

Tectonic and palaeostress evolution of the Tanganyika-Rukwa-Malawi rift segment, East African Rift System

Damien DELVAUX

Royal Museum for Central Africa, B-3080 Tervuren, Belgium

ABSTRACT

Fault systems of the Tanganyika-Rukwa-Malawi (TRM) segment of the East African Rift System (EARS) show evidence of repeated reactivation since the Palaeoproterozoic, controlling successive stages of sedimentary basin formation. During the last decade, important advances in understanding geological and geophysical processes affecting this region allow a new approach to the geodynamic evolution of this segment of the EARS. The evolution of the basement of the TRM rift segment started with the development of the NW-SE trending Palaeoproterozoic Ubende shear belt along the western margin of the Archean Tanzanian craton. This belt was repeatedly reactivated by left-lateral movements in retrograde greenschist facies during the Meso- and Neoproterozoic. A Permo-Triassic (Karoo) rift system developed in Late Carboniferous–Middle Triassic times, in response to compressional and transpressional deformations in east-central Africa. This intraplate deformation may have been induced by stress transmission through continental lithosphere over long distances from both the southern and the northern (Neo-Tethys) margins of the Gondwana continent. Rifting was probably minor during the Late Jurassic–Cretaceous in the TRM zone, but the existence of an Early Tertiary rifting stage is highlighted. The Late Cainozoic period of rifting started 8–9 Ma ago by semi-radial extension in the Rukwa-Malawi area. Since the middle Pleistocene, compressional intraplate stresses interfere with the evolution of the Late Cainozoic rift system. Volcanism and climatic fluctuations are, besides tectonism, additional factors that influence the sedimentary infill of the TRM rift basins.

RÉSUMÉ

Évolution de la tectonique et du paléostress sur le segment Tanganyika-Rukwa-Malawi du rift est Africain.

Le segment Tanganyika-Rukwa-Malawi (TRM) du rift est Africain a été réactivé de manière répétée au cours de son évolution, depuis le Paléoprotérozoïque. Ces réactivations ont contrôlé les stades successifs de la formation de bassins sédimentaires le long de la zone TRM. D'importants progrès dans la connaissance des processus géologiques et géophysiques de la zone TRM ont été réalisés au cours de cette dernière décennie. Ils permettent une nouvelle approche du développement géodynamique de ce segment du rift est Africain. L'évolution du socle du futur segment TRM a débuté par la formation de la chaîne mobile d'Ubende, en bordure ouest du craton tanzanien. Cette chaîne a été réactivée à plusieurs reprises par des

décrochements sénestres en conditions de métamorphisme schiste vert durant le Méso- et le Néoprotérozoïque. Un système de rift permo-triassique (Karoo) s'est développé à la suite d'une déformation intracontinentale en régime compressif à transpressif en Afrique centrale et de l'est. Cette déformation intraplaque a pu être induite par la transmission des contraintes tectoniques au travers de la lithosphère continentale sur de longues distances, depuis les bordures sud et nord (Néo-Téthys) du continent Gondwana. La riftogenèse a probablement été mineure durant le Jurassique supérieur-Crétacé, mais l'existence d'un stade de riftogenèse au Tertiaire inférieur est soulignée. La période de riftogenèse du Cénozoïque tardif commence il y a 8-9 Ma, par une extension semi-radiale dans la zone Rukwa-Malawi. Depuis le Pléistocène moyen, les contraintes intraplaques compressives générées en bordure de plaque interfèrent avec l'évolution interne du système de rift. Le volcanisme et les fluctuations climatiques sont, à côté de la tectonique, des facteurs additionnels qui influencent le remplissage sédimentaire des bassins de rift de la zone TRM.

INTRODUCTION

During the Late Palaeozoic to recent times, the area of the Tanganyika-Rukwa-Malawi (TRM) segment of the western branch of the East African Rift System (EARS) was affected by repeated rifting cycles (MCCONNELL, 1972). The western branch of the EARS displays a sigmoidal geometry and is superimposed on the Proterozoic mobile belts which surround the Archean Tanzanian craton (Fig. 1). The TRM zone shows evidence of Permo-Triassic and Late Mesozoic and/or Early Tertiary rifting, prior to a major Late Cainozoic rifting cycle (DELVAUX, 1991).

The Rukwa rift basin is located in the relay zone between the Tanganyika and Malawi (Nyasa) rift valleys (Fig. 1), which together form the NW-trending Tanganyika-Rukwa-Malawi (TRM) lineament. KAZMIN (1980) first interpreted the TRM lineament as an intracontinental transform fault zone, along which the Rukwa rift basin opened as a pull-apart basin in response to oblique, NW-SE extension. This model was adopted by CHOROWICZ & MUKONKI (1980) and supported by many others. It relies on the interpretation of satellite images, field observations on fault slip indicators in the Precambrian basement along the major border faults, and industrial reflection seismic profiles (e.g., TIERCELIN *et al.*, 1988; CHOROWICZ, 1989; KILEMBE & ROSENDAHL, 1992; WHEELER & KARSON, 1994). In contrast, MORLEY *et al.* (1992b) favoured an opening of the Rukwa rift basin in a NE-SW direction, sub-orthogonal to its general trend. Also SANDER & ROSENDAHL (1989) and SPECHT & ROSENDAHL (1989) suggested a sub-orthogonal opening of the Tanganyika and Malawi rift basins.

The major problem with the proposed mechanisms is the lack of control on the timing of fault movement. The multistage evolution of the Rukwa rift basin and the changes in extension direction during its evolution since the Late Palaeozoic was clearly described by MBEDE (1993). In the Rungwe volcanic province and in north Malawi, DELVAUX *et al.* (1992) and RING *et al.* (1992) recognized repeated changes in the kinematic regime during the Late Cainozoic. Palaeostress investigations were conducted along the major Late Cainozoic faults in dated sediments and volcanics, using an inverse method for reduced stress tensor reconstruction (as in ANGELIER, 1989). These show that, in late Miocene-Pliocene times, evolution of the EARS was dominated by a semi-radial extensional stress field, controlling the opening of the NW-trending Rukwa basin, the Songwe valley, the Livingstone basin and the NE-trending Usangu depression (DELVAUX *et al.*, 1992). During the middle Pleistocene, a major stress change occurred and the area was dominated by N-S horizontal principal compression, giving rise to a new, strike-slip, stress regime. Correspondingly, the faulting kinematics changed fundamentally. Activity along the major normal fault zones ceased or was strongly reduced, and only some of them were reactivated by strike-slip faulting (dextral movement along NW-trending faults and sinistral along NE-trending faults). This kinematic change coincided with a similar change in the Kenya rift (STRECKER *et al.*, 1990; DELVAUX, 1993).

The timing of the Mesozoic and Cainozoic tectonic events has been also constrained by apatite fission track (AFT) thermochronology (VAN DER BEEK *et al.*, 1998). AFT data showed several stages of rapid cooling and denudation of the Malawi and Rukwa rift flanks, which can be related to changes in the plate tectonic setting of Africa and the kinematics of the surrounding oceanic basins, and to changes along the system of sea-floor spreading axes.

Geological investigations since 1989, within the framework of collaborations between Belgium and Tanzania, have improved the understanding of the tectonic evolution of the TRM zone from the

Palaeoproterozoic development of the Ubende shear belt to the present. Many different aspects of the tectonic evolution have already been published in various papers and special issues (e.g., DELVAUX & KHAN, 1998). This paper provides a synthesis of recent advances in the knowledge of this area, including results obtained by other teams.

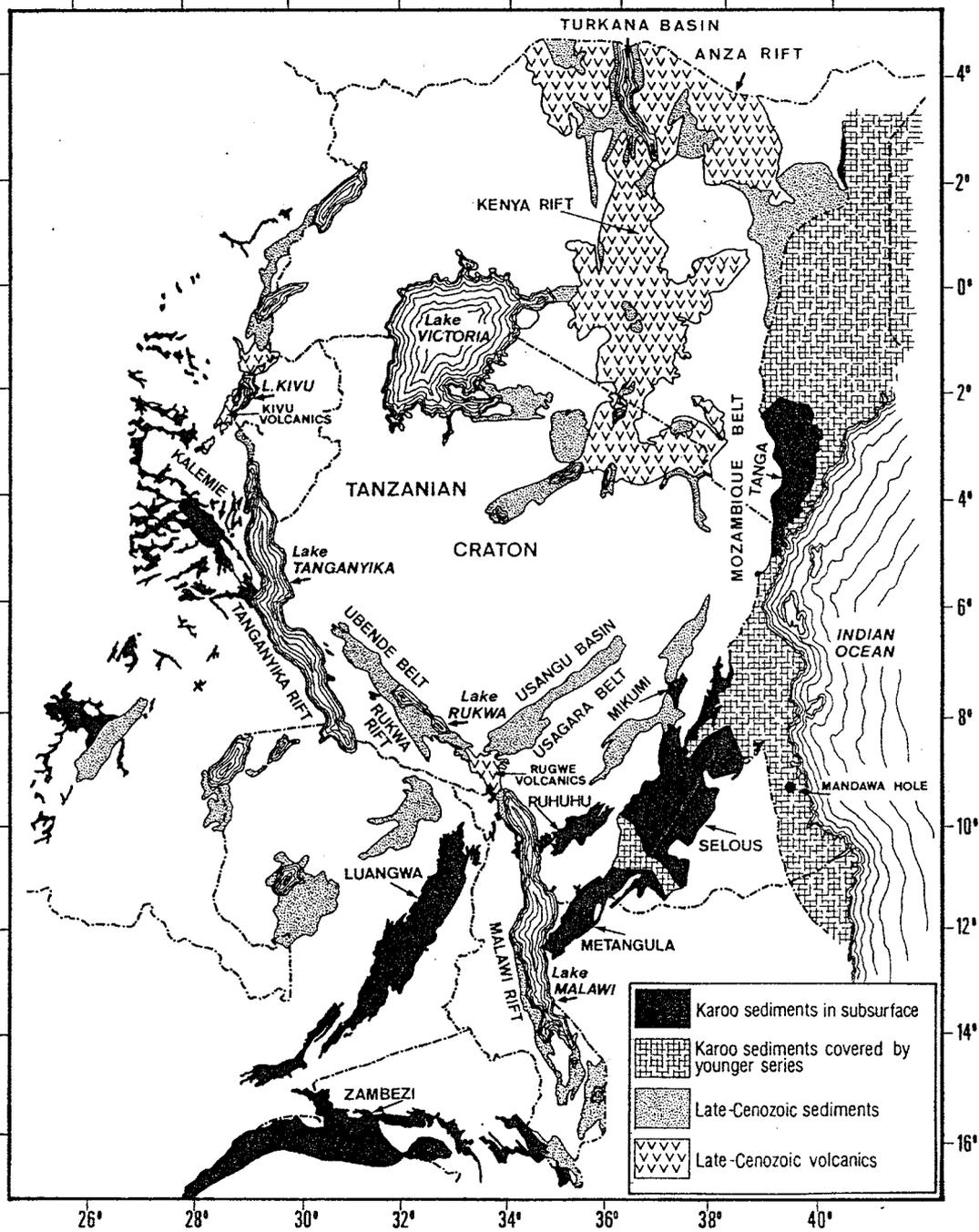


FIG. 1.— Karoo and Cenozoic rift depressions in southern east Africa (modified after VERNIERS *et al.*, 1989 and DELVAUX, 1992).

FIG. 1.— Dépressions de rift d'âge Karoo et Cénozoïque, en Afrique du sud-est (modifié d'après VERNIERS *et al.*, 1989 et DELVAUX, 1992).

STRUCTURE AND EVOLUTION OF RIFT BASINS

TANGANYIKA BASIN

The Tanganyika rift basin (Figs 1, 2) extends over 650 km, from the Kivu-Rusizi volcanic province in the north to the Mpulungu basin in the south. It has a width of up to 70 km. The surface of the lake is

773 m above the sea level. The rift shoulders reach elevations of 2000 m above lake level and the maximum lake depth is 1470 m. The Tanganyika rift basin is filled with an estimated 4000 to 5000 m of sediments. The vertical offset between the peneplain at the top of the rift shoulders and the base of the sediments in the rift is thus 7400-8500 m. The Lake Tanganyika rift was activated during the late Miocene-Pliocene. COHEN *et al.* (1993) suggested that the central basin started to subside between 9 and 12 Ma, the northern basin between 7 and 8 Ma and the southern one, between 2 and 4 Ma. Lake Tanganyika is drained by the Lukuga River to the Congo basin and the Atlantic Ocean (Fig. 2).

