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THE KAROO TO RECENT RIFTING IN THE WESTERN BRANCH OF THE EAST-AFRICAN RIFT SYSTEM : A BIBLIOGRAPHICAL SYNTHESIS

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SAMENVATTING. — In het kader van het projekt EGS (Erfelijkheid van Geologische Strukturen) wordt een bibliografisch overzicht gegeven van de geologische en tektonische evolutie van de westelijke tak van de Oost-Afrikaanse slenk, vanaf het Paleozoïcum tot op heden. De synthese herneemt de meest recente gedachten in verband met de geometrie, de geschiedenis en de kinematiek van de Karoo-, Krijt- en Cenozoïsche rift bekken vorming in Oost-Afrika, met bijzondere aandacht op de huidige ontwikkeling van de Tanganyika-, Rukwa- en Malawi-meren.

RÉSUMÉ. — Dans le cadre du projet IGS (Inheritance of Geological Structures), une revue bibliographique est présentée sur l'évaluation géologique et tectonique de la branche ouest du rift est-africain, du Paléozoïque jusqu'à l'Actuel. Cette synthèse reprend les concepts les plus récents sur la géométrie, l'histoire et la cinématique de la formation des rifts du Karoo, Crétacé et Cenozoïque en Afrique de l'Est, avec une attention particulière aux systèmes des lacs Tanganyika, Rukwa et Malawi.

I. INTRODUCTION

At the end of the Pan-African orogeny, all the continents were grouped together in the Pangaea supercontinent. The southern half of it (Gondwana) was submitted to a general extensional regime until the Early Permian. Since then, the tectonic evolution of the African continent has been dominated by rifting processes. Several major extensional events and related rift systems have been recognized in Africa (see e.g. Boswsorth, 1989; Fairhead & Green, 1989; Lambiase, 1989; Rogers & Rosendahl, 1989...). They can be classified into six major systems, based on the age of the youngest sediments in the rifts: (1) the Permo-Triassic (Karoo) system, (2) the Late Triassic-Early Jurassic system, (3) the Early Middle Jurassic (End Karoo) system, (4) the Mid Cretaceous system, (5) the Early Tertiary system and (6) the Late Tertiary to Recent system.

The *Permo-Triassic* rifts refer to the development of Karoo grabens which apparently preceded the onset of Gondwana's breakup. The Early Permian basins developed following a N-S trend coinciding with the present East-African coast and southwestern Madagascar. They correspond to a major rift

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system linked to a large extensional fault that penetrated deep into Gondwana, from its northern (Tethys) margin (De Wit & al., 1988; Wopfner, 1988). The large Karoo basins of South-Africa and Zimbabwe was also initiated at this time, but they are related to the compressive N-S tectonics of the Cape fold belt that have prevailed in South Africa during Permian to Early Triassic times (Hälbich, 1983). The *Late Permian-Early Triassic* (Karoo) event affected all of the eastern and southern Africa. It generated many new basins and reactivated some of the Permian ones.

The *Late Triassic-Early Jurassic* rift system is restricted to the northwest of Africa (Morocco) and is associated with the separation of Northwest Africa and North America.

A new rifting paroxysm occurred during the *Early to Middle Jurassic*. This episode is related to the opening of the Indian Ocean, due to the initial E-W separation of Gondwana into a western part, including Africa, and an eastern part, including India and Antartica (De Wit & al., 1988). It is not clear whether the Jurassic rifting is a distinct event rather than the continuation of the Karoo event. New basins formed in Kenya and Southern Sudan, but reactivation of Permian basins also occurred in Tanzania and Zambia (Kent & Perry, 1973; Kreuser, 1983; Utting, 1976; Kreuzer & Markwort, 1989; Verniers & al., 1989). According to these authors, most of the present Karoo rifts probably originated as tectonic sedimentary basins during Permo-Triassic times and evolved into grabens or half-grabens by downfaulting and tilting during the Early Jurassic.

The *Mid Cretaceous and Early Tertiary* rift systems affected a large portion of central to western Africa. They include the intracontinental Benue Trough, the Congola, East-Niger and Sudan rifts (Benkhelil, 1989; Bosworth, 1989; Daly & al., 1989; Fairhead & Green, 1989).The marginal Atlantic rift system is also of Cretaceous to Tertiary age (Uchupi, 1989). All of these systems formed due to the separation of South America from West-Africa. Remnants of a Cretaceous basin are also known along the Tanganyika-Rukwa-Malawi lineament (Versfelt & Rosendahl, 1989). Thick Early Tertiary syn-rift sequences were recognized in parts of Sudan (Anza basin) and in Kenya (Lake Turkana: Lambiase, 1989).

The *Late Tertiary to Recent rift* system corresponds to the East-African rift system, which shows actual seismic and igneous activity (fig.1). It is generally regarded as a classical example of active continental rift system. It is an onshore extension of the Red Sea - Gulf of Aden system. Rifting began during the Early Miocene. Seismic data suggest that it is still propagating to the southwest (Fairhead & Henderson, 1979). It contains new oceanic crust in its northern extremity, in the Red Sea and Gulf of Aden (Bohannon, 1989).

This bibliographical synthesis concentrates mainly on the western branch of the East-African rift. Three major rifting cycles have affected this area: the Karoo cycle, ending with the Late Jurassic (Gondwana) peneplain, the Cretaceous cycle, ending with the Late Cretaceous (African) Peneplain and the Late Tertiary to Recent cycle, still active (plates 1 & 2). The structural evolution of these rift systems is discussed, with reference to the most recent works. Kinematic and geodynamic models for the Karoo and Late Tertiary to Recent rifting are also briefly considered.

II. GEOLOGICAL SETTING

The Western branch of the East-African rift lies mainly in mobile belts of Lower Proterozoic origin, that evolve around the the Archean cratons of Tanzania and Bangweulu (fig.2). The Lower Proterozoic basement of SW Tanzania is characterized by two distinct mobile belts situated west (Ubende) and south (Usagara) of the Tanzanian craton (Harpum, 1970, McConnell, 1972; 1980). The NW-SE trending Ubende belt consists mainly of high to medium grade granitic to basic gneisses, in which narrow ductile shear zones of retrograde greenschist facies have developed. The E-W to ENE-WSW trending Usagara belt consists also of high to medium grade gneisses, affected by thrusting tectonics. At the end of the Lower Proterozoic times, extensive granitization occur in the Bangweulu block (Ngoyi & al., 1990) and at the southwestern part of the Usagara belt (Ubena plateau: Priem & al., 1979).

The Middle Proterozoic, period is characterized mainly by the development of the Kibara and Irumide mobile belts of NE-SW trend, and by the sedimentation and subsequent deformation of the Ukinga Group in the contact zone between the Ubena plateau and the Ubende belt. Also, the NW-SE shear zones of retrograde greenschist facies in the Ubende belt were possibly formed during this event (Harpum, 1970; McConnell, 1972; 1980; Klerkx & Nanyaro, 1988).

The Upper Proterozoic period is characterized by the Pan-African (sensu-lato) orogenesis which evolved in brittle-ductile conditions. The thermo-tectonic Mozambique belt trends N-S along the Indian coast from Kenya to Mozambique. It probably overprints the eastern border of the Tanzania craton, and also a great part of the Ukinga belt. Further to the SW, Zambia and Malawi are crossed by the continental scale ENE-WSW Mwembeshi-Chimaliro shear zone, of

Pan–African origin (De Swardt & al., 1965; Bloomfield, 1966; Daly, 1986; Daly & al., 1989; Porada, 1989). Near the western shore of Lake Malawi, the Mwembeshi–Chimaliro shear zone splits into a northern and a southern branch. Both are supposed to continue to the northeast across Tanzania, probably under the Ruhuhu and the Metangula–Ruvuma–Rufiji karoo basins. Some fractures inside and bordering the Karoo basins could link to the Mwembeshi–Chimaliro zone, however the existence of real shear zones under the Karoo basins are still to be proved (in Daly & al., 1989).

III. KAROO AND CRETACEOUS RIFT SYSTEMS

After a long period between Cambrian and Carboniferous, from which very few sediments are preserved, East-Africa underwent a period of widespread crustal extension during the Permo–Triassic (Karoo rifting).

1. TECTONO–SEDIMENTARY EVOLUTION

The Karoo series occur (1) in N–S trending grabens along the East-African coast, (2) in long elongate basins of general ENE–WSW trend in southern Tanzania and adjacent countries, (3) in small grabens aligned along the NW–SE trending Tanganyika–Rukwa–Malawi (TRM) lineament and also (4) in the eastern margin of the Zaire basin (plate 1). The recent Lake Malawi rift cuts across the NE–SW trend of long elongate Karoo basins, while the recent rifts of the TRM zone developed relatively parallel to the discontinuous occurrences of Karoo along the NW–SE TRM trend.

A. COASTAL BASINS

In coastal Kenya, Tanzania, Mozambique and also on the west–coast of Madagascar, Karoo basins developed since Early Permian along a N–S trend. They are remnants of the major rift system called Malagasy, that penetrated into Gondwana, from the Tethyan margin. The sedimentary and structural evolution of the coastal Tanzania basins was surveyed by Kent & Perry (1973) and Kreuser (1983). Karoo series of 6–10 km thick were revealed by geophysical evidence beneath the outcropping Jurassic. Vitrinite reflectance (Kreuser & al, 1988) show that the actual Karoo outcrops have been covered by some 3000m of sediments. The Karoo facies is mainly terrestrial (sandstone, conglomerate and coal measures), but short marine Permian incursions occur in the most westerly basins. The Karoo rifting and block–faulting features developed contemporaneously with deposition related to global tension, with the main vertical movements at the end of the Jurassic. Later faulting occurred during the development of Tertiary basins, but mainly along different lines, nearer to the continental border.

