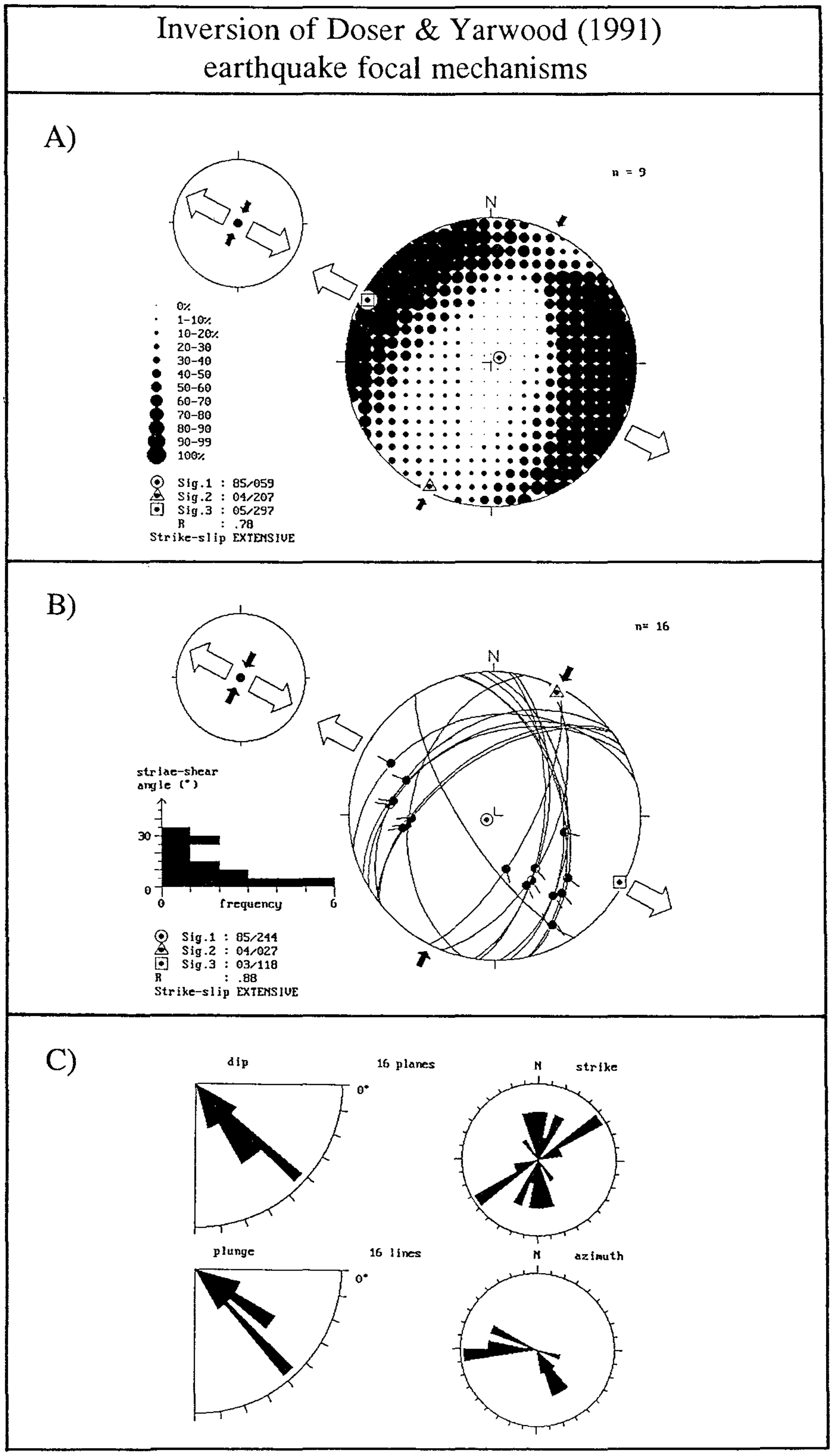

FIGURE 13

Direction of principal stress axes and stress ratio R obtained by inversion of focal mechanisms published by DOSER & YARWOOD (1991) for East Africa. A : Zones of minimum principal stresses (largest dots) and maximum stresses (smallest dots) deduced from the superposition of compressional and dilatational quadrants of 9 fault plane solutions. B : Stress tensor computed minimalisation of the angles between slip striae and theoretical shears, on compatible auxilliary planes. C : Rose diagrams of the retained auxilliary planes and associated slip directions. Schmidt projections, lower hemisphere. Stress axis : plunge angle/azimuth.