The geometry of the Tanganyika basin was defined by the PROBE multichannel reflection-seismic profiles (SANDER & ROSENDAHL, 1989; ROSENDAHL *et al.*, 1992). They showed that it can be sub-divided into half-graben units, 80-160 km long and 30-60 km wide (Fig. 2), delimited by major extensional border fault systems that are curved in map view. The individual half-graben units are separated from each other by accommodation zones, in which oblique-slip or strike-slip faulting dominates. A reconstruction of the tectonic and stratigraphic history of the lake shows that during rifting significant changes occurred in the location of depocentre. During the initial rifting stage the central basin developed along a pre-existing fracture system that strikes oblique to the general lake axis. Subsequently, isolated basins developed to the north and south of the central basin. Later, these coalesced to the present configuration of the Tanganyika rift basin.

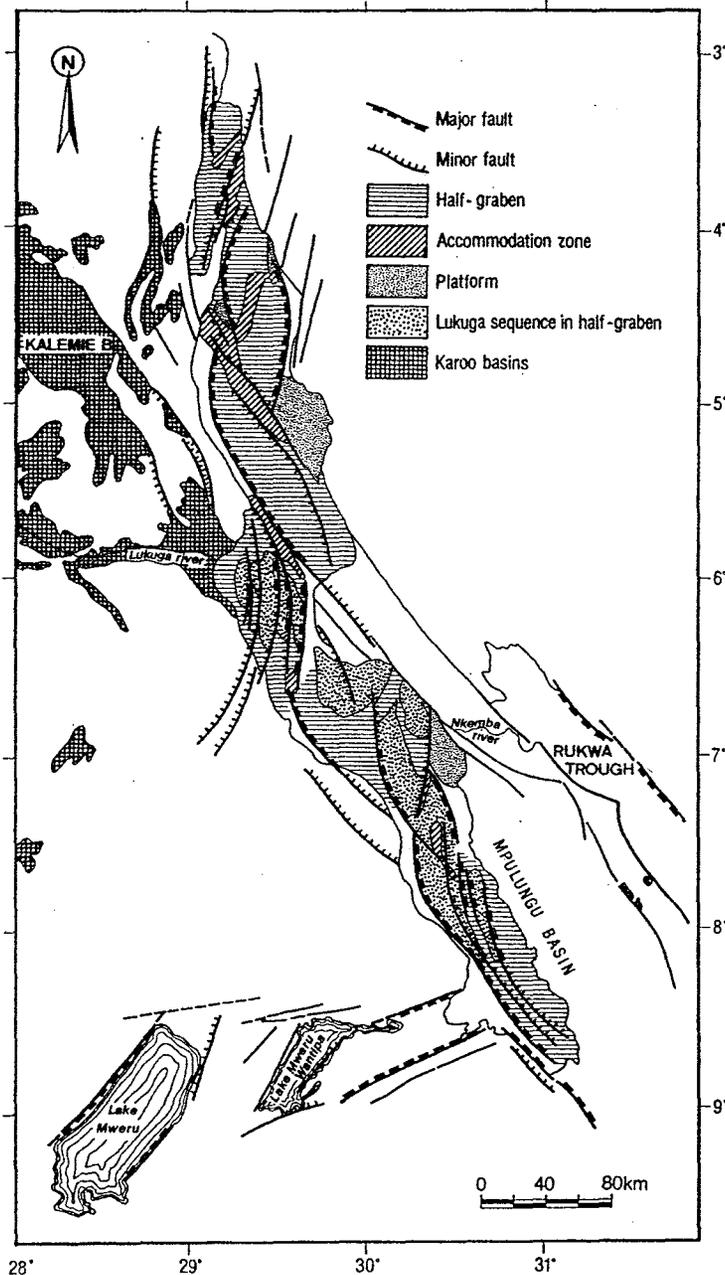


FIG. 2.— General structure of the Tanganyika rift, based on SANDER & ROSENDAHL (1989), compiled by DELVAUX (1991).

FIG. 2.— Structure générale du rift de Tanganyika, basé sur SANDER & ROSENDAHL (1989), compilé par DELVAUX (1991).

MALAWI BASIN

The Malawi rift basin (Figs 1, 3) extends southwards from the Kyela Plain, at the foot of the Rungwe volcanic field, over a distance of 750 km, to Lake Malombe. Much of the rift valley floor is occupied by Lake Malawi that is 570 km long and on average 60 km wide (Fig. 3). The surface of the lake is located at 474 m above sea level and its floor descends to 225 m below the sea level. Maximum depth is close to 700 m and the rift flanks rise to 400-2000 m above the surface of the lake. To the south, the Malawi depression is drained by the Shire River, which flows south to the Indian Ocean, through the Urema graben (Fig. 1).

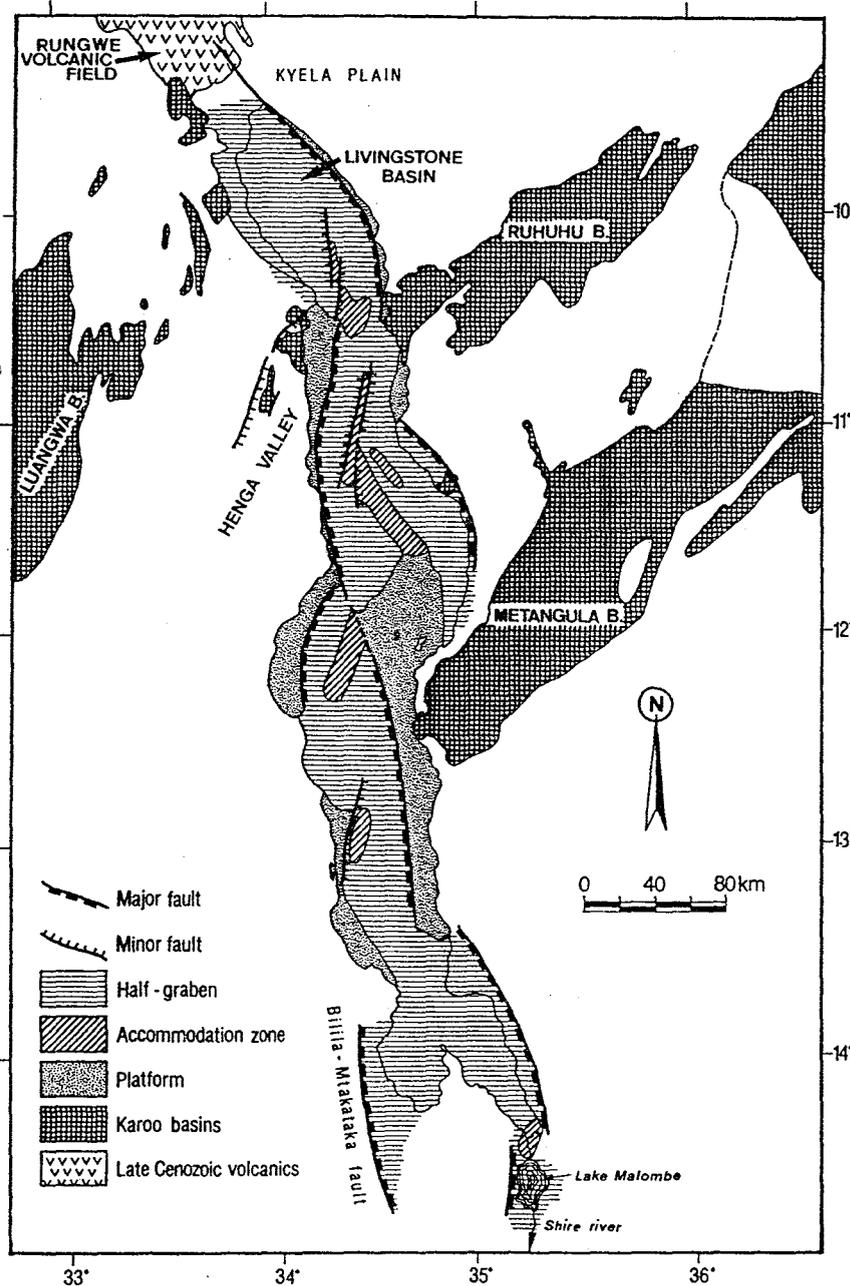


FIG. 3.— General structure of the Malawi rift, based on SPECHT & ROSENDAHL (1989), compiled by DELVAUX (1991).

FIG. 3.— Structure générale du rift de Malawi, basé sur SPECHT & ROSENDAHL (1989), compilé par DELVAUX (1991).

The Malawi rift is thought to have developed during the late Miocene-Quaternary (EBINGER *et al.*, 1989). Similar to the Tanganyika basin, the Malawi basin is also characterized by alternating half-grabens with opposing polarity, that are linked by underwater accommodation zones (SPECHT & ROSENDAHL, 1989; ROSENDAHL *et al.*, 1992).

RUKWA BASIN

The NW-trending Rukwa rift basin (Figs 1, 4) is 360 km long and 40-60 km wide. It is occupied in its south-eastern part by a wide but shallow lake, whose water level presently lies at an average elevation of 802 m. The lake level and the surface area occupied by water change rapidly as a function of climatic fluctuations. The lake, which now covers about half of the depression, was almost dry during the preceding century, and used to occupy almost the whole basin during the early Holocene (KENNERLEY, 1962).

The Rukwa rift basin developed during the Phanerozoic within the NW-SE trending Palaeoproterozoic Ubende belt, by reactivation of mainly Neoproterozoic sinistral shear zones that display the same trend (THEUNISSEN *et al.*, 1992; LENOIR *et al.*, 1994; THEUNISSEN *et al.*, 1996). The NW-trending Rukwa depression is bordered to the northeast by the Lupa fault and the Tanzanian craton and to the southwest, by the Ufipa fault and the uplifted Ufipa block (Fig. 4). The stratigraphy and structure of the Rukwa depression is relatively well known (WESCOTT *et al.*, 1991; MORLEY *et al.*, 1992b; KILEMBE & ROSENDAHL, 1992). In its northern half, the Precambrian basement is located at a depth of 4000 m, whereas in its southern half, it descends to 11000 m (PEIRCE & LIPKOV, 1988; MORLEY *et al.*, 1992b). The northern part of the Rukwa basin has the configuration of a symmetric graben (ROSENDAHL *et al.*, 1992). Southwards, this graben splits up into two opposing half-grabens in which sedimentary layers diverge towards the border faults. At the southeast extremity of the depression, the two half-grabens are progressively separated from each other by the Mbozi plateau (Fig. 4). The eastern branch (Songwe valley depression) is connected to the northern end of the Malawi rift basin (Livingstone or Karonga basin) and to the transverse Usangu depression. This triple-junction is occupied by the Rungwe volcanic field. The western branch (Msangano depression) dies out to the southeast.

Within the Rukwa basin, the earliest Phanerozoic sediments consist of deposits of the Late Carboniferous to Early Jurassic Karoo supergroup, up to 3-3.5 km thick (MORLEY *et al.*, 1992a). The next sedimentary unit is the fluvial Red Sandstone Group, the age of which is controversial and could be either Late Jurassic/Early Cretaceous or Eocene to middle Miocene (DYPVIK *et al.*, 1990; WESCOTT *et al.*, 1991; KILEMBE & ROSENDAHL, 1992; MBEDE, 1993; DAMBLON *et al.*, 1998). A shallow lacustrine to fluvial environment was established, during the deposition of the Pliocene-early Pleistocene Older Lake Beds and late Pleistocene-Holocene Younger Lake Beds (QUENNELL *et al.*, 1956).

USANGU DEPRESSION

The NE-SW striking Usangu depression formed orthogonal to the TRM trend. It joins the Rukwa-Malawi accommodation zone in the Rungwe volcanic field, thus forming a triple junction (Fig. 4). Reconnaissance reflection-seismic data (STONE *et al.*, in press) and geological investigations (EBINGER *et al.*, 1989) suggest that the Usangu depression is filled by no more than 1200 m of sediments, that are probably Plio-Pleistocene in age. Subsidence seems to have been mainly controlled by normal faulting along the Usangu border fault, forming the northern margin of the depression. The relatively high degradation of this fault scarp, and the occurrence of Late Quaternary sediments that seal the fault trace, show the fault was inactive during Late Quaternary times.

LATE PALAEOZOIC–EARLY TRIASSIC KAROO RIFTING STAGE

During the Late Carboniferous to Early Triassic times, the area of the EARS was transected by the so-called Karoo rifts. These form a series of basins along two orthogonal trends, that are characterized by different histories (Figs 1, 4).