B. KAROO BASINS OF ENE–WSW TREND

The Karoo grabens of the ENE–WSW trend are long elongate basins filled with dominantly clastic, continental sediments. The principal ones are the Metangula–Ruvuma–Rufiji basin in N–Mozambique and S–Tanzania (Verniers & al., 1989; Kreuzer, 1983; Kreuser & al., 1988), the Ruhuhu basin in SW–Tanzania (Kreuser & Semkiwa, 1987; Kreuzer & Markwort, 1989; Wopfner, 1990), and the Luangwa graben in E–Zambia (Utting, 1976).

The evolution of these basins are characterized by a tectonically controlled sedimentation in progressively susiding basins, from Late Carboniferous to Middle–Late Triassic or Early Jurassic. Organic matter analysis (Kreuser & al., 1988) suggest that no significant post–Karoo deposition occurred in the Ruhuhu basin. The deposition of Karoo sediments occurred initially in basins of different shape than the actual fault–bounded Karoo outcrops. Apart from a short period of faulting at the boundary Permian–Trias, the major down–faulting and half–graben tilting occurred in late– to post–Karoo times, that is Upper Triassic to Lower Jurassic. The present position morphology is interpreted to be the result of later tectonic reactivation, uplift and erosion, in relation with the Late Tertiary to Recent rifting. The deposition history of the Karoo ENE–WSW basins have probably been controlled by the reactivations of prominent mechanical anisotropies of the continental lithosphere, formed during Lower Proterozoic times (Bloomfield, 1966; Cannon & al., 1969; McConnell, 1972; Daly & al., 1989). The mechanism of the ENE–WSW Karoo basin evolution is still poorly understood. It ranges from normal faulting and half–graben tilting in an extensional context (Orpen & al., 1989; Delvaux, 1990), to a pull–apart evolution in a strike–slip context (Daly, 1986; Daly & al., 1989). However, the reactivation of pre–Karoo structural discontinuities seems to have played an important role in the basin geometry and evolution.

C. KAROO BASINS IN THE NW–SE TRENDING TANGANYIKA–MALAWI ZONE

Along the TRM lineament, the Karoo series outcrop in small basins, bordering the northwestern end of Lake Malawi and the Rukwa trough (McConnell, 1946; Bloomfield, 1957, 1966; McKinlay, 1965). They are also known in the Kalemie basin on the Zaire side of Lake Tanganyika and in the eastern side of the vast Zaire basin (Fourmarier, 1916; Cahen & al., 1946, 1960; Lepersonne, 1977; Cahen & Lepersonne). The presence of Karoo series under southern half of Lake Tanganyika and northern extremity of Malawi lake could be interpreted from seismic profiles, but has not been definitely proved yet (Morley, 1988; Sander & Rosendahl, 1989; Versfelt & Rosendahl, 1989).

The basal Karoo beds were deposited either in a tectonic basin (SW Tanzania), or in mountain valleys (East Zaire). Limited tectonic movement probably occurred during the deposition of the Permian, but the first important movements took place between Upper Permian and Lower Triassic. In East Zaire and in the Kalemie trough, sedimentation continues throughout the Triassic to Lower Jurassic. The latter basin was probably actively subsiding during all of the Triassic. An important sedimentary break between Lower and Upper Jurassic in East Zaire probably marks an episode of regional uplift and renewed tectonic activity. It is not known whether the major vertical movements along the TRM lineament took place between Upper Permian and Lower Triassic or in Lower to Middle Jurassic. The TRM lineament was still in depression during the deposition of Upper Jurassic to Cretaceous. Around northern part of Lake Malawi and Lake Rukwa, red beds and lake beds might represent remnants of a Cretaceous NW-SE basin. Reactivation of the NW-SE TRM trend, of course, occurred during the Tertiary to Recent rifting.

2. POST-KAROO ALKALINE MAGMATISM

Post-Karoo alkaline magmatism occurs in the Rukwa trough during Upper Jurassic and Lower Cretaceous (Le Bas, 1980). The alkaline complex of Mbeya comprises the carbonatites of Panda Hill and Mbalizi, dated at 128 ± 8 Ma to 118 ± 9 Ma (Lower Cretaceous) by Pentel'kov & Voronovskiy (1977). They are contemporaneous with the carbonatites of the Chilwa alkaline province, situated at the southern end of Lake Malawi (Garson, 1965). In the Ruhuhu basin, near the shores of Lake Malawi, kimberlite pipes and alkaline diabase dykes were seen intruding the Karoo sediments (McKinlay, 1958).

3. CONCLUSION

The Karoo basins of East-Africa were mainly intracratonic, until Early Jurassic. Their tectono-sedimentary evolution during this stage was mainly controlled by the interplay of two major stress fields: a dominantly extensional one at the Tethyan margin of Gondwana and a dominantly compressive one at its Pacific margin (Wopfner, 1988). Possibly as early as in Late Carboniferous, rifting was initiated along the Monbasa (Kenya) coastline. During the Karoo period, a relatively small E-W separation of Madagascar from East Africa occurred, with rifting parallel to the present coastline (Reeves & al., 1986/1987). This allowed Karoo sedimentation, but restricted Tethyan marine incursion (Permian evaporite deposits). The Karoo basins of Luwegu, Ruhuhu and Luangwa lie in the exact SSW prolongation of the Karoo basins of coastal Kenya (and of Madagascar at his initial location). In Early Jurassic, the intracratonic context evolves into a pericratonic one, with the complete separation of Madagascar and India from Africa.

A Mesozoic rift arm is running northwestward from the Kenya paleo-triple-junction near Monbasa, towards the actual lake Turkana: the Anza trough (Bosworth, 1989; Fairhead & Green, 1989). This basin was active during Upper Jurassic and Cretaceous. Geophysical data indicate a NE-SW extension of about 65 km, linked with an important crustal thinning (Reeves & al., 1986/87). The Upper Jurassic to Cretaceous event along the TRM zone in East-Central Africa is then contemporaneous with the development of the Anza graben.

VI. THE TANGANYIKA - MALAWI CENOZOIC RIFT SYSTEMS

The East-African Late Tertiary to Recent rift system lies atop the East-African plateau, and consists of two branches. The Eastern one extends from the Gulf of Aden to the Kenya (Gregory) rift and the Western one extends from Lake Albert to the Indian ocean, through the Tanganyika and Malawi (or Nyasa) rift valleys (fig.1). They developed mainly in the Proterozoic mobile belts, between the Archean cratons. The Western and Kenya rift systems follow Proterozoic mobile belts and avoid the central Tanganyika craton which acted as resistant block (see for e.g., McConnell, 1967; 1972). The western branch is developed mainly along the Ubende mobile belt (fig.2), characterized by northwest-trending mylonites and shear-zones (McConnell, 1950; Harpum, 1970; Daly, 1986; Klerkx & Nanyaro, 1988; Theunissen, 1988...). Mostly ductile movements have occurred along this zone, during the major Proterozoic orogenic events (Cahen & Snelling, 1966). Renewed, mainly brittle movements occurred since the Early Phanerozoic, down to present times (Karoo and Tertiary to Recent rifts).

The pre-rift structure of the Malawi - Tanganyika rift zone is the foliation related to mobile belts, trans-