(and probably still active) stress regime of phase II, characterized by the combination of horizontal compression and horizontal extension (normal extensive regime with strike-slip component at depth, and strike-slip regime at subsurface).

It is obvious that the opening of the NW-trending rift basin of the TRM lineament cannot be related to the second kinematic phase, considering its strike-slip characteristics and the associated horizontal principal compression. Subphases IIa & IIb with NW-SE and N-S direction of compression place these basins in transtensive and/or transpressive situations, while subphase IIc, with NE-SW direction of compression places them in compressive situations. This is consistent with microtectonic observations of inverse reactivations along the Mbeya fault, and also with interpretations of seismic data which suggest the presence of minor faults with reverse displacements in the Rukwa rift basin (KILEMBE & ROSENDAHL, in press). The opening of these rift basins may be related to the regional extensive regime of phase I, with the dominant ENE-WSW direction of extension.

The opening of the NE-trending Usangu rift may also be related to the kinematic phase I, since the extensive regime is near-radial and the NW-SE direction is also extensive.

4. — CONCLUSIONS

The Cenozoic evolution of rifting in the Rukwa – North Malawi area is based on fault stress analysis using the concept of reduced tensors. The general results obtained in this way are globally similar to those obtained by RING *et al.* (in press), relating fault-slip data to strain axes.

Rather than a single phase for rift evolution, it appears that the rift kinematics is polyphased, with successive reactivation of existing discontinuities mainly dating from the Precambrian age. This proposed polyphase evolution reconciles models based on total strain (global extension across rift basins) with models based on instantaneous kinematics (earthquake focal mechanisms).

This kinematic succession is compatible with results from other studies in the Malawi side of Lake Malawi (RING *et al.*, in press) and in the Central Kenya Rift (STRECKER *et al.*, 1990) but contradicts those proposed by CHOROWICZ *et al.* (1987).

In addition, the extensive radial character of the stress tensor for phase I, and the bimodal distribution of the $\sigma 3$ axes indicates that both directions, parallel and across the Rukwa – North-Malawi NW-SE trend, are extensive. Strain analysis (RING *et al.*, in press) indicates a NE principal extension direction for the Rukwa – North Malawi basins, while the opening of the transversal Usangu basin and reactivation of the Ruhuhu basin implies a NW principal extension. The result is in effect a radial extension in terms of strain and displacement on a regional scale. This bidirectional strain is likely to cause a space problem at the triple junction between the Songwe, Usangu and Livingstone basins, precisely where the Rungwe Volcanic Province lies.

Again we emphasize that the kinematic succession evidenced here concerns only the Cenozoic rifting period, and that the kinematics of the Karoo and Cretaceous periods is still to be precised.

Our data strengthen the idea of a major change in the Late Quaternary kinematic evolution for East Africa. STRECKER *et al.* (1990) first evidenced such a change for the Central Kenya rift at about 0.4 My, and RING *et al.* (in press) found the same kind of inversion for Malawi, but could only propose it at between 2 and 0.2 My. We confirm the existence of this kinematic inversion for the Tanzanian part of the Rukwa – North Malawi rift segment, and fixed its age between 0.55 and 0.42 My.

We also documented the progressive clockwise rotation of the horizontal stress axes towards a WNW-ESE direction for the horizontal extension, and NNE-SSW direction for horizontal compression, which are compatible with the present state of stress deduced from earthquakes' focal mechanisms.