NW-TRENDING LATE CARBONIFEROUS–PERMIAN BASINS

Along the NW-trending Ubende belt (TRM zone), Karoo basins contain Late Carboniferous to Late Permian sediments, but they lack Triassic sediments (DYPVICK *et al.*, 1990). Sedimentation was probably controlled by transpressional reactivation of the Ubende fabric (MBEDE, 1993; THEUNISSEN *et al.*, 1996; KLERKX *et al.*, 1998). Karoo sediments are present in the Kalemie graben (FOURMARIER, 1914; LEPERSONNE, 1977; CAHEN & LEPERSONNE, 1978), in the northwestern prolongation of the southern half of the Tanganyika basin (Figs 1, 2). They are suspected also to correspond to the lowermost seismostratigraphic unit in the southern half of the Tanganyika basin (SANDER & ROSENDAHL, 1989). Up to 3.5 km of Karoo sediments are present the Rukwa depression, where they have been drilled (WESCOTT *et al.*, 1991; MORLEY *et al.*, 1992b). Several large outcrops of Karoo series occur in the accommodation zone between the Rukwa and Malawi rift basins (Fig. 4).

Deposition of Karoo sediments along the TRM zone ended during the Late Permian due to N-S compression causing right-lateral transpressional deformation along the Ubende trend, involving Karoo sediments (DELVAUX *et al.*, 1998). Important deformation of the Permian sediments of the Lukuga region along the Congo side of Lake Tanganyika (Fig. 2), occurred at the transition from the Permian to the Triassic (CAHEN & LEPERSONNE, 1978). In the Congo basin itself, DALY *et al.* (1991) evidenced compressional flower structures from oil exploration data (Fig. 5). This N-S compression was coeval with the latest Permian–Early Triassic development of the Cape fold belt of South Africa (Fig. 5; HALBICH *et al.*, 1983). This belt forms part of the accretion type orogen that fringed the southern margin of Gondwana during Late Carboniferous to Mid-Triassic times, and that was associated with the Palaeo-Pacific subduction plate dipping beneath Gondwana (ZIEGLER, 1993; VISSER & PRAEKELT, 1996).

NE-TRENDING LATE CARBONIFEROUS–TRIASSIC BASINS

Another set of basins, that developed along a NE-trend, includes the Luangwa basin in Zambia (UTTING, 1976; NYAMBE & UTTING, 1997), the Ruhuhu and Metangula basins on the eastern side of the Lake Malawi (WÖPFNER & KAAYA, 1992; VERNIERS *et al.*, 1989), the Kilombero and Selous basins in east Tanzania (WÖPFNER & KAAYA, 1991; NILSEN *et al.*, 1999) and the Tanga basin in east Kenya (Figs 1, 5). These extensional to transtensional basins contain a more complete stratigraphic succession, ranging from Late Carboniferous to Middle Triassic (or even Early Jurassic in the Luangwa and the Metangula basins).

This basin system extends northeastwards up to the African coast. It formed an integral part of the east Africa–Malagasy Karoo rift system that reached the Neo-Tethys margin of the Gondwana continent (Fig. 5). Through this rift system, the Tethys Sea advanced southward to form the “Malagasy Gulf” (WÖPFNER & KAAYA, 1991; WÖPFNER, 1994; VISSER & PRAEKELT, 1996). This is confirmed by a short-lived uppermost Permian marine incursion in the Mikumi basin of east Tanzania, that is characterized by marine invertebrate fauna with Tethyan affinity (KREUSER, 1983, 1984), and also by the presence of Late Triassic–Early Jurassic evaporites in the Manadawa hole, in southern coastal Tanzania (Fig. 1; KAGYA, 1996).

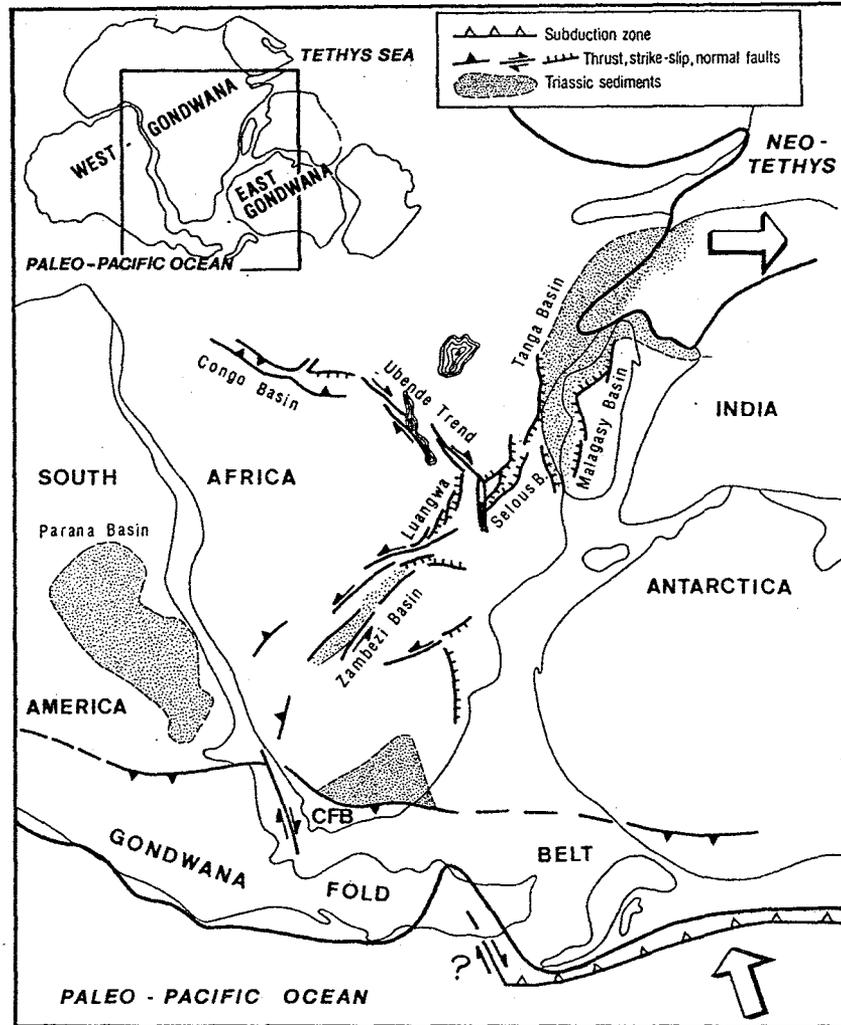


FIG. 5.— Palaeotectonic map for the Permo-Triassic transition in the African sector of Gondwana. Compilation after DALY *et al.* (1991) and VISSER & PRAEKELT (1996). CFB: Cape fold belt in South Africa.

FIG. 5.— Carte paléotectonique de la transition permo-triassique dans le secteur africain du Gondwana. Compilation d'après DALY *et al.* (1991) et VISSER & PRAEKELT (1996). CFB: Cape fold belt en Afrique du Sud.

TRIASSIC–EARLY JURASSIC REGIONAL UPLIFT

End Permian termination of Karoo sedimentation along the Ubende trend was also the consequence of regional uplift (Fig. 6). A Triassic–Early Jurassic regional cooling and denudation event was inferred from AFT thermochronology by MBEDE (1993) and VAN DER BEEK *et al.* (1998). This corresponds to a widely recognized major erosional event, expressed partly in the “Gondwana surface” (WÖPFNER, 1993). In the Ruhuhu basin, sedimentation continued during the Triassic, after an important unconformity at the Permo-Triassic boundary (WÖPFNER & KAAYA, 1992). At the junction between the Zambezi and Luangwa rifts in Zambia (Fig. 1), Early Triassic to Late Cretaceous extensional tectonics are recognized (OESTERLEN & BLENKINSHOP, 1994). The Metangula basin of north Mozambique (Fig. 1) evolved into a typical extensional graben after the Permo-Triassic transition, that probably remained active until Early Jurassic times (VERNIERS *et al.*, 1989). In coastal Tanzania, sedimentation continued during the Triassic with Karoo rifting activity ending during the Early Jurassic (e.g., KAGYA, 1996). Triassic–Early Jurassic Karoo rifting and Gondwana regional uplift was paralleled by intensified

rifting activity along the future zone of crustal failure between western and eastern Gondwana (FOSTER & GLEADOW, 1993). Moreover, it appears to be related to N-S compression and the evolution of the Gondwana orogen of South America and South Africa (Fig. 5).

MESOZOIC AND EARLY CAINOZOIC STAGES

During Late Jurassic and Cretaceous times, a second phase of cooling and denudation of more local importance occurred in the TRM zone (Fig. 6); it was accompanied by carbonatitic volcanism and possibly a resumption of sedimentation in the Karoo grabens (MBEDE, 1993; VAN DER BEEK *et al.*, 1998). The accumulation of the Red Sandstone Group, occurring in the Rukwa depression, has long been considered to be associated with this stage. The age of the Red Sandstone Group, originally attributed to Late Jurassic–Cretaceous, is however still controversial (e.g., DYPVIK *et al.*, 1990; WESCOTT *et al.*, 1991). The discovery of a fossil wood specimen in the Red Sandstone Group at Songwe-Kiwira, north of Lake Malawi, identified as *Pahudioxylon* (CHOWDHURY *et al.*, 1960), suggests, however, that it might be of Tertiary age (DAMBLON *et al.*, 1998). Therefore it is postulated that an Early Tertiary rifting phase affected the north Malawi–Rukwa rift segment, coeval with a cooling stage evidenced by AFT data (Fig. 6). Nevertheless, Mesozoic tectonic activity in the TRM zone cannot be ruled out, as shown by volcanic activity, the Late Jurassic–Cretaceous cooling stage, and by the presence of the Cretaceous dinosaur beds in North Malawi (DIXEY, 1928; JACOBS *et al.*, 1990).

Definition of an Early Tertiary rifting stage in the TRM zone depends on the stratigraphic position of the Red Sandstone Group. The most likely age for the fossil wood specimen in the Red Sandstone Group is Eocene–Miocene (DAMBLON *et al.*, 1998). More than 900 m of the Red Sandstone Group were drilled in the Rukwa basin (WESCOTT *et al.*, 1991; MORLEY *et al.*, 1992b), and several outcrops are present along the Rukwa–Malawi accommodation zone, unconformably overlying Karoo series. The Red Sandstone Group was apparently deposited during a phase of pure extensional faulting, with a horizontal principal extension directed NE–SW, orthogonal to the TRM rift axis (DELVAUX *et al.*, 1992; DAMBLON *et al.*, 1998). The cooling history, inferred from AFT thermochronology of a total of 2.7–3.8 km, suggests that of Cainozoic denudation, 1 km occurred in pre-middle Miocene times (VAN DER BEEK *et al.*, 1998). No Early Tertiary volcanism is known in the Rungwe volcanic field (HARKIN, 1960).

The presence of an Early Tertiary rifting stage in the western branch of the EARS is not an isolated feature in east Africa. Eocene rifting has been documented in the Sudan basin (BOSWORTH, 1992), and late Oligocene rifting in the Turkana basin, of the northern Kenya rift (Fig. 1; MORLEY *et al.*, 1992a). Moreover, Early Tertiary extension occurred also in the Anza rift of eastern Kenya (Fig. 1; BOSWORTH & MORLEY, 1994).

LATE CAINOZOIC RIFTING STAGE

The Late Cainozoic rifting cycle consists of two first-order phases that are separated by an early Pleistocene period of tectonic quiescence (Fig. 6). Volcanism, coarse clastic sedimentation and lake development commenced during the late Miocene, 8–9 Ma ago (HARKIN, 1960; EBINGER *et al.*, 1989, 1993). The late Miocene–Pliocene deposits are described as the Older Lake Beds (HARKIN, 1960). This period is characterised by the predominance of normal faulting, under a semi-radial extensional stress regime (Fig. 7). It caused reactivation of the NW–SE trending south Rukwa–north Malawi basins, their rapid subsidence, and the development of the NE–SW trending Usangu basin (DELVAUX *et al.*, 1992; RING *et al.*, 1992). The Rungwe volcanic field became active, at the intersection of these two rift trends.