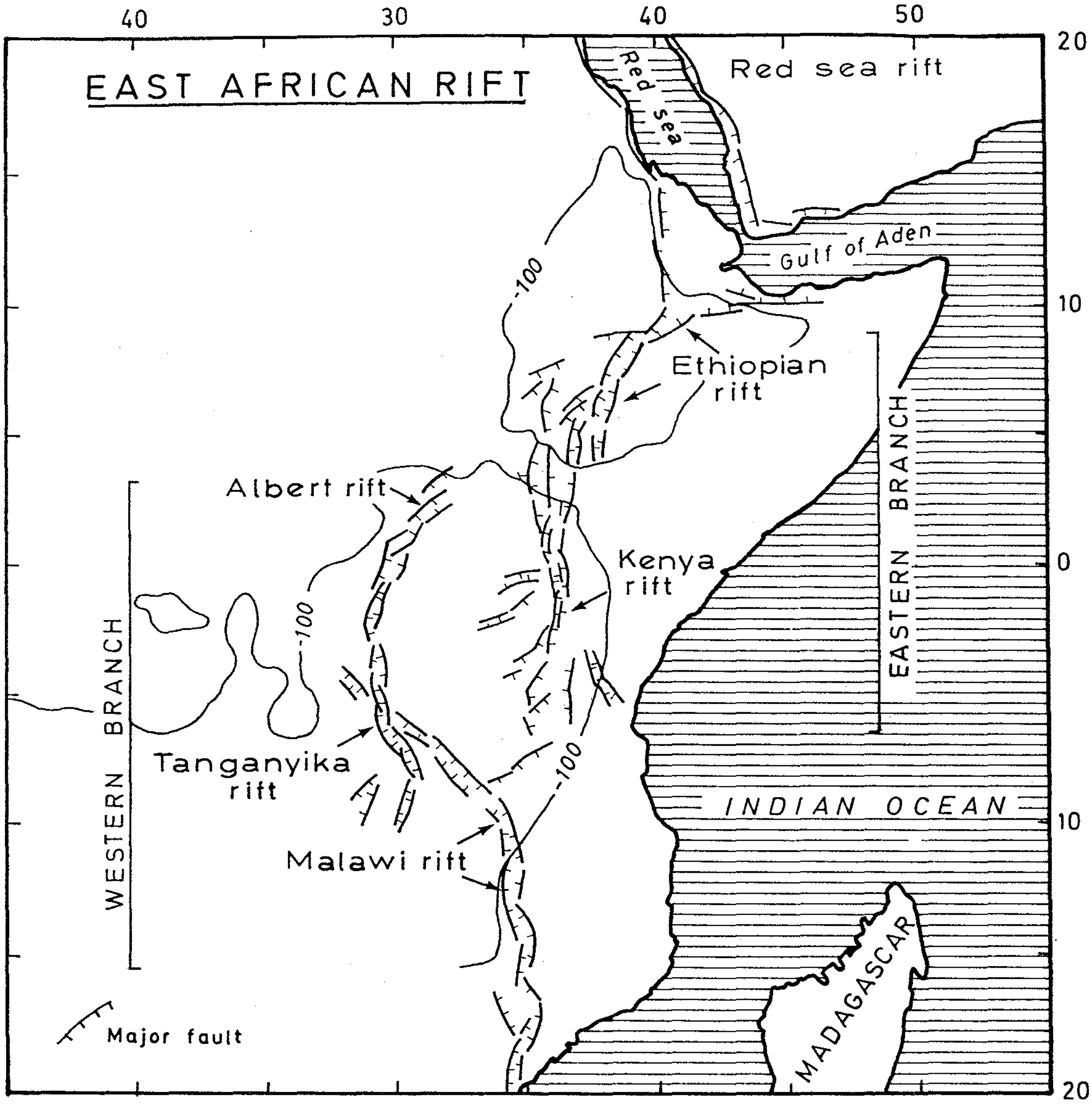

Fig. 1. - General map of the East-African Late Tertiary to Recent rift systems (after Bosworth, 1989). The -100 milliGal bouguer anomaly contour indicates approximatively the area of thinned continental lithosphere.

continental dislocation zones and earlier rift troughs (Permo-Triassic Karoo grabens and remnants of Cretaceous basins).

1. TECTONO-SEDIMENTARY EVOLUTION

From the Early Tertiary to the end of the Miocene, geological activity was relatively reduced. It consisted of two successive cycles of regional uplift and erosion, ending with a new peneplanization, during the Miocene (Dixey, 1943; plate 2).

The oldest known deposits belonging to the Late Tertiary to Recent rift system in the Rukwa-Malawi region are lacustrine series of terminal Miocene to Pliocene age. They are encountered along the northern shores of Lake Malawi, and around Lake Rukwa (Crossley & Crow, 1980; Kaufulu & White, 1981).

The western branch of the East-African rift system is composed by a series of deep troughs forming a typical rift valley. This alignment has a sigmoïdal shape, bordering the Tanzania craton to the west. The rifts contain thick Plio-Quaternary deposits and are partly occupied by deep lakes Mobutu (Albert), Idi-Amin (Edward), Kivu, Tanganyika, Rukwa and Malawi (Nyassa). Several transverse NE-SW shallow depressions are also related to the western branch of the rift system (Upemba flats, Mweru-Mweru Wantipa lakes, Usangu flats and Kilombero-Makata valleys: plate 1). They are filled with moderate thickness of recent sediments and are partly occupied by shallow lakes or swamps.

Tertiary volcanism occurs in four isolated provinces along the western rift (Toro-Ankole, Virunga, Kivu and Rungwe provinces: Le Bas, 1980; Karson & Curtis, 1989). They coincide with accomodation zones, suggesting an intimate relationship between

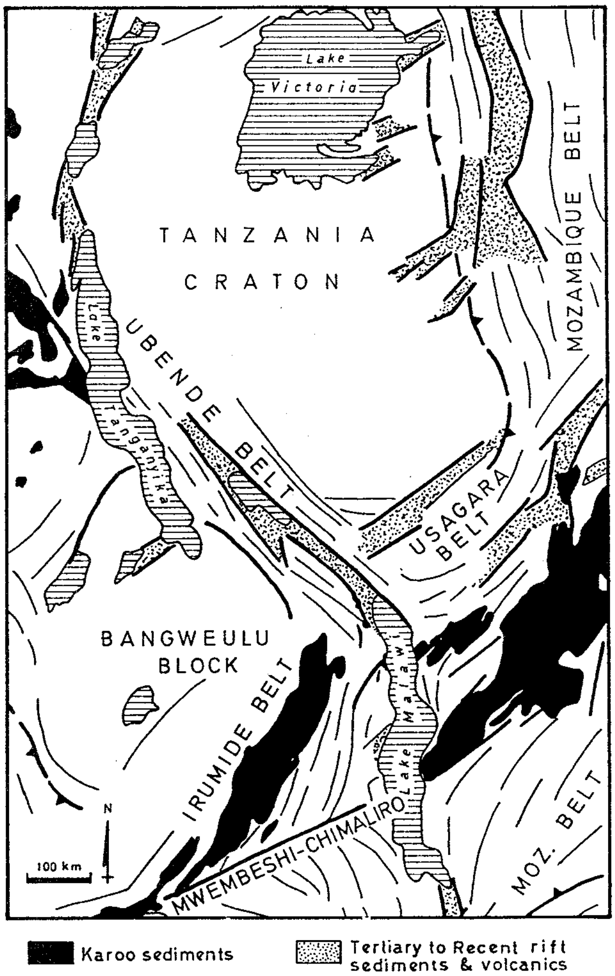

Fig. 2. - Geological sketch of the East-Central Africa basement and rift sediments (compilation from McConnell, 1972 and Daly, 1986).

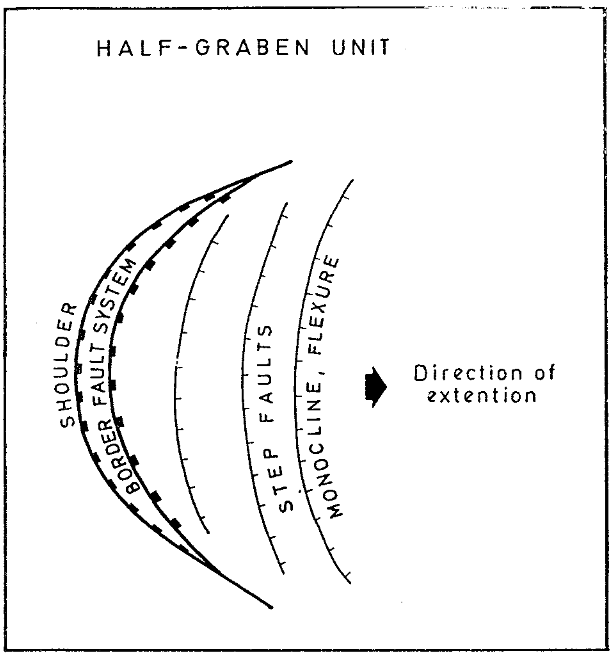

Fig. 3. - The half-graben unit, fundamental building block of Tanganyika - Malawi rift system (after Sander & Rosendahl, 1989 and Specht & Rosendahl, 1989).

volcanism and faulting during the initial stages of continental rift development. Tertiary volcanism started in the Miocene, 10–12 Ma ago, in the Kivu volcanic province at the northern end of Lake Tanganyika (Pasteels & al.1989; Ebinger, 1989b). Within the Rungwe region (between Lake Rukwa, Lake Malawi and the Usangu flats), volcanism started in Late Miocene times, 7 Ma ago (Harkin, 1960; Ebinger & al., 1990). It was prior to or concurrent with the development of high–angle border faults bounding the initially isolated Rukwa and North–Malawi (Livingstone) basins.

Recent sedimentary history of Lake Tanganyika and Malawi was greatly influenced by tectonic and climatic events. Several seismic and sedimentary discontinuities in Lake Tanganyika are thought to represent lake level variations (Tiercelin & al., 1988a; 1989). The depocenters and depositional facies was also controlled by the half–graben development (Crossley & Owen, 1987; Owen & Crossley, 1989; Scholz & al., 1990).

2. RIFT ARCHITECTURE AND GEOMETRY

In recent years, mainly multichannel seismic reflection data from Lakes Tanganyika and Malawi were collected by Project PROBE of Duke University. This study was dedicated to the architecture of continental rifting, mainly in the great rift valley–lakes of East–Africa. The results were published in several papers (Lake Tanganyika: Morley, 1988 & 1989; Sander & Rosendahl, 1989; Scott & al. 1989; Lake Malawi: Ebinger & al., 1987; Specht & Rosendahl 1989; Lake Victoria: Rach & Rosendahl, 1989; Lake Turkana: Dunkelman & al., 1989). The data obtained account greatly for the knowledge of continental rifting, and led to a generalized rifting model, with kinematic and stratigraphic implications.

The principal rift valley is segmented along its length into 60–100 km–long extensional basins, in a series of alternating half–grabens (fig.3). Only one side of them is bordered by steep normal faults showing important vertical throw. Depth of seismic activity ranges from 0 to 30 km, suggesting that the faults extend deep into the crust. The border faults are thought by Morley (1988) to extend downward to a depth of 15 to 25 km. In map view, the border faults display an en–echelon geometry and are linked by transfer faults or accomodation zones (fig.4). The basins were originally isolated and they are linked together by longitudinal propagation of border faults (Ebinger, 1989a; Ebinger & al., 1990).