The similar timing of kinematic evolution for the Central Kenya Rift and the Rukwa – North Malawi rift segment suggests that it could be a major process. The causes for this stress inversion and rotation are probably linked to limiting conditions at the boundaries of the African plate. In the Rukwa – North Malawi rift, the last kinematic stage significantly modifies the movements along the major border faults. With a principal compression at a high angle to the Rukwa-Malawi trend, it causes oblique to inverse reactivations of originally normal faults. Seismic activity in South Rukwa, recorded by a temporary station at Panda Hill (CAMELBEEK, in press) indicates that the Mbeya and Lupa faults are still active, just like the Mbozi block fault zone. It seems that actual tectonic activity is no longer compatible with basin-opening in the NW-striking Rukwa-Malawi rift valley, and may signify the abortion of rifting in this area. The migration of extensional deformation seems to occur southwesterly towards southern Africa, in NE-striking structures such as the Luangwa rift, the Lake Bangweulu trough, the Mweru-Wantipa trough systems and the Upemba graben in Zaire, as proposed by GIRDLER (1991).

Acknowledgements

Project IGS "Inheritance of Geological Structures", supported by the Belgian governement. We would like to thank the government of Tanzania, the University of Dar es Salaam, the UTAFITI commission and the MADINI geological survey Dodoma for research permits, the Mbeya Cement Company for authorisation to visit the travertine quarry, the Kiwira Coal Mine for an underground visit, U. RING and W. WHEELER for joint field work and C. EBINGER for providing us with geochronological data. J. KLERKX and K. THEUNISSEN are also acknowledged for the initiation of the IGS project. We have also benefitted from the constructive criticism given by J.P. RICHERT.

5. — REFERENCES

ANGELIER, J. (1989). — From orientation to magnitudes in paleostress determinations using fault slip data. — *J. Struct. Geol.*, **11**, 37-50.

ANGELIER, J. (1991). — Inversion directe de recherche 4-D : comparaison physique et mathématique de deux méthodes de détermination des tenseurs des paléocontraintes en tectonique de failles. — *C.R. Acad Sci.*, (Paris), **312**, 2, 1213-1218.

ANGELIER, J. & BERGERAT, F. (1983). — Stress system and continental extension. — *Bull. Centres. Rech. Explor.-Prod. Elf Aquitaine*, **7**, 1, 137-147.

ANGELIER, J. & MECHLER, P. (1977). — Sur une méthode graphique de recherche des contraintes principales également utilisable en tectonique et en seismologie : la méthode des dièdres droits. — *Bull. soc. géol. France*, (7), **19**, 1309-1318.

CAHEN, L. & LEPERSONNE, J. (1978). — Synthèse des connaissances relatives au Groupe (anciennement Série) de la Lukuga (Permien du Zaire). — *Ann. Mus. roy. Afr. Centr., Tervuren, Belgium*, in-8°, Sci. geol., **82**, 115-152.

CAMELBEEK, T. (in press). — Seismic activity in Southern Rukwa with data from Panda Hill Station (September — November 1991). — *In* : Geology for Economic Development, UNESCO (ed.), Newsletter n° 9, 1992.

CHOROWICZ, J. (1983). — Le rift est-africain : début d'ouverture d'un océan ? — *Bull. Centres. Rech. Explor.-Prod. Elf Aquitaine*, **7**, 1, 155-162.

CHOROWICZ, J. & MUKONKI, M.B. (1980). — Linéaments anciens, zones transformantes récentes et géotectonique des fossés dans l'est Africain, d'après la télédétection et la microtectonique. — Mus. roy. Afr. centr., Tervuren (Belg.), Dépt. Géol. Min., Rapp. ann. 1979, 143-146.

CHOROWICZ, J, LE FOURNIER, J. & VIDAL, G. (1987). — A model for rift development in Eastern Africa. — *Geol. J.*, **22**, Thematic Issue, 495-513.

CROSSLEY, R. & CROW, M.J. (1980). — The Malawi Rift. — *In* : Geodynamic evolution of the Afro-Arabian rift system. — Acad. Naz. Licei, Roma, 77-87.

