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ARCHITECTURE OF CONTINENTAL RIFTS WITH SPECIAL REFERENCE TO EAST AFRICA

B. R. Rosendahl

Project PROBE, Department of Geology, Duke University, Durham, North Carolina 27706

INTRODUCTION

The Earth's continental skin has been cracked many times in many places during the last several billion years. The resulting rifts number in the hundreds (Burke 1978, Ramberg & Neumann 1978a, Easton 1983, Milanovsky 1983, Ramberg & Morgan 1984), and they occur on virtually every continent. Although the actual land area occupied by rift structures is relatively small (less than 2% of the surface area of continents), at least 3,000,000 words on 10,000 pages in 700 papers have been written on the subject. If colligated, such a body of literature would be comparable to a set of Britainnica encyclopedia. There are many reasons for this attention, but current interests revolve around two main points: (*a*) Continental rifts are a precursor of ocean basins, and (*b*) much of the petroleum yet to be located is either directly or indirectly related to rift structures.

The vastness of the rift literature combined with manuscript limitations make it inappropriate to undertake a full review of rifts here. Even a restriction to African rifting could result in 50 printed pages of citations. Clearly, another approach is needed. The approach taken here is to focus on the morphology and structure of East African rift basins from the perspective of a rifting theme that is being developed by the author and his associates. We then explore some of the more salient implications of the theme, testing them against prevailing doctrines, sentiments, or opinions. The end product is a tightly focused review of African rift

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morphology and structure packaged within a single architectural theme. It might be noted that this approach automatically eliminates from discussion those topics that do not bear directly on the structural expressions of rifting (e.g. certain aspects of petrogenesis).

NOMENCLATURE FOR RIFTS

The nomenclature of the East African Rift (and of continental rifts in general) can be confusing and misleading. For example, most references to the East African Rift strictly apply only to the Kenya Rift, not the entire rift proper. The use of the word "rift" can refer either to something as large as the entire East African System or to features as small as the Lake Albert trough. The term "rift-valley" can describe something either larger than Lake Malawi or smaller than a football field. Before progressing further, it is useful to establish a more natural, "generic" nomenclature than those available to date. A multitiered scaling terminology is adopted here, building around a theme of blocks, within units, within zones, within branches, within systems. Throughout this discussion, comparisons within or between rift systems are made only at comparable generic scales.

System and Branch Scales

The largest rift scale to be dealt with here is the "system." Most workers agree that at least several rift systems have been operative in Africa since the Permian, but it is not always clear which rift elements belong to which system. The problem is illustrated in Figure 1, which shows that the Tertiary Rift System in East Africa apparently overprints a number of older rift structures. These older structures are mostly erosional remnants of Permo-Triassic to Jurassic Karroo troughs. The incompleteness of exposures, combined with poor age control and lack of subsurface information, makes it difficult to define the system(s). For this reason, the system scale is applied herein only to Cenozoic rifting in Africa.

The branch scale is the first-level subdivision of a rift system. It has long been recognized that the Tertiary System of East Africa is divided into Eastern and Western branches (Gregory 1896). Most workers have attributed the bifurcation to a deflection of rifting stresses around the Tanganyika Shield (e.g. McConnell 1967). It is significant that the division into branches coincides with marked differences in certain rifting traits. Most notable is the extreme difference in the quantity of volcanic effluents; the Eastern Branch is one of the "wettest" continental rift branches in the world, whereas the Western Branch is among the "driest" (Mohr 1982). In this regard, the contrast between these branches is as great as that between any two branches from any two rift systems. It is likely that the