Between 2 and 1 Ma, a tectonically quiet period occurred during which the Late Tertiary erosional and weathering surface formed (Fig. 6). During the middle Pleistocene, at about 1 Ma, a new first-order stress regime was initiated, that was dominated by N–S directed horizontal principal compression, causing dominantly strike-slip deformations (Fig. 8). This induced a major change in the kinematics of faulting and triggered a new volcanic pulse that was associated with a domal uplift centered on the Rungwe and Ngozi volcanoes (DELVAUX *et al.*, 1992; RING *et al.*, 1992; DELVAUX & HANON, 1993).

Tanganyika - Rukwa - Malawi rift zone

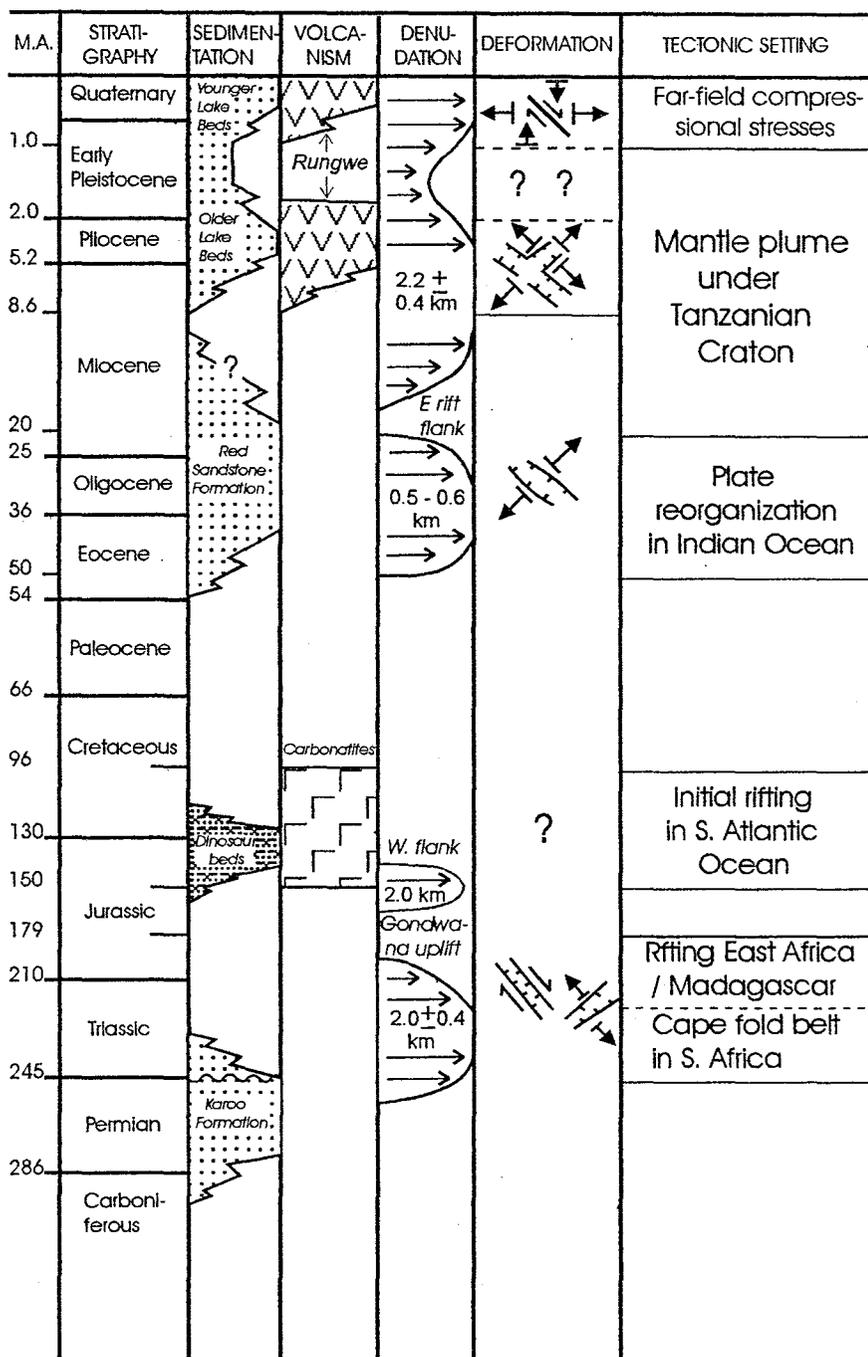


FIG. 6.— Correlation of the Late Carboniferous–Quaternary tectonic events in east Africa, in relation to the African plate setting. Amount of uplift and denudation ages from VAN DER BEEK *et al.* (1998). The Triassic–Early Jurassic regional cooling and denudation event corresponds to the Gondwana Regional Uplift which marks the termination of sedimentation in the NW-trending Karoo basins along the TRM rift zone. The Late Jurassic–Early Cretaceous, Early Tertiary and Late Cainozoic denudation events are more restricted to the rift shoulders. They reflect rift flank uplift during stages of rapid basin subsidence.

FIG. 6.— Corrélation des événements tectoniques du Carbonifère supérieur au Quaternaire en Afrique de l'est, en relation avec le contexte tectonique africain. Les valeurs et les âges des épisodes de soulèvement et dénudation sont tirés de VAN DER BEEK *et al.* (1998). L'événement régional de refroidissement et de dénudation du Trias-Jurassique inférieur correspond au soulèvement régional du Gondwana, qui marque la fin de la sédimentation dans les bassins Karoo d'orientation NW-SE dans la zone TRM. Les phases de dénudation du Jurassique supérieur–Crétacé inférieur, Tertiaire inférieur et Cénozoïque tardif sont restreintes aux épaules de rift. Elles reflètent le soulèvement des épaules de rift durant les phases de subsidence rapide des bassins.

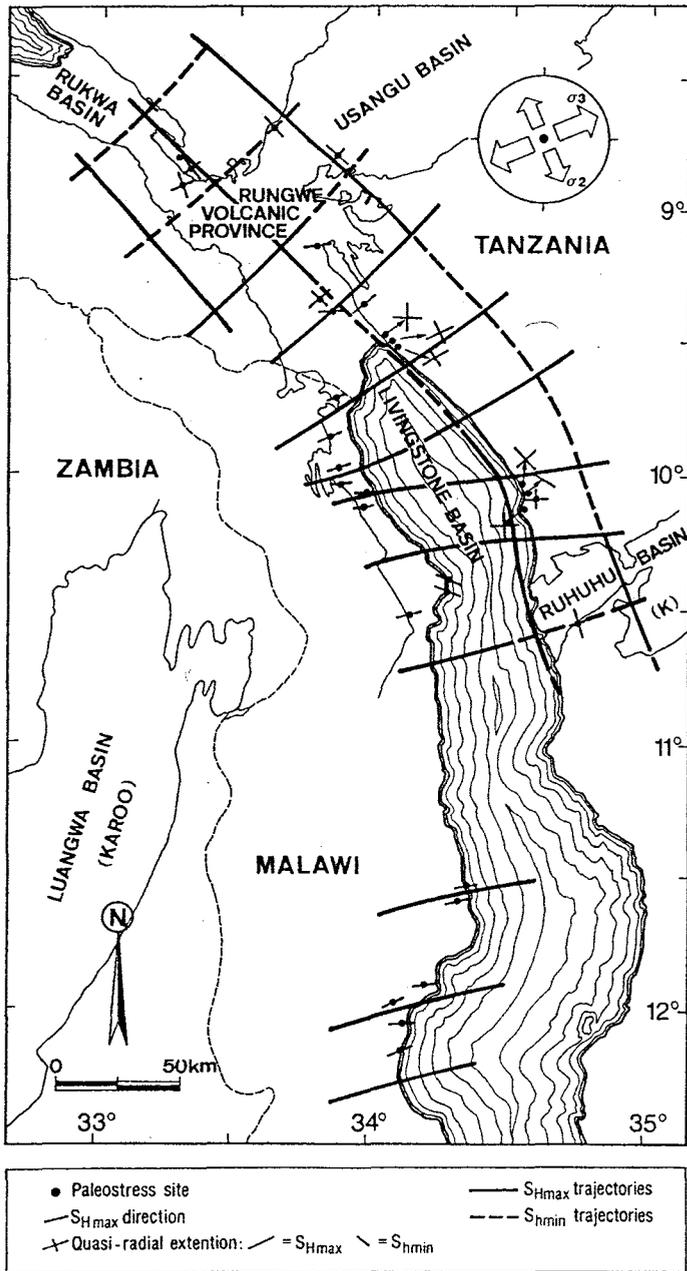


FIG. 7.— Late Miocene–Pliocene horizontal principal stress trajectories in the Rukwa–Malawi accommodation zone. Small bars: S_{Hmin} directions; crosses: radial extension; full lines: S_{Hmin} trajectories; dashed lines: S_{Hmax} trajectories. For close to radial extension, S_{Hmin} and S_{Hmax} axes cannot be differentiated. Compiled from DELVAUX *et al.* (1992) and RING *et al.* (1992). Adapted from DELVAUX (1993).

FIG. 7.— Trajectoire des contraintes horizontales principales pendant le Miocène tardif–Pliocène dans la zone relais Rukwa–Malawi. Petites barres : directions S_{Hmin} ; croix : extension radiale ; lignes continues : trajectoires de S_{Hmin} ; lignes discontinues : trajectoires de S_{Hmax} . Pour une extension de type radial, les axes S_{Hmin} et S_{Hmax} ne peuvent être différenciés. Compilé d'après DELVAUX *et al.* (1992) et RING *et al.* (1992). Adapté de DELVAUX (1993).

The recent volcanic centers are directly controlled by strike-slip faults. Sediments of middle Pleistocene–Holocene age are currently referred to as the Younger Lake Beds (HARKIN, 1960).

Between the middle and late Pleistocene, the direction of horizontal principal compression rotated to a NE–SW direction (Fig. 9). Since then, the Late Quaternary deformation in the Rukwa rift is partitioned between along-trend dextral strike-slip movement in the rift valley and normal faulting on the rift shoulders (VITTORI *et al.*, 1997; DELVAUX *et al.*, 1998). This Quaternary stress evolution is very similar and coeval with the one observed in the Kenya rift (STRECKER *et al.*, 1990). The present-day minimum horizontal stress trajectories in east Africa were also concentric around the Afar depression (Fig. 10). On the same figure, we added the stress tensors inverted from a series of earthquake focal mechanisms, compiled from DOSER & YARWOOD (1991), DZIEWONSKI *et al.* (1991a, b), KEBEDE & KULHANEK (1991), GAULON *et al.* (1992), GIARDINI & BERANZOLI (1992), JACKSON & BLENKINSHOP (1993) and

SENO & SAITO (1994). The orientations of the horizontal principal stress axes obtained for the different sectors are in general agreement with the horizontal stress trajectories (Fig. 10). This shows that the southern part of the EARS is currently submitted to stresses that are related to the Red Sea–Gulf of Aden spreading centres, as suggested by BOSWORTH *et al.* (1992).

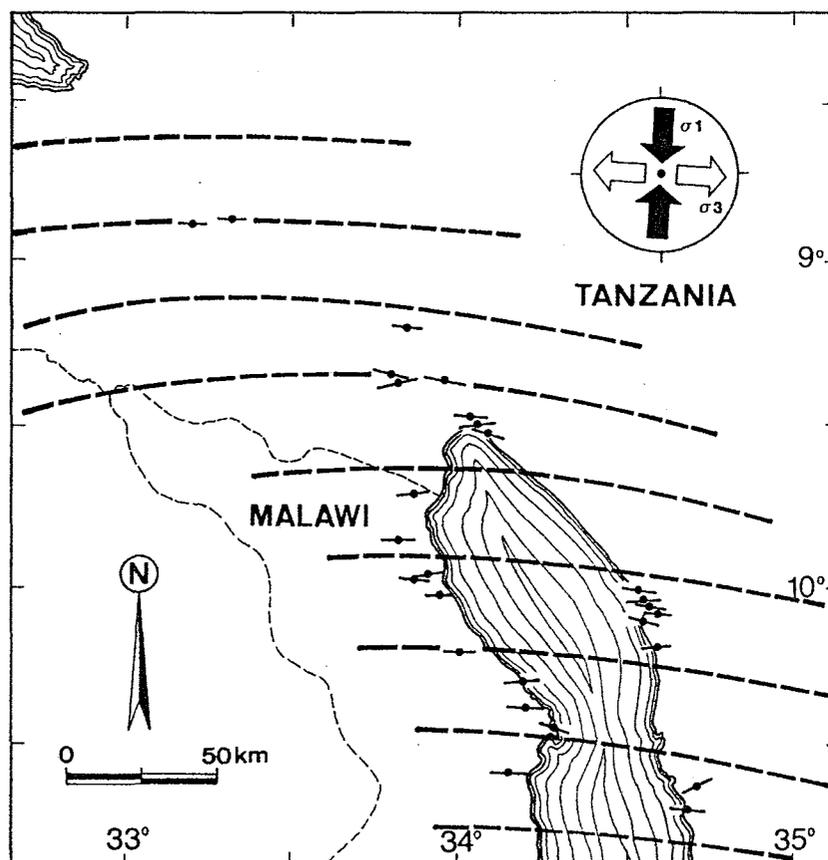


FIG. 8.— Middle Pleistocene horizontal principal stress trajectories in the Rukwa-Malawi accommodation zone. Legend as in figure 7.