DALY, M.C., CHOROWICZ, J. & FAIRHEAD, J.D. (1989). — Rift basin evolution in Africa. — the influence of reactivated steep basement shear zones. — *In* : COOPER, M.A. & WILLIAM, G.D., (eds.) : Inversion Tectonics. — *Spec. Publ. geol. Soc. London*, **44**, 309-334.

DALY, M.C., LAWRENCE, S.R., KIMUN'A, D. & BINGA, M. (1991). — Late Paleozoic deformation in central Africa : a result of distant collision ? — *Nature*, **350**, 605-607.

DELVAUX, D. (1990). — Structural control of the Karoo basins of SW-Tanzania by Pre-Karoo fracture pattern. — *In* : Etudes récentes sur la géologie africaine. Proceedings of the 15th Colloquium on African Geology, Nancy, 10-13 sept. 1990. — CIFEG (ed.), **22**, 293-296.

DELVAUX, D. (1991). — The Karoo to Recent rifting in the western branch of the East-African Rift System : A bibliographical synthesis. — Mus. roy. Afr. centr., Tervuren (Belg.), Dépt. Géol. Min., Rapp. ann. 1989-1990, 63-83.

DELVAUX, D. (in press). — Preliminary data on the kinematics of Rift faulting in the Livingstone Mountains, SW Tanzania. — *In* : Geology for Economic Development, UNESCO (ed.), Newsletter n° 9, 1992.

DELVAUX, D., LENOIR, J.-L., MRUMA, A., KAJARA, R.S.A., NANYARO, J.T. & THEUNISSEN, K. (in press). — Structural characteristics of the Upangwa and Mbozi Proterozoic terranes in SW Tanzania. — *In* : Geology for Economic Development, UNESCO (ed.), Newsletter n° 9, 1992.

DOSER, D.I., & YARWOOD, D.R. (1991). — Strike-slip faulting in continental rifts : examples from Sabukia, East Africa (1928), and other regions. — *Tectonophysics*, **197**, 213-224.

DYPVIK, H. (in press). — East African Rift Valley (W.Tanzania) : Possible Permian to Cretaceous/Tertiary hydrocarbon provinces ? — *J. Pet. Geol.*

DYPVIK, H., NESTBY, H., RUDENT, F., AAGAARD, P., JOHANSSON, T., MSINDAI, J. & MASSAY, C. (1990). — Upper Paleozoic and Mesozoic sedimentation in the Rukwa-Tukuyu Region, Tanzania. — *J. Afr. Earth Sci.*, **11**, 437-456.

EBINGER, C.J. (1989). — Tectonic development of the western branch of the East African rift system. — *Bull. geol. Soc. Amer.*, **101**, 885-903.

EBINGER, C.J., DEINO, A.L., DRAKE, R.E. & THESHA, A.L. (1989). — Chronology of volcanism and rift basin propagation : Rungwe volcanic province, East Africa. — *J. Geophys. Res.*, **94**, 15783-15803.

EBINGER, C.J., DEINO, A.L., TESHA, A.L., BECKER, T. & RING, U. (submitted). — Regional tectonic controls on rift basin geometry : Evolution of an East African Lake Basin. — *J. Geophys. Res.*

FAIRHEAD, J.D. & GIRDLER, R.W. (1972). — The seismicity of the East-African rift system. — *Tectonophysics*, **41**. T19-T26.

FAIRHEAD, J.D. & GREEN, C.M. (1989). — Controls on rifting in Africa and the regional tectonic model for Nigeria and East Niger rift basins. — *J. Afr. Earth Sci.*, **8**, 231-250.

FAIRHEAD, J.D. & STUART, G.W. (1982). — The seismicity of the East-African rift system and comparison with other continental rifts. — *In* : Palmason, G. (ed.) : Continental and Oceanic Rifts. — *Geodyn. Ser.*, **8**, 41-61.

GIRDLER, R.W. (1991). — The Afro-Arabian rift system — an overview. — *Tectonophysics*, **197**, 139-153.