The typical dimensions of the half–graben units are 80–160 km long and 30–60 km wide, with typical length/width ratio of ± 3. The idealized half–graben is a monocline structure, enclosed between border

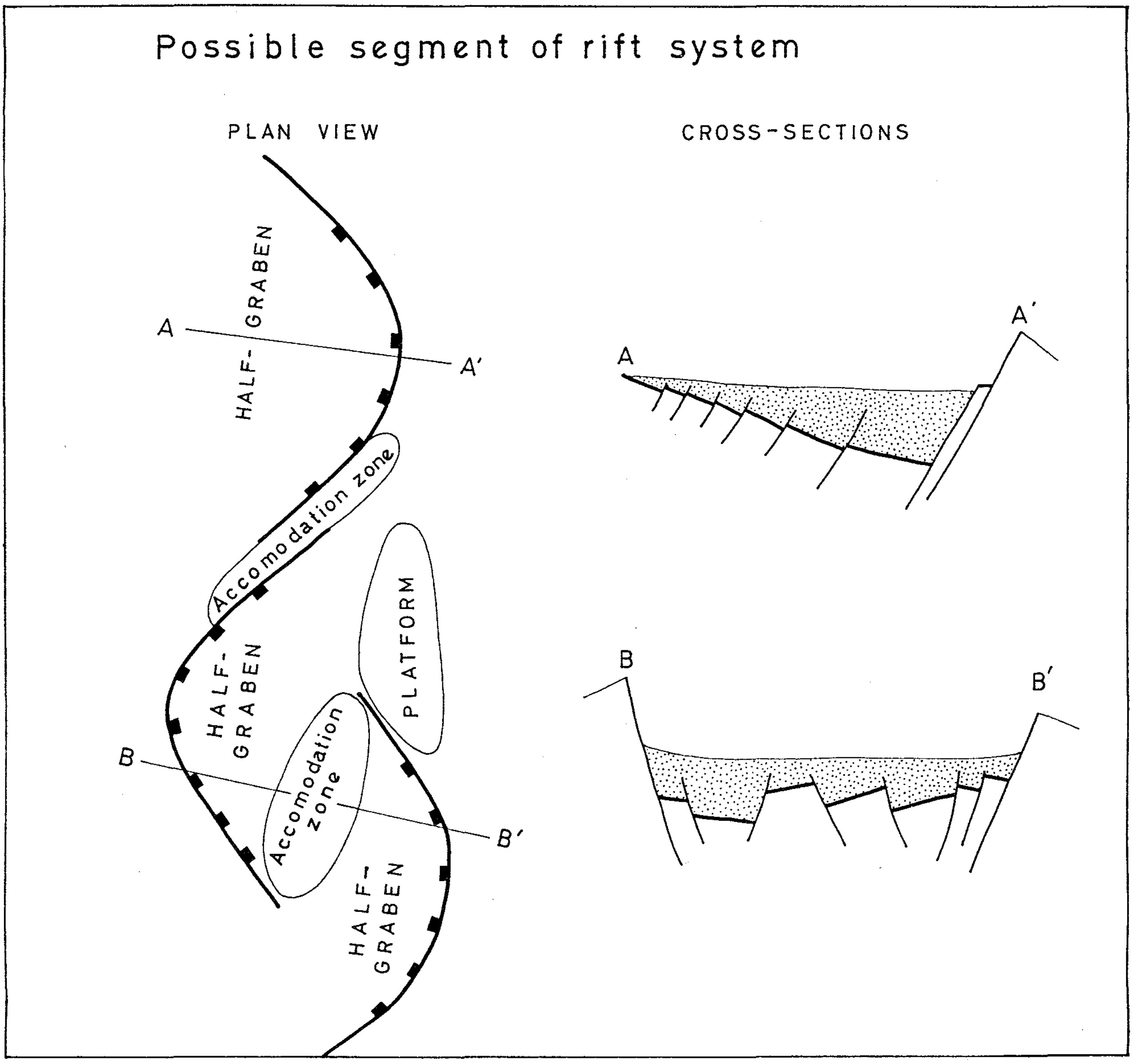

Fig. 4. - Possible segment of a rift system, formed by longitudinal association of half-graben units with development of accomodation zones and platforms (after Sander & Rosendahl, 1989 and Specht & Rosendahl, 1989).

fault systems (fig.3). The main border fault system develops at the site of maximum subsidence and shows important vertical downthrow. It separates the deepest basins from the uplifted rift mountains. The shoaling side of the half-graben is separated from the basement by small faults or flexures. The centre of the half-graben is either a simple monocline or a series of step faults striking and dipping parallel to the border fault systems. The border fault systems are usually arcuate in plan view, and they are assumed to be listric in cross section. They are relatively steeply inclined (60–70° in subsurface to 40° at depth, for listric faults). In detail, they seem to consist of a zig-zag, en-échelon arrangement of small linear faults. In the central area of the half-graben, the border faults display the maximum throw, with dominantly normal faulting. Toward the extremities of the half-graben units, the border faults usually display less throw and tend to have oblique-slip or strike-slip movements.

Around Lake Tanganyika, the great amount of subsidence along the major border fault system could be correlated with the height of the adjacent rift mountains. This suggests that the uplift of the rift flanks and the subsidence of the rift basins are associated in the same rifting mechanism (Sander & Rosendahl, 1989). As a consequence, the rift architecture also determine the drainage pattern. On the shoaling side of the half-grabens, the rift mountains are generally lower or even absent and these areas are the preferential location for the rift drainage systems and also for sediment inflow.

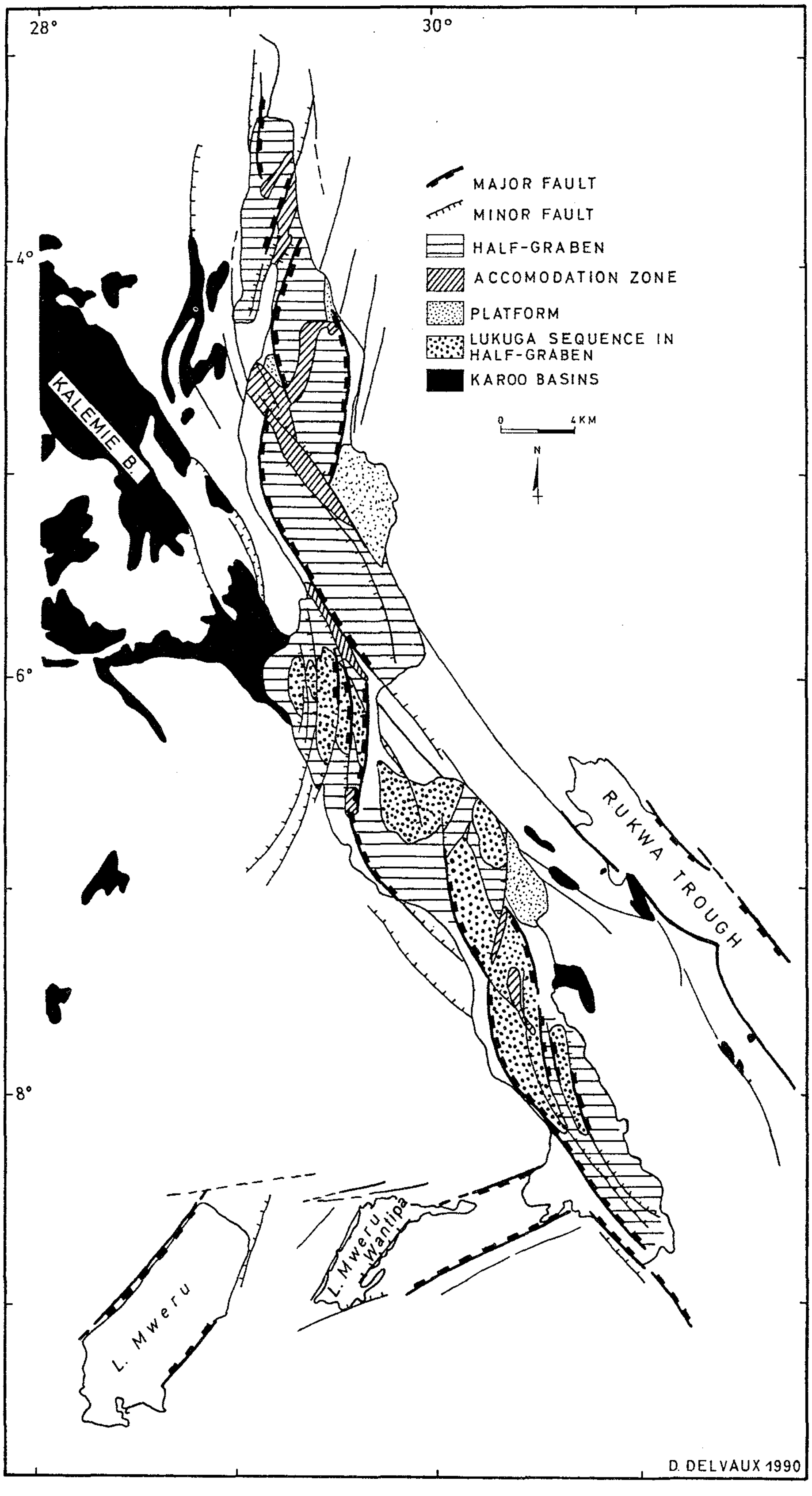

Fig. 5a. - General structure of the Lake Tanganyika rift zone (after Sander & Rosendahl, 1989), with associated fault zones (after Tiercelin & al., 1988; Mondeguer & all, 1989 and Pierce & Lipkov, 1989) and Karoo sediment outcrops.