FIG. 8.— Trajectoire des contraintes horizontales principales pendant le Pléistocène moyen dans la zone relais Rukwa-Malawi. Légende comme sur la figure 7.

NEOTECTONIC ACTIVITY

The entire western branch of the EARS is characterized by relatively high level of seismic activity (SIMIYU & KELLER, 1997). In the Mbeya area, at the junction between the Rukwa and Malawi rifts, seismic activity has been recorded by a local network of seismometers (Fig. 4).

During the Late Quaternary, both the Lupa and Ufipa fault scarps (Fig. 4) appear to have been weakly active. Geomorphology, air photographs and field work have failed to provide evidence of movements during the Late Quaternary (DELVAUX *et al.*, 1998). However, an axial zone of active deformation along the Galula-Mbaka-Kyela fault system is observed at the southern end of the Rukwa basin, in the Rungwe volcanic area and at the northern end of the Malawi basin (Fig. 4). In the Mbeya and Galula areas, this fault system corresponds to right-lateral NW-trending strike-slip faults, disrupting the Quaternary Lake Beds in the prolongation of the Mbeya range fault (DELVAUX *et al.*, 1998). In the floor of the Rukwa depression, high-resolution seismics (CERAMICOLA *et al.*, 1996) demonstrate that several faults offset the uppermost reflectors. Reflection seismic data and drilling (MORLEY *et al.*, 1992b) show that this surficial fault system coincides with a deeper fault that affects all the stratigraphic sequence of the Rukwa basin. The entire system might form a flower system, accommodating strike-slip deformation (WHEELER & KARSON, 1994). To the southeast, this fault zone extends into the northern part of the Lake Malawi depression (Fig. 4), where it is underlined by Late Quaternary volcanic centres, hydrothermal springs and earthquake epicentres (DELVAUX *et al.*, 1993).

Late Quaternary faulting seems also to affect both the Mbozi and Lupa blocks. Faults associated with the Lupa block extend into the Usangu depression, and displace the older Usangu border fault. Finally, a series of NE-trending sinistral strike-slip faults transect the floor of the Usangu depression near the junction with the Rungwe volcanic area. These faults clearly controlled the location of Late Quaternary phonolitic eruptive centers (DELVAUX & HANON, 1993).

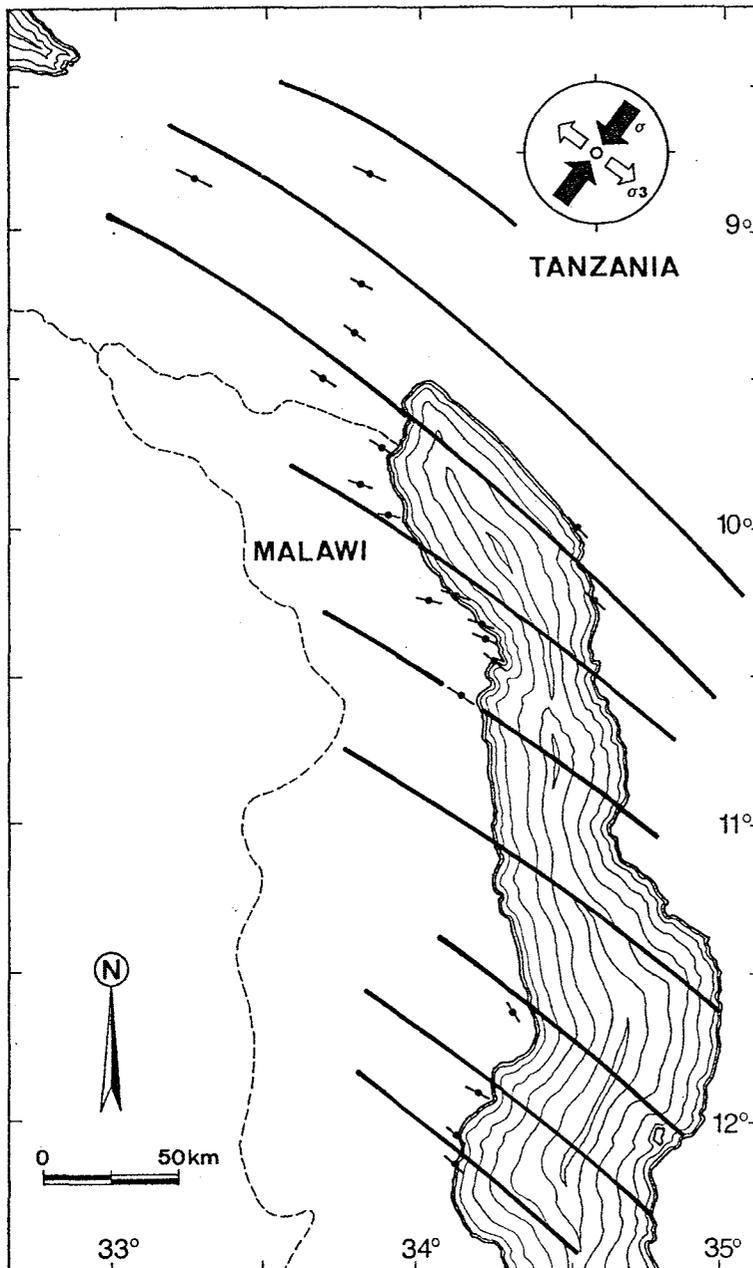


FIG. 9.— Late Pleistocene-Holocene horizontal principal stress trajectories in the Rukwa-Malawi accommodation zone. Legend as in figure 7.

FIG. 9.— Trajectoire des contraintes horizontales principales pendant le Pléistocène supérieur-Holocène dans la zone relais Rukwa-Malawi. Légende comme sur la figure 7.

On the Ufipa plateau rift shoulder (Fig. 4), the Kanda fault, together with the Mkunda and Mwimbi faults, form an active normal fault system (VITTORI *et al.*, 1997). Movement along the Kanda fault may have caused the M 7.4 Rukwa earthquake of 13th December 1910 (AMBRASEYS, 1991). Also on the northeast side of the Rukwa basin, the northern part of the Lupa fault is active, as indicated by the 18th August 1994 M 5.9 earthquake (Fig. 4), that displayed a typical normal faulting mechanism, with T axis orthogonal to the rift trend (CMT Harvard Solution). In southern Malawi, the 100 km long normal Bilila-Mtakataka fault borders the Malawi rift basin to the west (Fig. 3; JACKSON & BLENKINSHOP, 1997). Along this fault, a M 6.1 earthquake occurred on March 10th, 1989 with a focal depth of 32 ± 5 km and with a typical normal faulting mechanism (JACKSON & BLENKINSHOP, 1993).

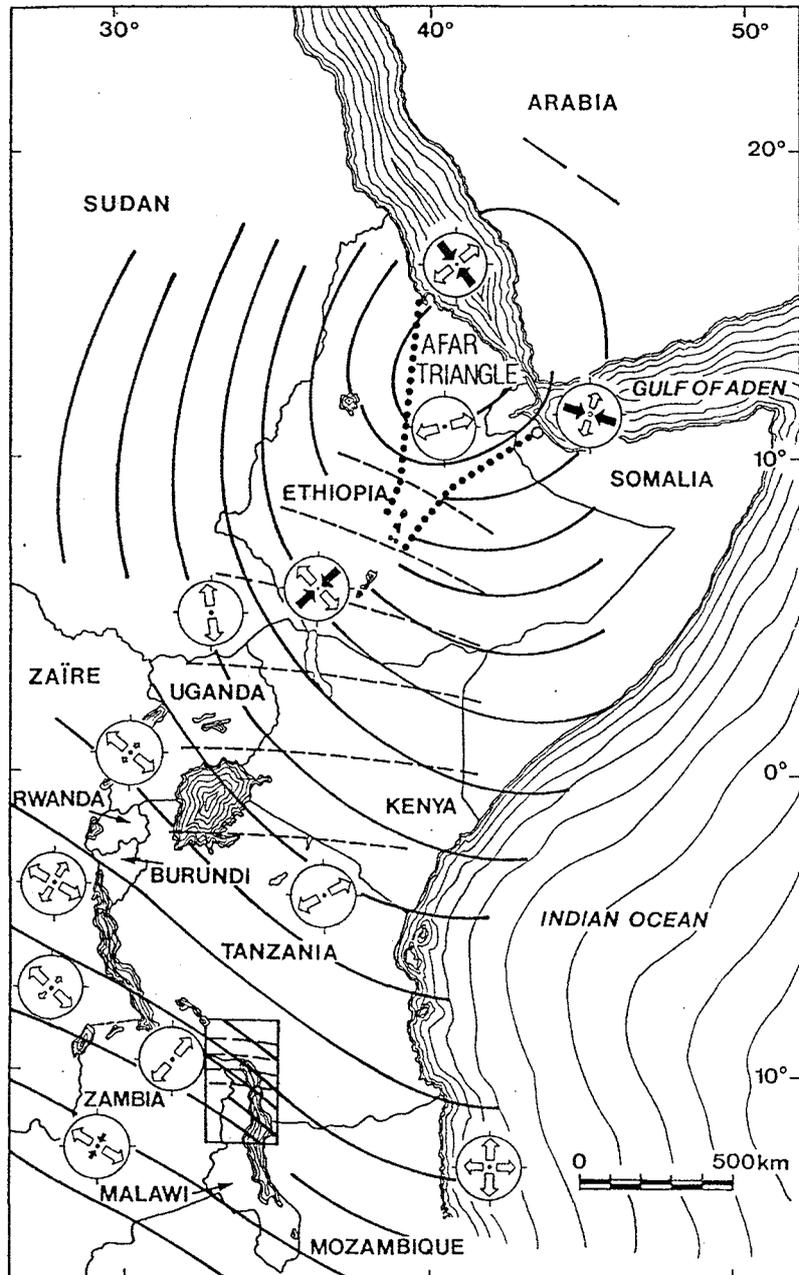
Consequently, the recent deformation of the TRM zone is characterized by a combination of strike-slip faulting in the valley floor of the Rungwe accommodation zone (Galula-Mbaka-Kyela fault system), and normal faulting along the main rift border faults, away from this accommodation zone. This suggests a mechanism of fault movement partitioning between rift-normal extension and rift-parallel dextral strike-slip. It is not clear whether this might be a manifestation of the combined effect of different sources of stress: far-field compressional stresses, concentrated in the accommodation zone, and locally generated extensional stresses, related to gravitational instabilities in the crust under the rift zone.

Late Quaternary vertical movements are also an important manifestation of the recent tectonic activity of this region. Detailed investigation on the lake floor morphology and of

palaeolacustrine terraces and fossil beaches demonstrate that both the floor of the north Malawi and the south Rukwa depressions are currently being tilted to the northwest (DELVAUX *et al.*, 1993, 1998). In addition to this tilting movement, a regional doming of the area, centered on the Rungwe and Ngozi volcanoes (Fig. 4) is also associated with the Late Quaternary activity of the Rungwe volcanic centre.

FIG. 10.— Comparison of middle Pleistocene (dashed lines) and late Pleistocene–Holocene (full lines) trajectories of horizontal principal extension (S_{hmin}) in east Africa. Compiled from STRECKER *et al.* (1990), BOSWORTH *et al.* (1992), DELVAUX *et al.* (1992) and RING *et al.* (1992). Stress tensors inverted from focal mechanisms for different sectors (compiled from DOSER & YARWOOD, 1991; DZIEWONSKI *et al.*, 1991a, b; KEBEDE & KULHANEK, 1991; GAULON *et al.*, 1992; GIARDINI & BERANZOLI, 1992; JACKSON & BLENKINSHOP, 1993 and SENO & SAITO, 1994). Legend as in figure 7.