GRANTHAM, D.R., TEALE, E.O., SPURR, A.M.M., HARKIN, D.A. & BROWN, P.E. (1958). — Quarter Degree Sheet 70 SW. — Geol. Surv. Tanzania, Dodoma.

GUIRAUD, M., LABORDE, O. & PHILIP, H. (1989). — Characterization of various types of deformation and their corresponding deviatoric stress tensor using microfault analysis. — *Tectonophysics*, **170**, 289-316.

GUIRAUD, R. & MAURIN, J.C. (1991) — Le rifting en Afrique au Crétacé inférieur : synthèse structurale, mise en évidence de deux étapes dans la genèse des bassins, relations avec les ouvertures océaniques péri-africaines. — *Bull. Soc. géol. France*, **162**, 811-823.

HARKIN, D.A. (1960). — The Rungwe Volcanics at the northern end of Lake Nyasa. — *Mem. geol. Surv. Tanzania*, **2**, 172 pp.

JAKOBS, L.L., WINKLER, D.A., KAUFULU, Z.M. & DOWNS, W.R. (1989). — The Dinosaur Beds of Northern Malawi, Africa. — *Nat. Geographic Res.*, **6**, 196-204.

KAUFULU, Z.E.V. & WHITE, T. (1981). — Age of the Chiwondo Beds, northern Malawi. — *Ann. Transvaal Mus.*, **33**, 1-8.

KILEMBE, E.A. & ROSENDAHL, B.R. (in press). — Structure and stratigraphy of the Rukwa rift. — *Tectonophysics*.

KREUSER, T. & MARKWORT, S. (1989). — Facies evolution of a fluvio-lacustrine Permo-Triassic basin in Tanzania. — *Zbl. Geol. Paläont.* [Teil I], **7/8**, 821-837.

LAMBIASE, J.J. (1989). — The framework of African rifting during the Phanerozoic. — *J. Afr. Earth Sci.*, **8**, 183-190.

MCCONNELL, R.B. (1950). — Outline of the geology of Ufipa and Ubende. — *Bull. geol Surv. Tanganyika*, **19**, 62 pp.

MCCONNELL, R.B. (1972). — Geological development of the rift system of eastern Africa. — *Bull. geol. Soc. Amer*, **83**, 2549-2572.

MONDEGUER, A., RAVENNE, C., MASSE, P. & TIERCELIN, J.-J. (1989). — Sedimentary basins in an extension and strike-slip background. — the "South Tanganyika troughs complex", East African Rift. — *Bull. Soc. geol. France*, **8**, 5, 501-522.

MORLEY, C.K. (1988). — *Variable extension in Lake Tanganyika.* — *Tectonics*, **7**, 785-801.

MORLEY, C.K. (1989). — Extension, detachments, and sedimentation in continental rifts (with particular reference to East Africa). — *Tectonics*, **8**, 1175-1192.

MORLEY, C.K., CUNNINGHAM, S.M., HARPER, R.M. & WESCOTT, W.A. (1992). — Geology and geophysics of the Rukwa rift, East Africa. — *Tectonics*, **11**, 68-81.

PEIRCE J.W. & LIPKOV, L. (1988). — Structural interpretation of the Rukwa Rift, Tanzania. — *Geophysics*, **55**, 824-836.

PENTEL'KOV, V.G. & VORONOVSKIY, S.N. (1977). — Radiometric age of the Mbalizi carbonatite, Tanzania, and correlation with other carbonatites of the Rukwa-Malawi rift zone. — *Dokl. Akad. Nauk SSSR*, **235**, 92-94.

QUENNELL, A.M., MCKINLEY, A.C.M. & AIKTKEN, W.G. (1956). — Summary of the geology of Tanganyika. Part I : Introduction and stratigraphy. — *Mem. geol. Surv. Tanganyika*, **1**, 264 pp.

RING, U., BETZLER, C. & DELVAUX, D. (1992). — Normal vs. strike-slip faulting during rift development in East Africa : the Malawi rift. — *Geology* (in press).