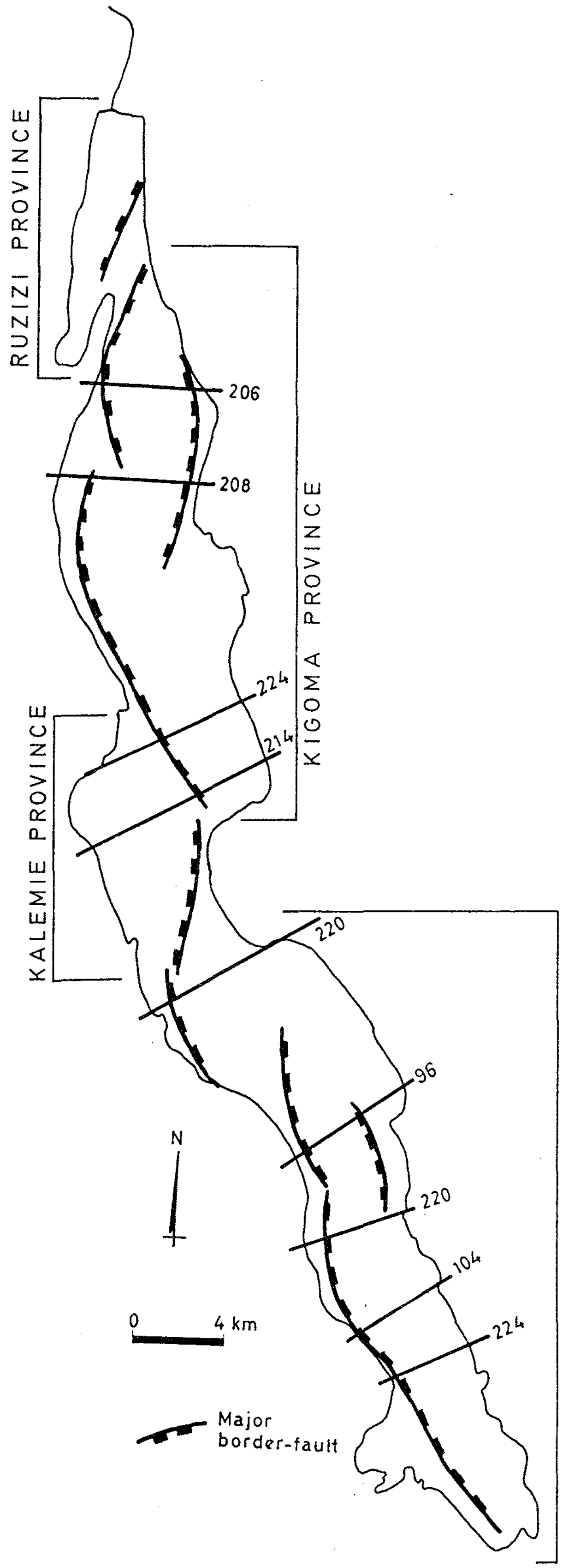

Fig. 5b. - Main subdivisions of the Tanganyika rift zone and location of the seismic cross-sections presented in fig.6.

A. LAKE TANGANYIKA RIFT SYSTEM

The Lake Tanganyika rift extends over 670 km southward from the Kivu–Rusizi volcanic province and has a width of 50 to 80 km. The surface of the lake is 762m above the sea level. The rift mountains reach elevations of 2000m above lake level and maximum depth of the lake is 1400–1500 m. The rift is filled with an estimated 4000 to 5000 m of sediments. The vertical throw between the pene-plain surface at the top of the rift mountains and at the base of the rift sediments is thus 7400–8500 m. The onset of Tertiary to Recent rifting in Lake Tanganyika is estimated to have started between the Early Miocene to Late Miocene, but rifting along the TRM zone most probably started as early as late Paleozoic (Karoo deposits). The geometry of rifting in Lake Tanganyika is interpreted mainly from PROBE multi-channel seismic reflection profiles (Sander & Rosendahl, 1989) and from the works of Mondeguer & al. (1986; 1989) on both extremities of the lake. The Tanganyika rift zone has a complex structural history. It can be divided into typical half-graben units of 80–160 km in length and 30–60 km wide (fig.5a). A reconstruction of the tectonic and stratigraphic history of the lake shows that significant changes occurred in depocenter locations during the rifting. The rift appears to have been initiated as several discrete areas and the earlier basins are located along a pre-rift lineament, at oblique angle to the axis of the rift.

Sander & Rosendahl (1989) have divided the Tanganyika rift into four structural and deposition provinces, grouping one or several half-graben units: the Rusizi, Kigoma, Kalemie and Mpulungu Provinces (fig.5b, 6).

The Kalemie half-graben cuts across the Permian Karoo rift which is known to the west of Lake Tanganyika (Lukuga series; Lepersonne, 1977). The lower seismic discontinuity in the Tanganyika sedimentary sequence is only present in the southern half of the lake. It corresponds to the upper limit of the Lukuga sequence, possibly related to the Karoo (or early Cenozoic) rifting (Tiercelin & al., 1989). From these seismic evidence and the trend of the Karoo rift, Sander & Rosendahl (1989) postulated that the Kalemie Karoo graben may continue beneath the southern half of Lake Tanganyika and influence the modern rifting pattern.

The Kalemie Province and the Mpulungu Province together form a single deposition basin, where the units are separated by low-relief accomodation zones. Three major sedimentary sequences were recognized on the seismic profiles, from bottom to top: the Lukuga (Karoo), Mahali and Songwe series. In the Mpulungu Province, the depo-

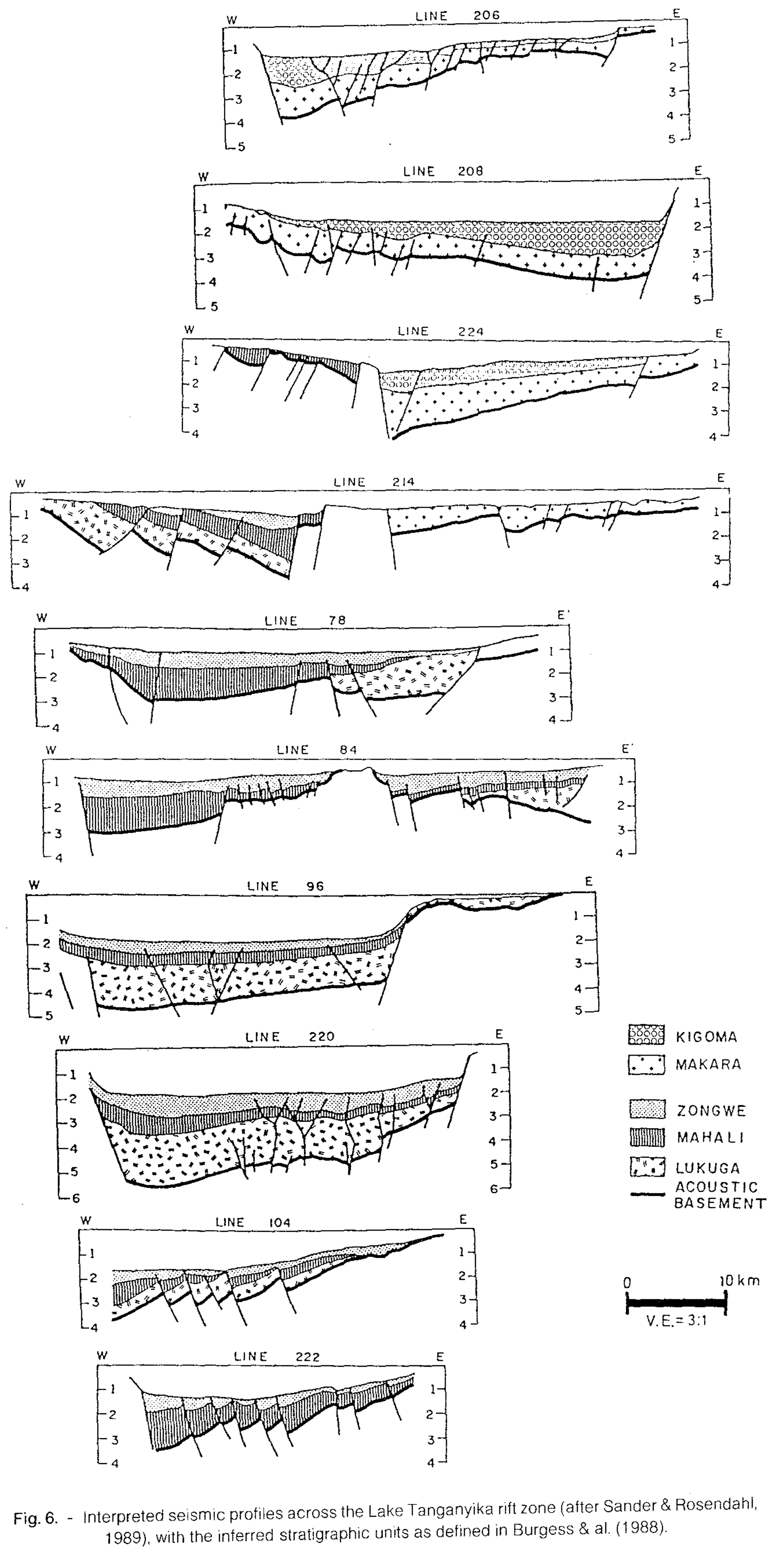

Fig. 6. - Interpreted seismic profiles across the Lake Tanganyika rift zone (after Sander & Rosendahl, 1989), with the inferred stratigraphic units as defined in Burgess & al. (1988).

centers are located mainly on the western side, next to the major border fault systems. Sedimentation is induced by subsidence, which is in turn controlled by the activity of the border fault systems.

B. LAKE RUKWA RIFT SYSTEM

The Rukwa rift lies between Lakes Tanganyika and Malawi. It consists of a 25–36 km wide and 350 km long valley, partly covered by the shallow Lake Rukwa, no deeper than 13 m. However, sediment thickness might be as much as 7.5 km (Morley, 1989).

Peirce & Lipkov (1988) found evidence for a first-order half-graben structure in the Rukwa rift, tilted to the NE. It is bounded to the northeast by a listric normal fault (Lupa fault), striking N130°E, with 5 to 10 km throw. To its southwestern side, it is bounded by a younger fault system (Ufipa fault), which creates a major relief of 3 km. The present-day structure of the Rukwa rift is the result of successive influence of Precambrian structural lineaments, Mesozoic rifting and the Tertiary to Recent rifting. The Mesozoic rifting phase in the Rukwa valley is poorly known, but it may have caused to a large degree, by a normal extensional tectonic style. However, the Present-day faulting appears to be dominated by right lateral strike-slip strain, subparallel to the Lupa fault (Chorowicz & al., 1987).