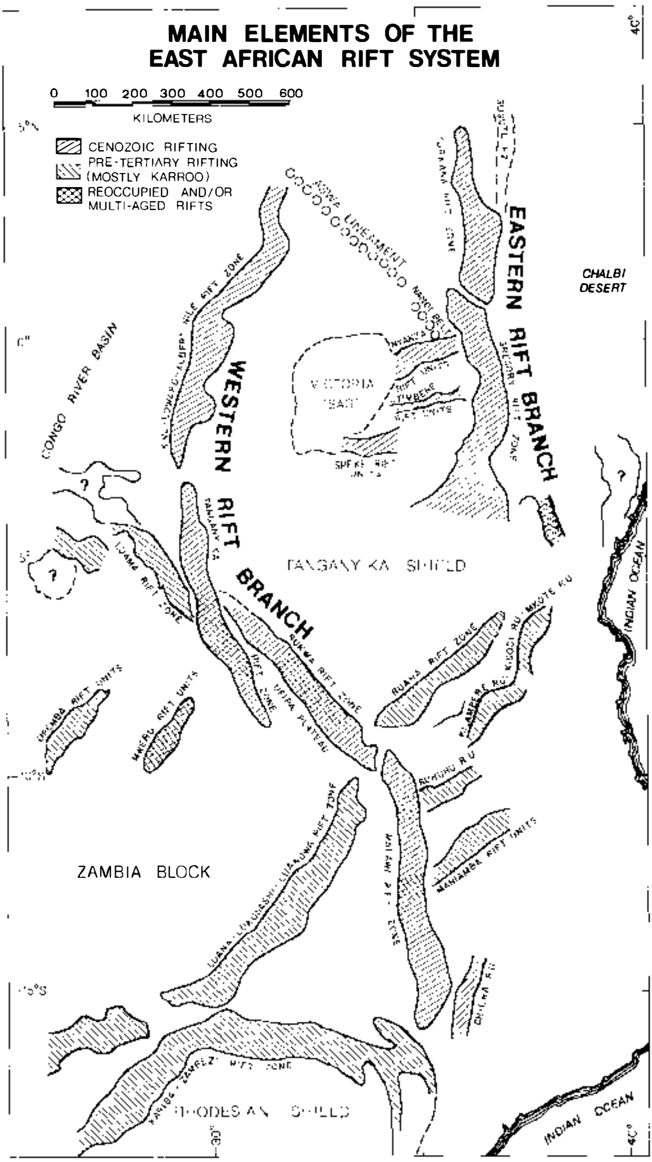


Figure 1 Map portfolio. Figure 1*a* (*above*) shows the main rift elements, especially zones. Note that the Malawi Zone is associated with the Western Branch, which overprints pre-Tertiary zones. Zonal terminations usually coincide with major kinks, offsets, or bends. Figure 1*b* shows sedimentary and volcanic cover. Figure 1*c* presents an interpretation of the inferred rift units throughout East Africa (see text for explanation of terminology). Figure 1*d* shows a possible trailing plate margin configuration for East Africa.

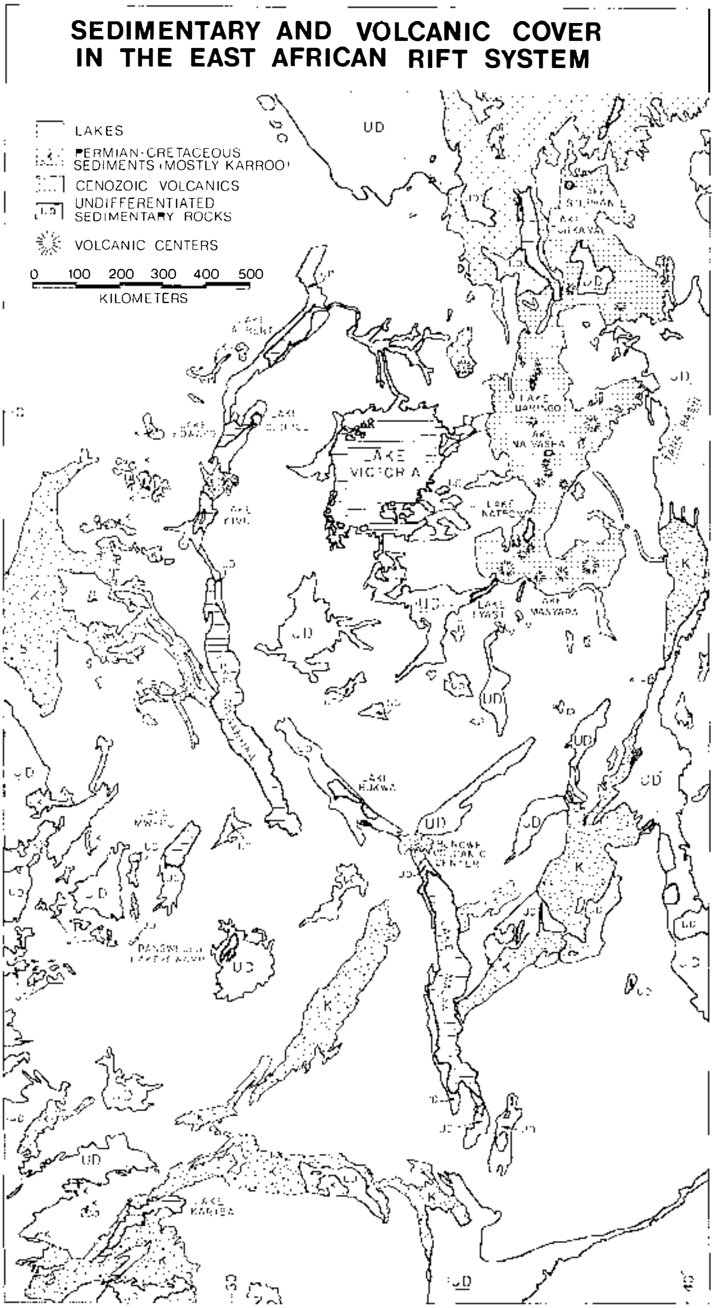

SEDIMENTARY AND VOLCANIC COVER
IN THE EAST AFRICAN RIFT SYSTEM
LAKES
PERMIAN-CRETACEOUS SEDIMENTS (MOSTLY KARROO)
CENOZOIC VOLCANICS
UNDIFFERENTIATED SEDIMENTARY ROCKS
VOLCANIC CENTERS
0 100 200 300 400 500
KILOMETERS
LAKE VICTORIA
LAKE BARINGO
LAKE NATRON
LAKE MANYARA
LAKE RUKWA
LAKE KARIBA
UD
K