FIG. 10.— Comparaison entre les trajectoires de contrainte horizontale minimale (S_{hmin}) en Afrique de l'est, pour le Pléistocène moyen (lignes discontinues) et le Pléistocène supérieur–Holocène (lignes continues) Compilé d'après STRECKER *et al.* (1990), BOSWORTH *et al.* (1992), DELVAUX *et al.* (1992) et RING *et al.* (1992). Tenseurs de contrainte inversés pour les mécanismes au foyer dans différents secteurs (compilé de DOSER & YARWOOD, 1991; DZIEWONSKI *et al.*, 1991a, b; KEBEDE & KULHANEK, 1991; GAULON *et al.*, 1992; GIARDINI & BERANZOLI, 1992; JACKSON & BLENKINSHOP, 1993 et SENO & SAITO, 1994). Légende comme sur la figure 7.



DEEP RIFT STRUCTURE

High quality earthquake data were collected by the Mbeya seismic network with five three-component digital seismic stations during 30 months of operation (CAMELBECK & IRANGA, 1996). Results indicate that the seismic activity in the area between lakes Malawi and Rukwa occurs over a

depth range of 6 to 34 km under the rift, with the peak of seismic activity at 12-14 km. The crustal thickness is estimated to be of the order of 42 ± 5 km. Along the eastern border of south Rukwa basin, the earthquake distribution is concentrated along a narrow, 70° SW-dipping zone that corresponds at the surface to a series of currently active faults. The distribution of microseismic epicenters suggests the presence of a seismic surface between 10 and 28 km. The upward projection of this surface coincides with the geometry of the Lupa fault zone which was traced down to 7-8 km on industrial reflection seismic profiles (MORLEY *et al.*, 1992b). Further south, JACKSON & BLENKINSHOP (1993) showed that the "Malawi March 10th, 1989 earthquake", with a focal depth of 32 ± 5 km, is probably related to slip along the deep part of a major normal fault zone bounding the Malawi rift basin. However, they could not determine whether this postulated fault zone forms a continuous seismogenic surface that extends to upper crustal levels.

VAN DER BEEK *et al.* (1998) applied a detachment model in order to model rift fault uplift and erosion; of the Livingstone basin, at the northern end of Lake Malawi. They showed that the best fit for the depth to basement under the Livingstone basin is obtained with a detachment depth of 30 km, and 7.2 km extension on the Livingstone fault. When erosion of the rift flanks is incorporated, the additional isostatic rebound provides a much better fit to the observed topography, assuming an elastic thickness T_e values of 20-30 km. In this model, extension is accommodated by the Livingstone fault, which is inferred to be listric at depth. The best-fit 30 km detachment depth is close to the lower limit of seismic activity observed by the Mbeya seismic network (CAMELBEECK & IRANGA, 1996), and the depth of the 10th March 1989 earthquake in the central part of the Malawi rift (JACKSON & BLENKINSHOP, 1993).

A present-day geothermal gradient of the order of $40^\circ\text{C}/\text{km}$ was calculated by MBEDE (1993) for the Rukwa rift on the basis of well data. VAN DER BEEK *et al.* (1998) considered that a mean $25\text{-}30^\circ\text{C}/\text{km}$ is reasonable for the entire Malawi-Rukwa rift region. The occurrence of deep crustal earthquakes and the relatively low T_e values point to a rather cold and strong crust under the Malawi-Rukwa rift, despite the presence of the Rungwe volcanic field.

TECTONICS AND LAKE LEVEL FLUCTUATION

Lakes Tanganyika and Malawi are long-lived deep water lakes. They resulted from very fast subsidence of the rift valley floor, which is not yet compensated by sediment infilling. The Rukwa basin is a shallow topographic depression that is almost filled with sediments, and that contains an episodic lake which fluctuates in response to climatic factors. The level of lakes Tanganyika and Malawi dropped considerably several times during their histories, but they have never dried out completely (OWEN *et al.*, 1990; LEZZAR *et al.*, 1996; COHEN *et al.*, in press).

These three rift basins are geologically unstable, their dynamic evolution being primarily controlled by tectonic movement causing the opening of rift valleys. These movements were concentrated along major border faults and were accompanied by the subsidence of the valley floors and uplift of the rift shoulders. The outlet of Lake Tanganyika, through which the lake overflows into the Lukuga River, crosses the rift shoulder (Fig. 2). A major consequence of this lateral outlet is that this lacustrine system is controlled by the progressive uplift of the rift shoulder and concomitant subsidence of the lake floor. This process is only partly compensated by erosion of the overflow sill, which tends to lower the lake level, and by sedimentation in the basin, which tends to decrease the water depth. In contrast, Lake Malawi is drained by the Sire River, which flows southwards through the rift valley axis (Fig. 3). In this case, the altitude of the outlet is controlled by the subsidence of the rift valley floor (e.g., DELVAUX, 1995).

A second factor controlling lacustrine evolution is the activity in the Kivu volcanic field, located north of Lake Tanganyika (Fig. 1) and in the Rungwe volcanic field, located between Lakes Rukwa and Malawi (Figs 1, 4), as well as by the associated regional doming that accompanies each renewal of volcanic activity. However, this influence is very slow and occurs at a geological time scale.

The third important factor controlling lake levels is obviously related to secular climatic changes. In general, climatic fluctuations are more rapid and intense than tectonic processes (COHEN *et al.*, in press). Lake Tanganyika is presently outflowing to the Lukuga River, and Lake Malawi to the Shire River, but during dryer climates, the lake levels dropped far below the level of these outflows. The Rukwa basin is

presently a closed depression, containing a shallow lake. The watershed between the Rukwa and Tanganyika drainage basins (980 m a.s.l.) is about 200 m above the present-day level of Lake Rukwa (802 m a.s.l.). During the last early Holocene climatic optimum, the level of Lake Rukwa had risen to the point that its waters flowed out across the watershed and were drained into Lake Tanganyika (762 m a.s.l.), at Karema via the Nkamba River (Figs 2, 4; DELVAUX *et al.*, 1998).

DISCUSSION

One of the main purposes of this review is to highlight the repeated reactivation of the Ubende belt structures. This is a good example of time and again reactivation of pre-existing basement discontinuities. It has been demonstrated that, following earlier rifting phases, as e.g., during the Karoo period, the stretched lithosphere is re-equilibrated and becomes rheologically stronger than the adjacent unstretched lithosphere. This increase in strength tends to lock the system and impedes further deformation of the basin (ZIEGLER *et al.*, 1995). This is particularly the case after prolonged (e.g., 100 Ma) phases of tectonic quiescence, allowing for cooling of the lithosphere and strengthening of the basin centre relative to its margins. Therefore, a mechanical weakening process is required to explain the timing and nature of repeated reactivation of many basin systems, particularly in the Ubende belt. ZIEGLER (1990) showed that localised deformation of a large number of intra-plate basins in Europe are probably controlled by lithospheric strength reduction due to the presence of pre-existing crustal, and possibly also mantle-lithospheric discontinuities (ZIEGLER *et al.*, 1995). These discontinuities permanently weaken the lithosphere and provide weakness zones that can be reactivated during the next tectonic stage, as long as the new stress tensor is adequate and has the suitable orientation relatively to the pre-existing discontinuity. In the Rukwa rift, some 200 Ma elapsed between the Karoo and the Early Tertiary rifting cycles. The Late Tertiary cycle followed after a much shorter (10-20 Ma ?) period of tectonic quiescence. It is therefore one of the few well documented examples of a rift that was tensionally reactivated after more than 100 Ma of tectonic quiescence since the preceding rift stage.

The Karoo rift systems of southeast Africa bear much similarities with the Alpine foreland of western Europe during the Early Tertiary. The evolution of the European Cainozoic rift system is broadly contemporaneous with the compressional intra-plate deformations of the north-western Alpine foreland. They result from a strong collisional coupling between the Afro-Arabian and European plates during their convergence, and the building-up of compressional stresses, transmitted from the Alpine collision front into the foreland (e.g., ZIEGLER *et al.*, 1995). In Africa, the formation of compressional structures in the Congo basin (DALY *et al.*, 1991), transtensional grabens along the NW-trending Ubende belt (TRM zone) and more extensional structures along a NE-trend (Fig. 1) are also broadly contemporaneous with the Late Carboniferous–Early Triassic subduction and terrane accretion along the Palaeo-Pacific margin of Gondwana (ZIEGLER, 1993; VISSER & PRAEKELT, 1996). Specifically, the latest Permian–Early Triassic compressional regime, that affected the southern half of Africa, is related to the development of the Cape fold belt (Fig. 5). The reason for a compressional stress built-up in the African part of Gondwana might be linked to the termination of the Palaeo-Pacific plate subduction beneath the south American sector of Gondwana, while it continued under the Antarctic sector (Fig. 5). The eastern and western sectors of the Palaeo-Pacific margin of Gondwana were probably separated by a transfer fault zone (Fig. 5) to accommodate differential movements which should have been dextral, and not sinistral as inferred by VISSER & PRAEKELT (1996). Therefore, intraplate compressional stresses probably built-up in response to collisional coupling, and were transmitted into the foreland, far away from the collisional zone. This confirms that compressional stresses, related to plate interaction, can be transmitted through continental lithosphere over long distances (e.g., CLOETINGH *et al.*, 1993).

As stated by ZEYEN *et al.* (1997), far field stresses, and the presence or absence of a mantle plume, are the main factors controlling the process of continental rifting after rift initiation. Far-field extension may induce continental break-up, while far-field compression can cause only a small amount of rift opening. In a cold and strong lithosphere, plume activity, by causing weakening of the lithosphere, contributes towards rifting. However, because cratonic lithosphere is too strong to break, a plume rising under a craton might expand laterally until it encounters a weaker zone. This mechanism is believed to have triggered rifting in east Africa, producing elongated and single rift systems with deep sedimentary basins along the western margin of the Tanzanian craton (ZEYEN *et al.*, 1997). Finite element analysis of

the stress state, resulting from variations in the gravitational potential energy of the lithosphere produced by lateral density variations in the African plate, was performed by COBLENTZ & SANDIFORD (1994). This modelling predicts large extensional stresses in the east African rift, in general agreement with the long-wavelength pattern of the observed stress field deduced from the World Stress Map (ZOBACK, 1992). Therefore, extensional stresses produced by density variations, caused by the rise of a mantle plume, can be an important factor for the dynamics of rifting, that is not related to far-field plate boundary forces. In the case of the TRM rift zone, the coincidence of both plume activity under the Tanzanian craton and far-field stresses seem to be the major driving mechanisms for Late Cainozoic rifting. For the earlier rifting stages, the influence far-field stresses seems a major controlling mechanism, as there is no evidence of a palaeo-mantle plumes.

During the Late Cainozoic rifting stage, the middle Pleistocene build-up of intraplate compressional stresses, as evidenced by DELVAUX *et al.* (1992, 1998) and RING *et al.* (1992), apparently interfered with the evolution of the rift system, as indicated by basin subsidence through normal faulting in the Mbeya triple junction. Along the NW-SE trend of the Ubende belt, this stress reorientation caused strike-slip reactivation of normal fault systems, narrowing the active deformation zone to the centre of the basin. Away from the Mbeya triple junction, the effect of the compressional stresses is less obvious, as normal faulting is still dominant. On the other hand, this stress change coincides with the termination of the Usangu basin, border faults of which were not suitably oriented to be reactivated. Instead, transpressional structures appear inside this basin. In addition, between the middle and late Pleistocene the direction of horizontal principal compression rotated clockwise by 45°. Similar changes in stress field with comparable timing have been observed in the Kenya rift (STRECKER *et al.*, 1990), the Ethiopian rift and in the Gulf of Aden-Red Sea (BOSWORTH *et al.*, 1992) up to the southern Gulf of Suez (BOSWORTH & TAVIANI, 1996). These changes appear to be related to a plate-scale phenomena, the potential cause for which is still unclear (BOSWORTH & TAVIANI, 1996; BOSWORTH & STRECKER, 1997). However, this points to the fact that compressional stresses propagate rapidly and over great distances in the African lithospheric crust, also during the Late Cainozoic.

CONCLUSION

The TRM segment of the EARS is a good example of a long-lived weakness zone that was repeatedly reactivated, even after long periods of tectonic quietness. It appears to be located on a pre-existing crustal-scale discontinuity, that caused a permanent strength reduction of the lithosphere. This zone is therefore very sensitive to the fluctuation of lithospheric stresses, both extensional and compressional, and this will be the preferred locus of deformation during each periods of stress build-up.