C. LAKE MALAWI RIFT SYSTEM

The Malawi rift extends over 700 km from the Rungwe volcanic province in the north to the Urema graben in the south. Lake Malawi has 550 km long by 50–80 km width. Its surface is 474 m above the sea-level, it has a maximum depth of 700m and the rift flanks rise 400–2000m above the lake level.

The Malawi rift is seismically active, but magmatism is restricted to alkalic volcanics at the northern end of the lake (Rungwe province: Harkin, 1960). The recent rift structures of Lake Malawi are assumed to be younger than Mid Miocene (Ebinger & al., 1987).

A first tectonic model of the Malawi rift is proposed by Ebinger & al. (1987). The rift geometry was later refined by the interpretation of PROBE multichannel seismic reflection profiles (Specht & Rosendahl, 1989: fig.6, 8). They subdivide the lake into seven half-graben units, typically 120 km long by 40 km wide (from north to south: Livingstone, Usisya, Mbamba, Bandawale, Metangula, Mwanjage and Mtakataka half-grabens). These basins are separated by accomodation zones and platforms, in a variety of linking modes.

The Livingstone basin tilts towards the northeast (Specht & Rosendahl, 1989). This side is bounded by the steeply dipping Livingstone border fault system (Wheeler & Karson, 1989). To the SW, it is limited by a series of small horsts and grabens (Crossley and Crow, 1980; Crossley & Owen, 1987 and Owen & Crossley, 1989). The northern part of the Livingstone border fault system is nearly rectilinear and displays maximum vertical throw (10 km after Wheeler & Karson, 1989). Towards the south, the structural evolution of the basin is marked by a decrease in vertical displacement along the Livingstone border fault and by an increase in the number of internal faults which are increasingly close to one another.

The Livingstone border fault system appears to be confined to a relatively narrow fault-zone developed in a 1–3 km-wide belt of Precambrian NW–SE ductile shear zone (Wheeler & Karson, 1989). Conversely, the major internal faults, oriented more N–S (Versfelt & Rosendahl, 1989) and presumably cross the pre-existing structural trend. Field evidence suggests that the Livingstone border fault system may have experienced a significant component of dextral-slip motion (Tiercelin & al., 1988b ; Wheeler & Karson, 1989). Small carbonatite intrusive bodies were found to cut the ductile shear fabrics and to be cut in turn by fractures bearing slickensides.

Sediment thickness in the northernmost basin (Livingstone basin) varies considerably, with an estimated maximum of 4 km and an average of perhaps 2.5 km, but a continuous reflection from the crystalline basement has not yet been identified. Seismic and field evidence on the southwestern side of the lake indicate that Mesozoic sediments (Karoo or Cretaceous) may be present in the deepest part of the basin (Specht & Rosendahl, 1989). However, this is still to be proved.

There is little seismic evidence that the area in the prolongation of the Ruhuhu and Livingstonia Karoo basins is underlain by Karoo sediments, as postulated by Crossley & Owen (1987), but is seems likely that parts of the Usisya basin may contain Mesozoic sediments.

D. TROUGHS AT HIGH ANGLE THE RIFT AXIS

Post Karoo rift depressions oriented at high angle to the major rift axis are numerous in Tanzania and adjacent countries (plate 1). They generally trend NE–SW and are filled with Neogene to Recent sediments in moderate thickness (max. 2000m). They have a vertical throw of less amplitude than in the major rift system. They are often bordered by NE–SW lineaments observed on satellite images (Villeneuve, 1983; Dehandschutter & Lavreau, 1985a).

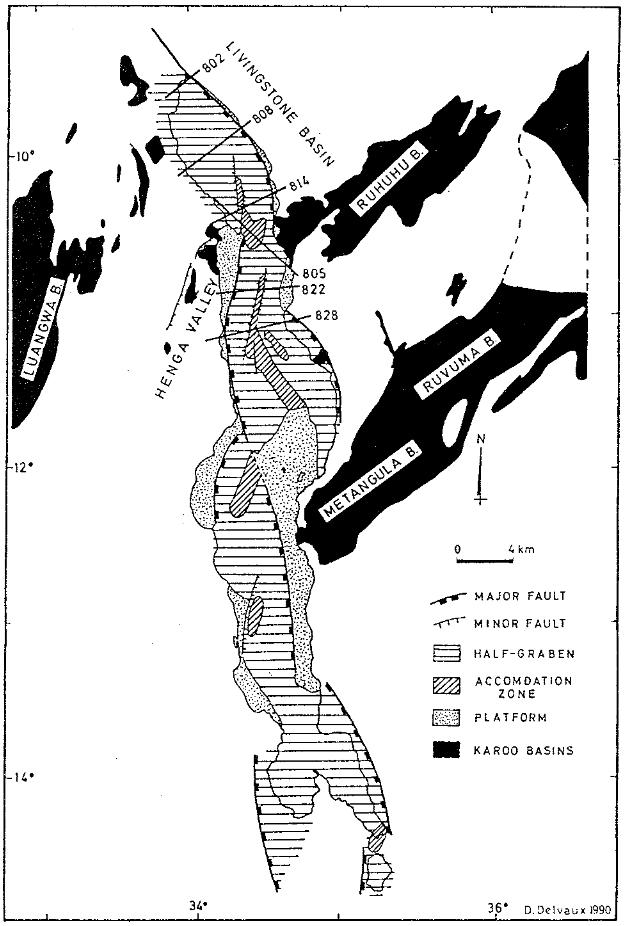

Fig. 7. - General structure of the Lake Malawi rift zone (after Specht & Rosendahl, 1989), with Karoo sediment outcrops.

The Mweru-Mweru Wantipa fault-troughs system corresponds to a series of N60°E to N40°E elongated horsts and grabens, enclosed in a fault zone of general N70°E orientation. They are interpreted as en-échelon structures, representing pull-apart basins, resulting from sinistral strike-slip movements in a general N115-135°E extension context (Mondeguer & al. 1989).

The Kilombero valley (Ulanga Flats) are bordered by NE-SW trending faults with vertical movements exceeding 1000 m (Brinckmann, 1965; Fesefelt, 1965). The fresh appearance of the fault scarps indicate recent movements (post-Karoo). They are still active today, as proved by seismic activity. They separate the basement hills from the valleys filled with Neogene to Quaternary sediments. The border faults trend subparallel to shear zones and dolerite dykes of Precambrian origin. The Luangwa Karoo rift in Zambia also has the same NE-SW direction. The NE-SW trending Karoo grabens were locally reactivated during the Tertiary to Recent period. In NE Zambia, Utting (1976) signaled renewed vertical movements in the northern part of the Karoo Luangwa-graben, where the Mid to Late Tertiary post-Karoo erosional surface is faulted.

3. KINEMATICS OF THE WESTERN RIFT DEVELOPMENT

A. ESTIMATION OF CRUSTAL EXTENSION

Upper crustal extension across the Tanganyika-Malawi rift zone can be estimated by constructing balanced cross-sections from seismic profiles and fault geometry. The reference surface used is the pre-rift erosional surface which marks the top of the crystalline basement. It can be identified in some seismic profiles and it is also recognized in the uplifted rift flanks. The values obtained are apparent extension normal to the rift axis. Because the orientation of the extension is not accurately known, these values may show only a percentage of the total extension.

For Lake Tanganyika, Morley (1988) found maximum extension of 4.5 km at the central part of the rift (± 10%) and minimum extension of 0.5-1 km at the northern and southern ends of the lake. The extension across the Rukwa rift is estimated by Morley (1988) to be 4 km. In the Rungwe accomodation zone, between lakes Rukwa and Malawi, (Ebinger & al., in press) found 2.7-3.5 km (5-9%) extension. In Lake Malawi, Specht & Rosendahl (1989) estimate the extension between 6.5 to 7%, which gives 3.5 to 5.6 km at right angle to the rift axis.

B. PRINCIPAL DIRECTION OF EXTENSION FROM RIFT GEOMETRY

For Lake Tanganyika, Scott & al. (1989) assumed a NNW to NW extension direction, which places it in the transtensional category, but Morley (1989a) stated that an E-W extension seems more appropriate. Sander & Rosendahl (1989) suggest E-W extension direction for the individual rift half-grabens, orthogonal to where the border fault system shows the greatest subsidence (or normal component). Mondeguer & al. (1989) propose a NN115-135°E extension for the conjugate system formed by the southern end of Lake Tanganyika and the pull-apart Mweru-Mweru Wantipa basin system.