SANDER, S. & ROSENDAHL, B.R. (1989). — The geometry of rifting in Lake Tanganyika, East Africa. — *J. Afr. Earth Sci.*, **8**, 323-354.

SHUDOVSKY, G. (1985). — Source mechanisms and focal depths of East African earthquakes using Rayleigh wave inversion and body-wave modelling. — *Geophys. J. r. astron. Soc.* **83**, 563-614.

SHUDOVSKY, G., CLOETHINGH, S., STEIN, S. & WORTEL, R. (1987) — Unusually deep earthquakes in East Africa : constraints on thermo-mechanical structure of a continental rift system. — *Geophys. Res. Letters*, **14**, 741-744.

SMIRNOV, V., PENTELKOV, V., TOLOCHOV, V., TRIFAN, M. & ZHUKOV, S. (1974). — Geology and Minerals of the Central Part of the Western Rift. — Unpubl. report to Ministry of Commerce and Industry, Dodoma, Tanzania. 333 pp.

SPECHT, T.D. & ROSENDAHL, B.R. (1989). — Architecture of the Lake Malawi Rift, East Africa. — *J. Afr. Earth Sci.*, **8**, 355-382.

STRECKER, M.R., BLISNIUK, P.M. & EISBACHER, G.H. (1990). — Rotation of extension direction in the central Kenya Rift. — *Geology*, **18**, 299-302.

THEUNISSEN, K., LENOIR, J.-L., LIEGEOIS, J.-P., DELVAUX D. & MRUMA A. — (1992). — Empreinte mozambiquienne majeure dans la chaîne ubendienne de Tanzanie sud-occidentale : géochronologie U-Pb sur zircon et contexte structural. — *C.R. Acad. Sci.*, (Paris), **314** 2, 1355-1362.

TIERCELIN, J.-J., LE FOURNIER, J., HERBIN, J.P. & RICHERT, J.P. (1980). — Continental rifts : modern sedimentation, tectonic and volcanic control. Example from the Bogoria-Baringo graben, Gregory rift, Kenya. — *In* : Accademia Nationale Dei Lincei (ed.) : Geodynamic Evolution of the Afro-Arabian Rift System, Rome, **47**, 143-163.

TIERCELIN, J.-J., CHOROWICZ, J., BELLON, H., RICHERT, J.P., MWANBENE, J.T. & WALGENWITZ, F. (1988). — East African rift system : offset, age and tectonic significance of the Tanganyika-Rukwa-Malawi intracontinental transcurrent fault zone. — *Tectonophysics*, **148**, 241-252.

UTTING, J. (1976). — The Karoo stratigraphy of the northern part of the Luangwa valley. — *Mem. geol. Surv. Zambia*, **4**, 131 pp.

VERNIERS, J., JOURDAN, P.P., PAULIS, R.V., FRASCA-SPADA, L. & de BOCK, F.R. (1989). — The Karoo Graben of Metangula, northern Mozambique. — *J. Afr. Earth Sci.*, **9**, 137-158.

WESCOTT, W.A., KREBS, W.N., ENGELHARDT, D.W. & CUNNINGHAM, S.M. (1991). — New biostratigraphic age dates from the Lake Rukwa rift basin in Western Tanzania. — *Bull. amer. Assoc. Petroleum Geol.*, **75**, 1255-1263.

WOPFNER, H. (1991). — Riftphasen und deren Einfluß auf das Öl- und Gas-Potential tansanischer Karoo-Becken. — *Zbl. Geol. Paläont. I*, **11**, 273-2712.

WOPFNER,H. & KAAYA, C.Z. (in press). — Syndepositional rifting in the Ruhuhu and Selous basin — Tanzania. — *In* : Geology for Economic Development, UNESCO (ed.), Newsletter n° 9, 1992.

WHEELER, W.H. & KARSON, J.A. (1989). — Structure and kinematics of the Livingstone Mountains border fault zone, Nyasa (Malawi) Rift, Southwestern Tanzania. — *J. Afr. Earth Sci.*, **8**, 393-414.