The TRM rift zone illustrates the dependence of continental rift dynamics on plate tectonic setting. The development of the NW-trending Karoo basins along the Ubende belt seems to be controlled by far-field compression related to orogenic activity in the Cape fold belt. Far-field extension related to the rifting between east Africa and Madagascar caused late Karoo extensional faulting along the NE-trending Karoo basins and a regional uplift, cooling and denudation event in the TRM area. Also, reactivation of the Ubende belt, accompanied by the deposition of the Red Sandstone Group of possible Eocene-middle Miocene age seems to be related to far-field extensional stresses during the coeval major plate boundary reorganization in the Indian Ocean (ZIEGLER *et al.*, 2001). Radial extensional stresses developed during the late Miocene-Pliocene at the intersection between of NW-trending Rukwa and north Malawi rift segments and the NE-trending Usangu basin. The Rungwe volcanic field developed in the centre of the triple junction. At a larger scale, extensional forces along the western branch of the EARS may be related to the ascent of a mantle plume under the Tanzanian craton. Far-field compressional stresses interfered during the Late Quaternary, with internally generated plume-related extensional stresses. This modified significantly the kinematics of rifting and triggered a new pulse of volcanic activity in the Rungwe field.

ACKNOWLEDGMENTS

This article is based on the work carried out in the framework of the CASIMIR project—Comparative Analysis of Sedimentary Infill In Rifts, initiated by J. KLERKX. Since this work is based on a long-term collaboration, other colleagues are also acknowledged for their collaboration, specially E. MBEDE, E. KILEMBE, T. CAMELBEECK, M. DE BATIST, P. VAN DER BEECK and K. THEUNISSEN. We thank particularly the leaders of the IGCP 369 projects, W. CAVAZZA, A.H.F. ROBERTSON & P.A. ZIEGLER for their efforts in preparing the Peri-Tethys Memoir. Critical review by B. BOSWORTH and A. KHAN and additional comments and suggestions by P.A. ZIEGLER, greatly improved the manuscript. This paper is a contribution of IGCP 400 project Geodynamics of Continental Rifting. D. DELVAUX is working in the frame of programme TECTORIFT of the SSTC, Belgian State (Services du Premier ministre—Services fédéraux des affaires scientifiques, techniques et culturelles).

REFERENCES

- AMBRASEYS, N.N., 1991.— The Rukwa earthquake of 13 December 1910 in East Africa. *Terra Nova*, **3**: 202-211.
- ANGELIER, J., 1989.— From orientation to magnitudes in paleostress determinations using fault slip data. *Journal of Structural Geology*, **11** (1-2): 37-50.
- BOSWORTH, W., 1992.— Mesozoic and Early Tertiary rift tectonics in East Africa. In: C.J. EBINGER, H.K. GUPTA & I.O. NYAMBOK (eds), *Seismology and Related Sciences in Africa. Tectonophysics*, **209**: 115-137.
- BOSWORTH, W. & MORLEY, C.K., 1994.— Structural and stratigraphic evolution of the Anza rift, Kenya. In: C. PRODEHL, G.R. KELLER & M.A. KHAN (eds), *Crustal and Upper Mantle Structure of the Kenya rift. Tectonophysics*, **236**: 93-115.
- BOSWORTH, W. & STRECKER, M.R., 1997.— Stress changes in the Afro-Arabian rift system during the Miocene to Recent period. In: K. FUCHS, R. ALTHERR, B. MÜLLER & C. PRODEHL (eds), *Stress and stress release in the lithosphere of the Afro-Arabian rift system. Tectonophysics*, **278**: 47-62.
- BOSWORTH, W. & TAVIANI, M., 1996.— Late Quaternary reorientation of stress field and extension direction in the southern Gulf of Suez, Egypt: evidence from uplifted coral terraces, mesoscopic fault arrays and borehole breakouts. *Tectonics*, **15**: 791-802.
- BOSWORTH, W., STRECKER, M.R. & BLISNIUK, P.M., 1992.— Integration of East African Palaeostress and Present-Day Stress Data: Implications for Continental Stress Field Dynamics. *Journal of Geophysical Research*, **97** (B8): 11851-11865.
- CAHEN, L. & LEPERSONNE, J., 1978.— Synthèse des connaissances relatives au Groupe (anciennement Série) de la Lukuga (Permien du Zaïre). *Sciences géologiques, Tervuren*, **82**: 115-152.
- CAMELBEECK, T. & IRANGA, M.D., 1996.— Deep crustal earthquakes and active faults along the Rukwa trough, Eastern Africa. *Geophysical Journal International*, **124**: 612-630.
- CERAMICOLA, S., VANHAUWAERT, P., KILEMBE, E. & BATIST, M. DE, 1996.— *High-Resolution Reflection Seismic Investigation of Lake Rukwa. EC, DGXII Environment Programme. I. 1: Natural Climatic Change, Rukwa project, Progress report.* Renard Center for Marine Geology, Gent University, Belgium: 1-33.
- CHOROWICZ, J., 1989.— Transfer and transform fault zones in continental rifts: examples in the Afro-Arabian rift system. Implications of crust breaking. *Journal of African Earth-Sciences*, **8**: 203-214.
- 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. *Rapport Annuel 1979 du Musée royal d'Afrique centrale, Tervuren, Belgium*: 143-146.
- CHOWDHURY, K.A., GHOSH, S.S. & KASMI, M.H., 1960.— *Pahudioxylon bankurensis* gen. et sp. nov. - A fossil wood from the Miocene bed of Bankura District, West Bengal, India. *National Institute of Sciences of India Proceedings*, **26B** (1): 22-28.
- CLOETINGH, S., SASSI, W. & HORVATH, F. (eds), 1993.— The Origin of Sedimentary Basins: Inference from Quantitative Modeling and Sedimentary Basin Analysis. *Tectonophysics*, **226**: 1-518.
- COBLENTZ, D.D. & SANDIFORD, M., 1994.— Tectonic stresses in the African plate: Constraints on the ambient lithospheric stress state. *Geology*, **22**: 8311-834.
- COHEN, A.S., SOREGHAN, M.J. & SCHOLZ, C., 1993.— Estimating the age of formation of lakes: an example from Lake Tanganyika, East African Rift System. *Geology*, **21**: 511-514.
- COHEN, A.S., LEZZAR, K.E., TIERCELIN, J.-J. & SOREGHAN, M.J., in press.— New palaeogeographic and lake level reconstructions of Lake Tanganyika: implications for tectonic, climatic and biologic evolution in a rift lake. *Basin Research*.
- DALY, M.C., LAWRENCE, S.R., KIMUN'A, D. & BINGA, M., 1991.— Late Palaeozoic deformation in central Africa: a result of distant collision? *Nature*, **350**: 605-607.

- DAMBLON, F.D., GERRIENNE, PH., D'OUTRELEPONT, H., DELVAUX, D., BEECKMAN, H. & BACK, S., 1998.— Identification of a fossil wood in the Red Sandstone Group of Southwestern Tanzania: stratigraphic and tectonic implications. In: D. DELVAUX & M.A. KHAN (eds), *Tectonics, Sedimentation and Volcanism in the East African Rift System. Journal of African Earth-Sciences*, **26** (3): 387-396.
- DELVAUX, D., 1990.— Structural control of the Karoo basins of SW-Tanzania by prekaroo fracture pattern. In: *15th Colloquium on African Geology*. CIFEG, Paris: 293-296.
- DELVAUX, D., 1991.— The Karoo to Recent rifting in the western branch of the East-African Rift System: a bibliographical synthesis. *Rapport Annuel 1989-1990 du Musée royal d'Afrique centrale, Tervuren, Belgium*: 63-83.
- DELVAUX, D., 1993.— Quaternary stress evolution in East Africa from data of the western branch of the East African rift. In: U. THORWEIHE & H. SCHANDELMEIER (eds), *Geoscientific Research in Northern Africa*. Balkema, Rotterdam; Brookfield: 315-318.
- DELVAUX, D., 1995.— Age of Lake Malawi (Nyasa) and water level fluctuations. *Rapport Annuel 1993-1994 du Musée royal d'Afrique centrale, Tervuren, Belgium*: 99-108.
- DELVAUX, D. & HANON, M., 1993.— Neotectonics of the Mbeya area, SW Tanzania. *Rapport Annuel 1991-1992 du Musée royal d'Afrique centrale, Tervuren, Belgium*: 87-97.
- DELVAUX, D. & KHAN, A., 1998.— Tectonics, sedimentation and volcanism in the East African Rift System: introduction. In: D. DELVAUX & M.A. KHAN (eds), *Tectonics, Sedimentation and Volcanism in the East African Rift System. Journal of African Earth-Sciences*, **26** (3): 343-346.
- DELVAUX, D., LEVI, K., KAJARA, R. & SAROTA, J., 1992.— Cenozoic palaeostress and kinematic evolution of the Rukwa - North Malawi rift valley (East African rift system). *Bulletin des Centres de Recherche Exploration-Production Elf-Aquitaine*, **16** (2): 383-406.
- DELVAUX, D., KERVYN, R., VITTORI, E., KAJARA, R.S.A. & KILEMBE, E., 1998.— Late Quaternary tectonic activity and lake level change in the Rukwa rift basin, East Africa. In: D. DELVAUX & M.A. KHAN (eds), *Tectonics, Sedimentation and Volcanism in the East African Rift System. Journal of African Earth-Sciences*, **26** (3): 397-421.
- DIXEY, F., 1928.— The Dinosaur Beds of Lake Nyasa. *Transactions of the Geological Society of South Africa*, **16**: 55-66.
- 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.
- DYPIK, H., NESTEBY, H., RUDENT, F., AAGAARD, P., JOHANSSON, T., MSINDAI, J. & MASSAY, C., 1990.— Upper Palaeozoic and Mesozoic sedimentation in the Rukwa-Tukuyu Region, Tanzania. *Journal of African Earth-Sciences*, **11**: 437-456.
- DZIEWONSKI, A.M., EKSTRÖM, G., WOODHAUSE, J.H. & ZWART, G., 1991a.— Centroid-moment tensor solutions for April-June, 1990. *Physics of the Earth and Planetary Interiors*, **66**: 133-143.
- DZIEWONSKI, A.M., EKSTRÖM, G., WOODHAUSE, J.H. & ZWART, G., 1991b.— Centroid-moment tensor solutions for July-September, 1990. *Physics of the Earth and Planetary Interiors*, **66**: 211-220.
- EBINGER, C.J., DEINO, A.L., DRAKE, R.E. & THESA, A.L., 1989.— Chronology of volcanism and rift basin propagation: Rungwe volcanic provinces, East Africa. *Journal of Geophysical Research*, **94**: 15.783-15.803.
- EBINGER, C.J., DEINO, A.L., TESSA, A.L., BECKER, T. & RING, U., 1993.— Regional tectonic controls on Rift Basin Morphology: Evolution of the Northern Malawi (Nyasa) Rift. *Journal of Geophysical Research*, **98**: 17.821-17.836.
- FOSTER, D.A. & GLEADOW, A.J.W., 1993.— Episodic denudation in East Africa: a legacy of intracontinental tectonism. *Geophysical Research Letters*, **20**: 2395-2398.
- FOURMARIER, P., 1914.— Le Bassin charbonnier d'âge Permo-Triassique de la Lukuga. Étude géologique de la région de la Lukuga et de la Lubumba au voisinage du lac Tanganyika. *Annales de la Société géologique de Belgique, Publications relatives au Congo belge*, **41**: C77-227.
- GAULON, R., CHOROWICZ, J., VIDAL, G., ROMANOWICZ, B. & ROULT, G., 1992.— Regional geodynamic implications of the May-July 1990 earthquake sequence in southern Sudan. *Tectonophysics*, **209**: 87-103.
- GIARDINI, D. & BERANZOLI, L., 1992.— Waveform modeling of the May 20, 1990 Sudan earthquake. *Tectonophysics*, **209**: 105-114.
- HALBICH, I.W., FITCH, F.J. & MILLER, J.A., 1983.— Dating the Cape orogeny. *Special Publication of the Geological Society of South Africa*, **12**: 149-164.
- HARKIN, D.A., 1960.— The Rungwe volcanics at the northern end of Lake Nyasa. *Memoir of the Geological Survey of Tanganyika*, **11**: 1-172.
- JACKSON, J. & BLENKINSHOP, T., 1993.— The Malawi earthquake of March 10, 1989: deep faulting within the East African rift system. *Tectonics*, **12**: 1131-1139.
- JACKSON, J. & BLENKINSHOP, T., 1997.— The Bilila-Mtakataka fault in Malawi: an active, 100-long, normal fault segment in thick seismogenic crust. *Tectonics*, **16**: 137-150.
- JACOBS, L.L., WINKLER, D.A., KAUFULU, Z.M., DOWNS, W.R. & CONGLETON, J.D., 1990.— The Dinosaur Beds of Northern Malawi, Africa. *National Geographic Research*, **6**: 196-204.
- KAGYA, M.L.N., 1996.— Geochemical characterization of Triassic petroleum source rock in the Mandawa basin, Tanzania. *Journal of African Earth-Sciences*, **23** (1): 73-88.
- KAZMIN, V., 1980.— Transform faults in the East African rift system. In: *Geodynamic Evolution of the Afro-Arabian Rift System. Atti dei Convegni Lincei*, **47**: 65-73.