Tiercelin & al., 1988b suggest strictly NW-SE dextral strike-slip movement for the Livingstone border fault at the northern end of Lake Malawi. However, this would cause a restraining bend between Lake Rukwa and Lake Tanganyika and there is little evidence of major Cenozoic compressional structures in this area. On the contrary, the 4 km extension reported by Morley, 1989 should indicate a more E-W extension direction, which places the Rukwa rift in a transtensional situation. Wheeler & Karson (1989) interpret the Livingstone basin, as a pull-apart rela-

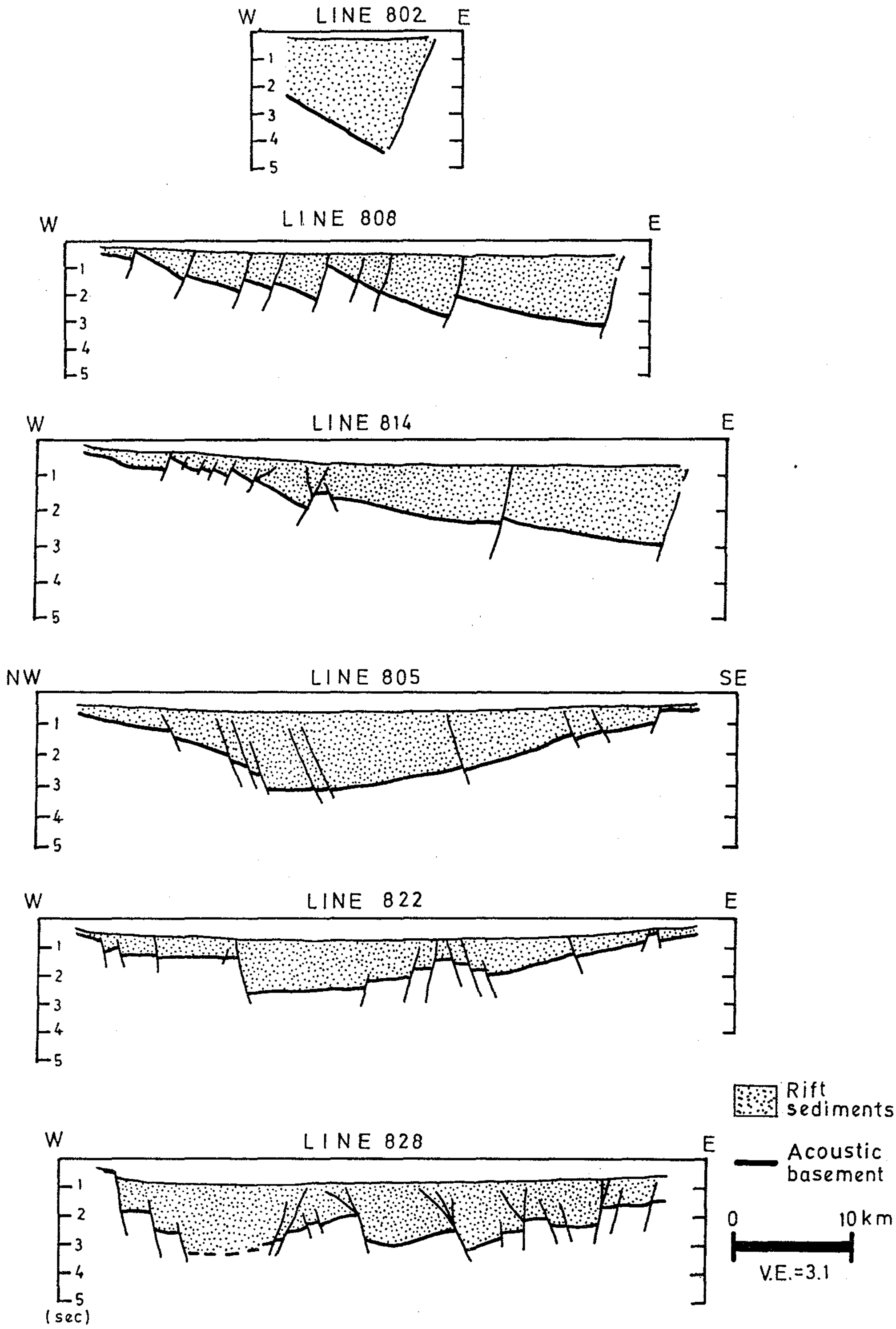

Fig. 8. - Interpreted seismic profiles across the northern part of the Lake Malawi rift zone (after Specht & Rosendahl, 1989).

ted to oblique–slip, normal–dextral movement along the Livingstone border–fault.

For central portions of Lake Malawi, the dominantly N-S striking of border fault systems favour an E–W extension direction over much of the Malawi rift zone (Specht & Rosendahl 1989). The southern part of Lake Tanganyika, Lake Rukwa and northern Lake Malawi (TRM zone) lies on a Precambrian structural lineament which act as a strike–slip shear zone several times during the Proterozoic (McConnell, 1980; Klerkx & Nanyaro, 1988). Wrench faulting probably also occurs along it in recent times (Chorowicz & al., 1983) but their relative age with respect to border fault formation is not well constrained.

C. PALEOSTRESS DIRECTIONS FROM FAULT DATA

Tentative reconstructions of the paleostress principal directions from fault-striation analysis were made by Chorowicz & Mukonki (1980), Chorowicz & al., (1983) and Tiercelin & al. (1988b), using the right dihedron method of Angelier & Mechler (1977). They concluded in dextral strike–slip movements along NW–SE inherited fractures and later local oblique–slip movements. They stated that the direction of maximum extension remained fixed in a NW–SE (N140°) direction, while the direction of maximum compressive stress was more variable, being horizontal for the regional strike–slip movements and more vertical for the later movements.

A revision of the fault slip data by Daly & al. (1989) indicate dextral oblique–slip to normal dip–slip movements, compatible with a general WNW–ESE to E–W extension direction for the whole western branch of the rift. This movement is also confirmed by Wheeler & Karson (1989) for the Livingstone border–fault system, at the NW end of Lake Malawi. However, they reported the presence of several sets of slickensides, some subhorizontal, some subvertical but the majority of them plunging moderately to the NW. As a consequence, rift faulting is probably more complex than a single event and the precise paleostress regimes that have prevailed during the Tertiary to Recent rifting is still to be determined, as well as its evolution in time and space.

D. ACTUAL STRESS DIRECTIONS FROM MICRO-SEISMICITY

The solution of earthquake focal mechanisms associated with the East–African rift system gives a great variety of extension directions: ENE–WSW, E–W and WNW–ESE (Fairhead & Girdler, 1972; Fairhead & Stuart, 1982; Shudovsky, 1985). This is due to somewhat ambiguous results as well as to different geological interpretations (e.g.: E–W regional extension for Morley, 1988 & 1989a and NNW–SSE to NW–SE for Scott & al., 1989).

Chorowicz & al. (1987) present a compilation of earthquake foci from which they deduced that most of the actual fault mechanism are compatible with NW–SE to WNW–ESE extension and that some of them show E–W extension or, very rarely, NE–SW extension. In the less evolved Lake Mweru area, extension trends are exclusively NW–SE to WNW–ESE, while in the more evolved northern part of the Western rift, extension strikes between NW–SE and NE–SW.

The Livingstone area is known to be seismically active (Crossley & Crow, 1980). In addition, recent strike–slip or oblique–slip movements along the Livingstone border fault system is indicated by minor NW–trending faults with gently plunging slickensides that cut recent lava flows in the Rungwe caldera (Wheeler & Karson, 1989).

E. KINEMATIC MODELS OF RIFT EVOLUTION

The kinematic evolution of the East–African rift system is interpreted by Chorowicz & al. (1987) in a succession of four major stages, characterized by a progressive rotation of compression direction from horizontal (strike–slip regime) to vertical (extension regime), with the extension axis remaining in a fixed horizontal NW–SE to E–W direction.

This model was already proposed in a more theoretical way by Dehandshutter and Lavreau (1985b), following the idea of Cloos (1955) that the onset of regional lithospheric arching or updoming should be marked by a transition from compressional to tensional stress regimes. Therefore, two successive stages should be recognized in the evolution of regions of updoming: (1) strike–slip movements along the inherited lines of weakness, as the result of compressional strike–slip regime (E–W minimum compression, N–S maximum compression) and (2) evolution to dip–slip movements as the result of gradational permutation of the maximum principal stress axis from horizontal to vertical.

An alternative model should be tested for western branch of the rift system, following the results recently proposed by Strecker & al. (1990) for the Kenya rift. They determined paleostress axis orientation from faults observed in chronologically well defined stratigraphic units and found that the extension direction rotates clockwise from NE–SW to NW–SE, while the intermediate direction remained fixed in a vertical position. Due to the clockwise rotation of extension direction, the previously formed N–S, NNW & NW faults were reactivated with a strong dextral component. This new NW–SE extension direction is corroborated by earthquake focal mechanism and also by borehole–breakout data. They suggest that the mechanism that brought about the rotation of the stress field could result in a recent change in tectonic evolution between the boundaries of the Nubia and Somalia plates along the Red Sea and the Gulf of Aden spreading zones.

A similar mechanism should be tested for the TRM zone. Effectively, as reported above, horizontal slickensides were reported on recent fault planes in the Rungwe caldera, and several authors suggest that E–W to ENE–WSW extension should have acted as dominant mechanism for the formation of half–graben structures. In addition, the fault analysis for paleostress axis determination that was performed along the TRM zone are not always done in chronologically well–defined units and the relative chronology between the several set of slickensides is often difficult to establish.

F. INFLUENCE OF PRE–RIFT STRUCTURES

For many authors, it is clear that both the pre–rift structures and the evolution of the stress field orientation played a great influence in the rift evolution (McConnell, 1980; Daly & al., 1989; Versfelt & Rosendahl, 1989; Wheeler & Karson, 1989...). The presence of anisotropies in the basement, such as major shear zones is likely to have a controlling effect on the location of the overall western branch of the rift system, as well as for smaller-scale structures, as half–grabens and border–fault systems. These prerift structures might be shear zones of Proterozoic to Early Cambrian age, as well as Karoo faults or half–graben structures. Reactivation of these old lines of weakness is very likely along the TRM zone.

4. GEODYNAMICS OF RIFTING

A. STRUCTURE OF THE LITHOSPHERE

Interpretation of the large–scale Bouguer gravity anomalies and teleseismic delay times for the whole African continent indicate that the lithosphere is thinned beneath much of the East–African rift system (Fairhead and Reeves, 1977; Brown & Girdler, 1980).The lithosphere is the thinnest beneath the eastern branch (Kenya rift) and the thinning decreases towards the south. The greatest lithospheric thinning occur in the region of the most intense rift volcanism, which could be normally expected. The area of thinned lithosphere also corresponds fairly well to the extensive regions of high plateaus, but it has no simple correlation with the distribution of active seismicity. The cause of this thinning should be due either to mechanical necking of the lithosphere or to a thermal replacement of the lower part of the lithosphere by less dense asthenosphere, as the result of an upward movement of the lithosphere–asthenosphere boundary (Fairhead, 1977). The progressive thinning of the lithosphere probably begun as early as 35 Ma ago (Wendlandt & Morgan, 1982). The lateral extension of the supposed region of lithosphere thinning is not restricted to the immediate underground of the major rift valleys, but it has a width of about 1500 km, which comprises all the region bounded by the eastern and the western branch of the East–African rift.

B. RIFTING MODELS

Following the development of the concept of mid–oceanic ridge systems, it has been suggested that the oceanic ridge of the Gulf of Aden bifurcates in the Afar depression in Ethiopia, into the Red sea branch and the East–African branch. However, as recalled by McConnell (1972), the East–African rift system is fundamentally different from typical mid–oceanic ridges because it is not spreading and does not

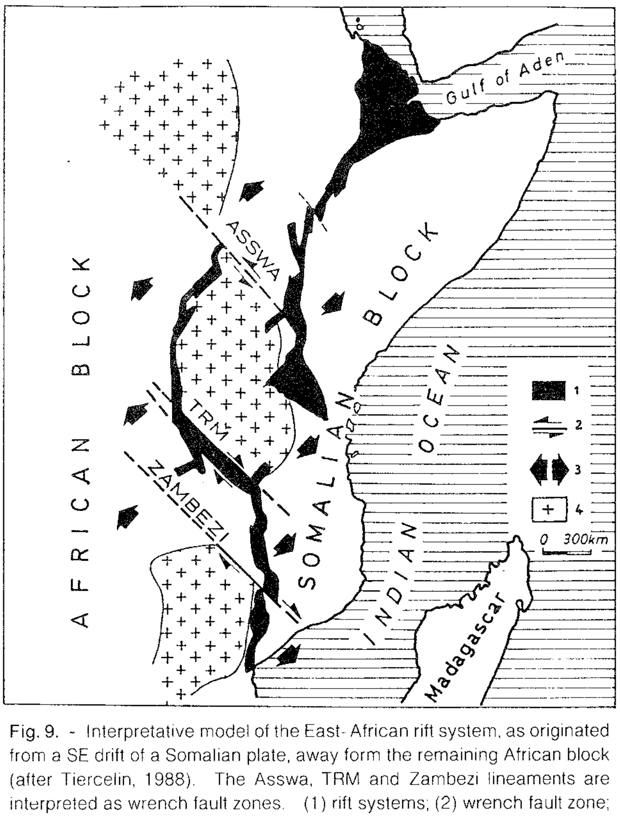

Fig. 9. - Interpretative model of the East- African rift system, as originated from a SE drift of a Somalian plate, away form the remaining African block (after Tiercelin, 1988). The Asswa, TRM and Zambezi lineaments are interpreted as wrench fault zones. (1) rift systems; (2) wrench fault zone; (3) inferred direction of movement; (4) cratons.

contain new oceanic crust. He also emphasized that the African plate has remained in a stable position until the onset of Gondwana breakup, being squeezed between the mid-Atlantic and mid-Indian Ocean spreading ridges. Its distension is then impeded by the geologic setting.

Chorowicz (1983, 1989), Daly & al. (1989) and Tiercelin & al. (1988b) suggest that the East-African rift system results from the separation of the Somalian plate from the rest of the continent (fig.9). They stated that this plate moves away from Africa in a general movement along NW-SE direction. In this model, the central part of the western branch (rifts South-Tanganyika, Rukwa and North-Malawi, zone TRM) forms a linear geometrical arrangement of en-échelon faults. Following this model, the TRM zone is subjected to oblique extension (transtensional) while the northern and southern parts of the western rift are subjected to pure extension. The relative movement between the Somalian and African plates thus implies dextral strike-slip movements along the TRM zone, which acts as a transfer fault zone. The southeastward drift of the Somalian plate also implies sinistral movements along the Aswa lineament and dextral movements along the Zambezi lineament.

It has been suggested that the rifting geometry in East-Africa could be described as a relay of detachment structures, like in the Basin and Range tectonic province of the western United States (Morley 1989b, Bosworth, 1987). The detachment structures can be identified in association with the border fault zones of alternating polarity that were revealed in the PROBE seismic reflection surveys (Bosworth, 1989). By analogy with the Basin and Range model, the crustal extension in the East-African rift could be entirely accommodated in the continental plate, as a consequence of increased lithosphere ductility. At depth, the low-angle detachment may traverse the entire crust and pass to the mantle (simple-shear model of Wernicke, 1985) or it may be taken up by distributed stretching in the lower part of the crust (pure-shear model of McKenzie, 1978). The absence of complete crustal separation of the Somalian plate from the rest of Africa suggests that East-Africa is not representative of an early stage in the development of oceanic rifting (Bosworth, 1989). The latter also stated that the direction of movement of the upper plate should be roughly normal to the detachment geometries. This gives a general E-W extension direction for the whole East-African rift system.

For the East-African rift, Bosworth (1987) have applied the simple-shear model in the Kenya rift, but Morley (1989b) favour the pure-shear stretching model. The latter present a comparison between the western branch of the rift (Tanganyika rift) and the eastern branch (Kenya rift), in which the Kenya rift may represent a more evolved rift system than the Tanganyika one. However, Morley (1989) does not take into account the fact that the southern part of the Tanganyika rift may have been originated as early as in Karoo times.

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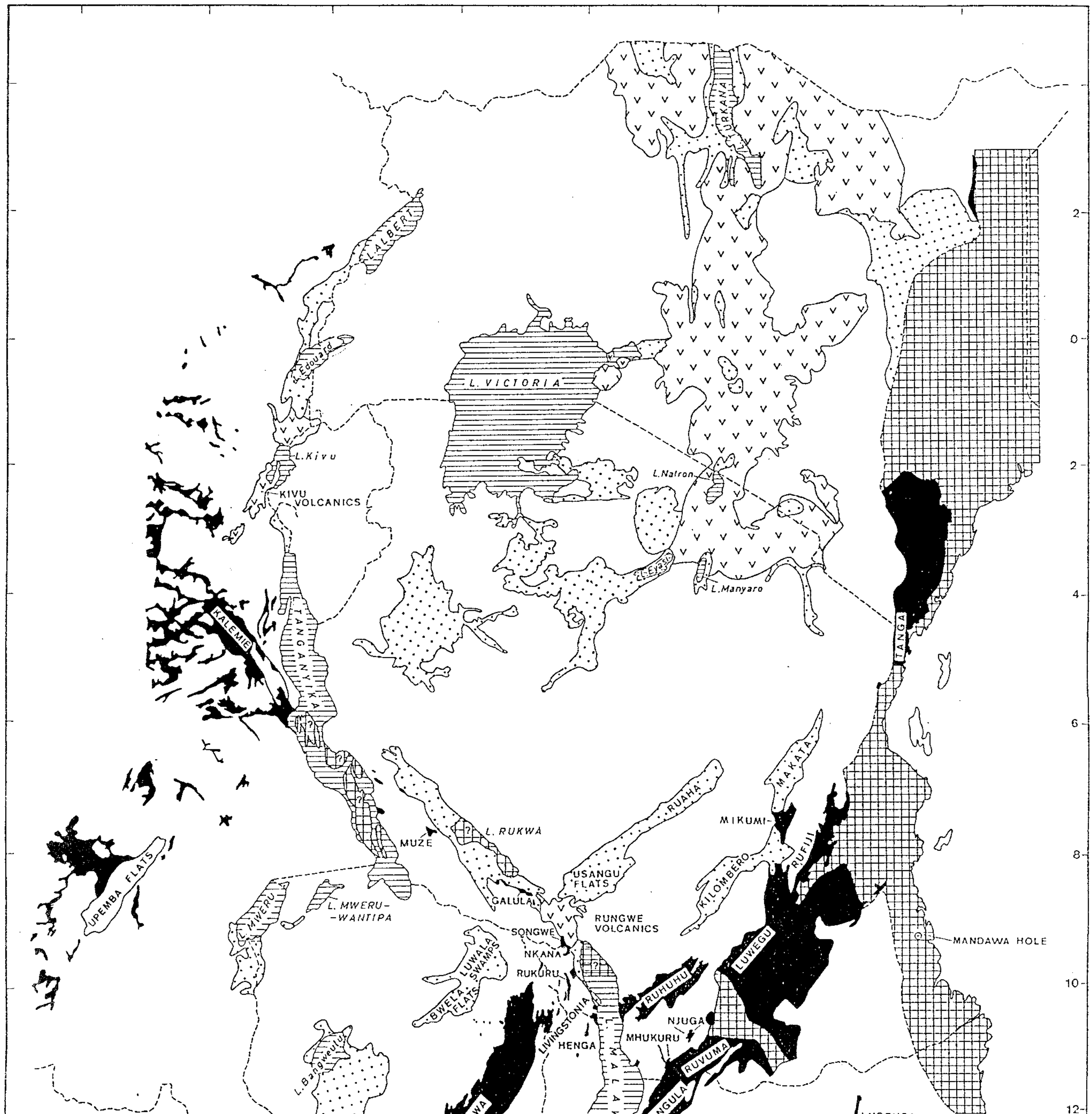

PLATE 1. - Distribution of Karoo and Late Tertiary to Recent sediments and volcanics in East Africa.