- KEBEDE, F. & KULHANEK, O., 1991.— Recent seismicity of the East African Rift system and its implications. *Physics of the Earth and Planetary Interiors*, **68**: 259-273.
- KENNERLEY, J.B., 1962.— Quarter degree sheet 243, Itaka. 1:125,000 geological map. *Geological Survey of Tanganyika*.
- KILEMBE, E.A. & ROSENDAHL, B.R., 1992.— Structure and stratigraphy of the Rukwa rift. *Tectonophysics*, **209**: 143-158.
- KLERKX, J., THEUNISSEN, K. & DELVAUX, D., 1998.— Persistent fault controlled basin formation since the Proterozoic along the western branch of the East African Rift. In: D. DELVAUX & M.A. KHAN (eds), *Tectonics, Sedimentation and Volcanism in the East African Rift System*. *Journal of African Earth-Sciences*, **26** (3): 347-361.
- KREUSER, T., 1983.— Stratigraphie des Karoo-Becken in Ost Tanzania. *Sonderveröffentlichung Geologisches Institut Universität Köln*, **45**: 1-217.
- KREUSER, T., 1984.— Source rock analysis of two Karoo basins of coastal Tanzania. *Journal of Petroleum Geology*, **7** (1): 47-54.
- LENOIR, J.-L., LIÉGEOIS, J.-P., THEUNISSEN, K. & KLERKX, J., 1994.— The Palaeoproterozoic Ubendian shear belt in Tanzania: geochronology and structure. *Journal of African Earth-Sciences*, **19** (3): 169-184.
- LEPERSONNE, J., 1977.— Structure géologique du bassin inférieur du Zaïre. *Bulletin de l'Académie royale belge, classe des Sciences*, **63** (5): 941-965.
- LEZZAR, K.E., TIERCELIN, J.-J., BATIST, M. DE, COHEN, A.S., BANDORA, T., VAN RENSBERGEN, P., LE TURDU, C., MIFUNDU, W. & KLERKX, J., 1996.— New stratigraphy and Late Tertiary history of the North Tanganyika Basin, East African Rift system, deduced from multichannel and high-resolution reflection seismic data and piston core evidence. *Basin Research*, **8**: 1-28.
- MBEDE, E.I., 1993.— Tectonic development of the Rukwa rift basin in SW Tanzania. Ph.-D. Dissertation. *Berliner Geowissenschaftliche Abhandlungen*, **A152**: 1-92.
- MCCONNELL, R.B., 1972.— Geological development of the rift system of eastern Africa. *Geological Society of America, Bulletin*, **83**: 2549-2572.
- MORLEY, C.K., WESCOTT, W.A., STONE, D.M., HARPER, R.M., WIGGER, S.T. & KARANJA, F.M., 1992a.— Tectonic evolution of the northern Kenyan Rift. *Journal of the Geological Society, London*, **149**: 333-348.
- MORLEY, C.K., CUNNINGHAM, S.M., HARPER, R.M. & WESCOTT, W.A., 1992b.— Geology and geophysics of the Rukwa rift, East Africa. *Tectonics*, **11**: 68-81.
- NILSEN, O., DYPVIK, H., KAAYA, C. & KILEMBE, A., 1999.— Tectono-sedimentary development of the (Permian) Karoo sediments in the Kilombero Rift valley, Tanzania. In: S. MUHONGO & A.N. OPIYO (eds), *Geology and mineral resources of East Africa*. *Journal of African Earth-Sciences*, **29** (2): 393-409.
- NYAMBE, I.A. & UTTING, J., 1997.— Stratigraphy and palynostratigraphy, Karoo Supergroup (Permian and Triassic), mid-Zambezi Valley, southern Zambia. *Journal of African Earth-Sciences*, **24**: 563-584.
- OESTERLEN, P.M. & BLENKINSHIP, T., 1994.— Extension directions and strain near the failed triple junction of the Zambezi and Luangwa Rift zones, southern Africa. *Journal of African Earth-Sciences*, **18**: 175-180.
- OWEN, R.B., CROSSLEY, R., JOHNSON, T.C., DAVISON-HIRSCHMANN, S., TWEDDLE, D. & ENGSTROM, D.E., 1990.— Major low levels of Lake Malawi and implications for evolution rates in cichlid fishes. *Proceedings of the Royal Society of London*, **B240**: 519-553.
- PEIRCE, J. & LIPKOV, L., 1988.— Structural interpretation of the Rukwa rift, Tanzania. *Geophysics*, **53** (6): 824-836.
- QUENNEL, A.M., MCKINLAY, A.C.M. & AITKEN, W.G., 1956.— Summary of the geology of Tanganyika. Part I: Introduction and stratigraphy. *Memoir of the Geological Survey of Tanganyika*, **1**: 1-264.
- RING, U., BETZLER, C. & DELVAUX, D., 1992.— Normal vs. strike-slip faulting during rift development in East Africa: the Malawi rift. *Geology*, **20**: 1015-1018.
- ROSENDAHL, B., KILEMBE, E. & KACZMARICK, K., 1992.— Comparison of the Tanganyika, Malawi, Rukwa and Turkana rift zones from analyses of seismic reflection data. *Tectonophysics*, **213**: 235-256.
- SANDER, S. & ROSENDAHL, B.R., 1989.— The Geometry of rifting in Lake Tanganyika, East-Africa. *Journal of African Earth-Sciences*, **8**: 323-354.
- SENO, T. & SAITO, A., 1994.— Recent East African earthquakes in the lower crust. *Earth and Planetary Science Letters*, **121**: 125-136.
- SIMIYU, S.M. & KELLER, G.R., 1997.— An Integrated analysis of lithospheric structures across the East African plateau based on gravity anomalies and recent seismic studies. *Tectonophysics*, **278**: 291-313.
- SPECHT, T.D. & ROSENDAHL, B.R., 1989.— Architecture of the Lake Malawi Rift, East-Africa. *Journal of African Earth-Sciences*, **8**: 355-382.
- STONE, D., HARPER, R.M. & MORLEY, C.K., in press.— Geophysics of the Usangu flats. In: C.K. MORLEY (ed.), *Continental rifting in East Africa, structural and sedimentary geometries, processes and evolution: as revealed by hydrocarbon exploration*. *Special Publications- AAPG*.
- 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., KLERKX, J., MELNIKOV, A. & MRUMA, A., 1996.— Mechanism of inheritance of rift faulting in the western branch of the East African Rift, Tanzania. *Tectonics*, **15**: 776-790.

- THEUNISSEN, K., LENOIR, J.-L., LIÉGEOIS, 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. *Comptes Rendus de l'Académie des Sciences, Paris*, **314** (II): 1355-1362.
- TIERCELIN, J.-J., CHOROWICZ, J., BELLON, H., RICHERT, J.-P., MWAMBENE, J.T. & WALGENWITZ, F., 1988.— East African rift system: offset, age and tectonic significance of the Tanganyika-Rukwa-Malawi intracontinental fault zone, *Tectonophysics*, **148**: 241-252.
- UTTING, J., 1976.— The Karoo stratigraphy of the northern part of the Luangwa valley. *Memoir of the Geological Survey of Zambia*, **4**: 1-131.
- VAN DER BEEK, P., MBEDE, E., ANDRIESSEN, P. & DELVAUX, D., 1998.— Denudation history of the Malawi and Rukwa rift flanks (East African Rift System) from apatite fission track thermochronology. In: D. DELVAUX & M.A. KHAN (eds), *Tectonics, Sedimentation and Volcanism in the East African Rift System. Journal of African Earth-Sciences*, **26** (3): 363-385.
- VERNIERS, J., JOURDAN, P.P., PAULIS, R.V., FRASCA-SPADA, L. & DE BOCK, F.R., 1989.— The Karoo graben of Metangula, northern Mozambique. *Journal of African Earth-Sciences*, **9**: 137-158.
- VISSER, J.N.J. & PRAEKELT, H.E., 1996.— Subduction, mega-shear systems and the Late Palaeozoic basin development in the African segment of Gondwana. *Geologisches Rundschau*, **85**: 632-646.
- VITTORI, E., DELVAUX, D. & KERVYN, F., 1997.— Kanda Fault: a major seismogenic element west of the Rukwa rift (East Africa, Tanzania). In: P.L. HANCOCK & A.L. MICHETTI (eds), *Palaeoseismology: using Quaternary geology to understand past earthquakes. Journal of Geodynamics*, **24** (1-4): 139-153.
- WESCOTT, W.A., KREBS, W.K., ENGELHARDT, D.W. & CUNNINGHAM, S.M., 1991.— New biostratigraphic age dates from the Lake Rukwa rift basin in Western Tanzania. *AAPG Bulletin*, **75** (7): 1255-1263.
- WHEELER, W.H. & KARSON, J.A., 1994.— Extension and subsidence adjacent to a "weak" continental transform: an example of the Rukwa Rift, East Africa. *Geology*, **22**: 625-628.
- WÖPFNER, H., 1993.— Structural development of Tanzanian Karoo basins and the break-up of Gondwana. In: R.H. FINDLAY, R. UNRUG, M.R. BANKS & J.J. VEEVERS (eds), *Gondwana Assembly, Evolution and Dispersal*. Balkema, Rotterdam: 531-540.
- WÖPFNER, H., 1994.— The Malagasy Rift, a chasm in the Tethyan margin of Gondwana. *Journal of Southeast Asian Earth-Sciences*, **9** (4): 451-461.
- WÖPFNER, H. & KAAYA, C.Z., 1991.— Stratigraphy and morphotectonics of Karoo deposits of the northern Selous Basin, Tanzania. *Geological Magazine*, **128** (4): 319-334.
- WÖPFNER, H. & KAAYA, C.Z., 1992.— Syndepositional rifting in the Ruhuhu and Selous basin - Tanzania. In: UNESCO (ed.), *Geology for Economic Development. Newsletter*, **9**: 159-168.
- ZEYEN, H., VOLKER, F., WEHRLE, V., FUCHS, K., SOBOLEV, S.V. & ALTHERR, R., 1997.— Styles of continental rifting: crust-mantle detachment and mantle plumes. In: K. FUCHS, R. ALTHERR, B. MÜLLER & C. PRODEHL (eds), *Stress and stress release in the lithosphere of the Afro-Arabian rift system. Tectonophysics*, **278**: 329-352.
- ZIEGLER, P.A., 1990.— *Geological Atlas of Western and Central Europe*. 2nd ed. Shell International Petroleum Mij. B. V., The Hague: 1-232.
- ZIEGLER, P.A., 1993.— Plate-moving mechanisms: their relative importance. *Journal of the Geological Society, London*, **150**: 927-940.
- ZIEGLER, P.A., CLOETHINGH, S. & VAN WEES, J.-D., 1995.— Dynamics of intra-plate compressional deformation: the Alpine foreland and other examples. *Tectonophysics*, **252**: 7-59.
- ZIEGLER, P.A., CLOETHINGH, S., GUIRAUD, R. & STAMPELI, G.M., 2001.— Peri-Tethyan platforms: constraints on dynamics of rifting and basin inversion. In: P.A. ZIEGLER, W. CAVAZZA, A.H.F. ROBERTSON & S. CRASQUIN-SOLEAU (eds), *Peri-Tethys Memoir 6: Peri-Tethyan Rift / Wrench Basins and Passive Margins. Mémoires du Muséum national d'Histoire naturelle*, **186**: 000-000.
- ZOBACK, M.L., 1992.— First- and Second-Order Patterns of Stress in the Lithosphere: the World Stress Map Project. *Journal of Geophysical Research*, **97**: 11703-11728.