Figure 1b

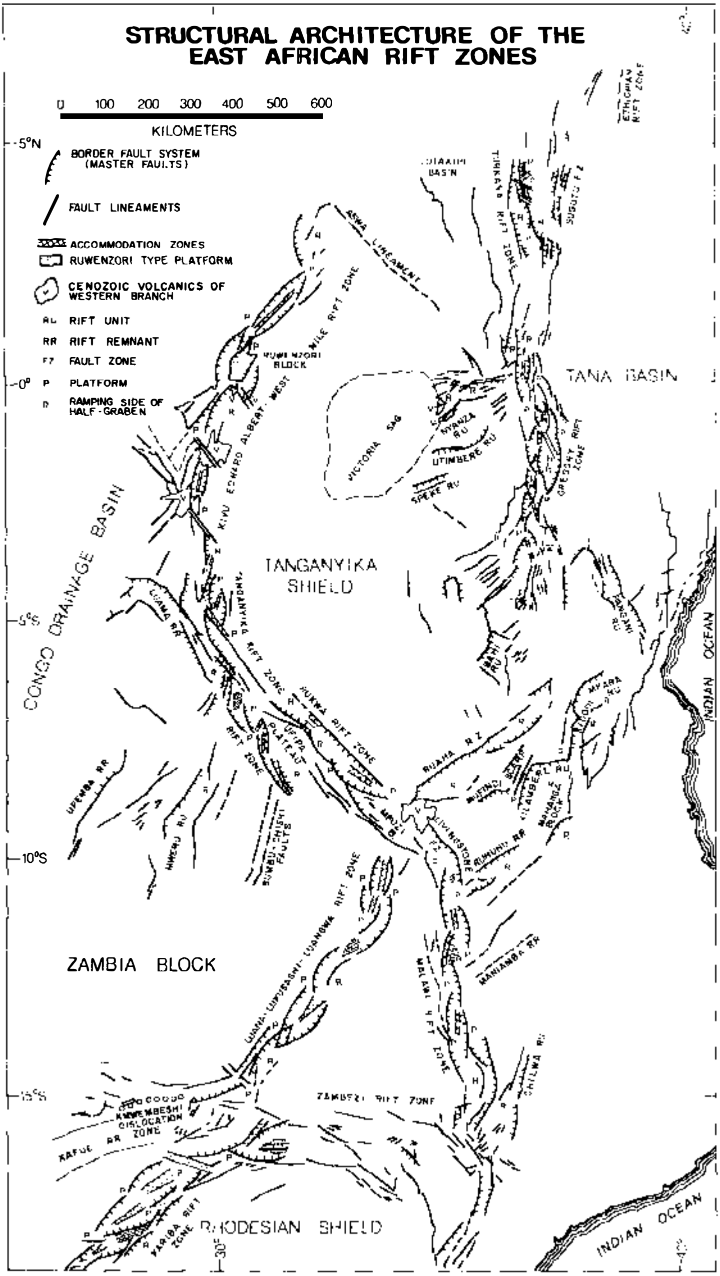

STRUCTURAL ARCHITECTURE OF THE EAST AFRICAN RIFT ZONES
0 100 200 300 400 500 600
KILOMETERS
BORDER FAULT SYSTEM (MASTER FAULTS)
FAULT LINEAMENTS
ACCOMMODATION ZONES
RUWENZORI TYPE PLATFORM
CENOZOIC VOLCANICS OF WESTERN BRANCH
RU RIFT UNIT
RR RIFT REMNANT
FZ FAULT ZONE
P PLATFORM
R RAMPING SIDE OF HALF-GRABEN
5°N
0°
5°S
10°S
15°S
30°E
ETHIOPIAN RIFT ZONE
ASWA LINEAMENT
NILE RIFT ZONE
RUWENZORI BLOCK
TANA BASIN
VICTORIA SAG
NYANZA RU
UTIMBERE RU
SPEKE RU
GREGORY RIFT ZONE
KIVU EDWARD ALBERT WEST
CONGO DRAINAGE BASIN
TANGANYIKA SHIELD
TANGANYIKA RIFT ZONE
LUAMA RR
RUKWA RIFT ZONE
UFIPA PLATEAU
RIFT ZONE
RUAHA RZ
UPEMBA RR
MWERU RU
MBALA FZ
LIVINGSTONE FZ
RUHUHU RR
MAHENGE BLOCK
KILOMBERO RU
INDIAN OCEAN
ZAMBIA BLOCK
LUANGWA RIFT ZONE
MALAWI RIFT ZONE
MANIAMBA RR
SHIRE RIFT ZONE
ZAMBEZI RIFT ZONE
MWEMBESHI DISLOCATION ZONE
KAFUE RR
KARIBA RIFT ZONE
RHODESIAN SHIELD
INDIAN OCEAN

Figure 1c

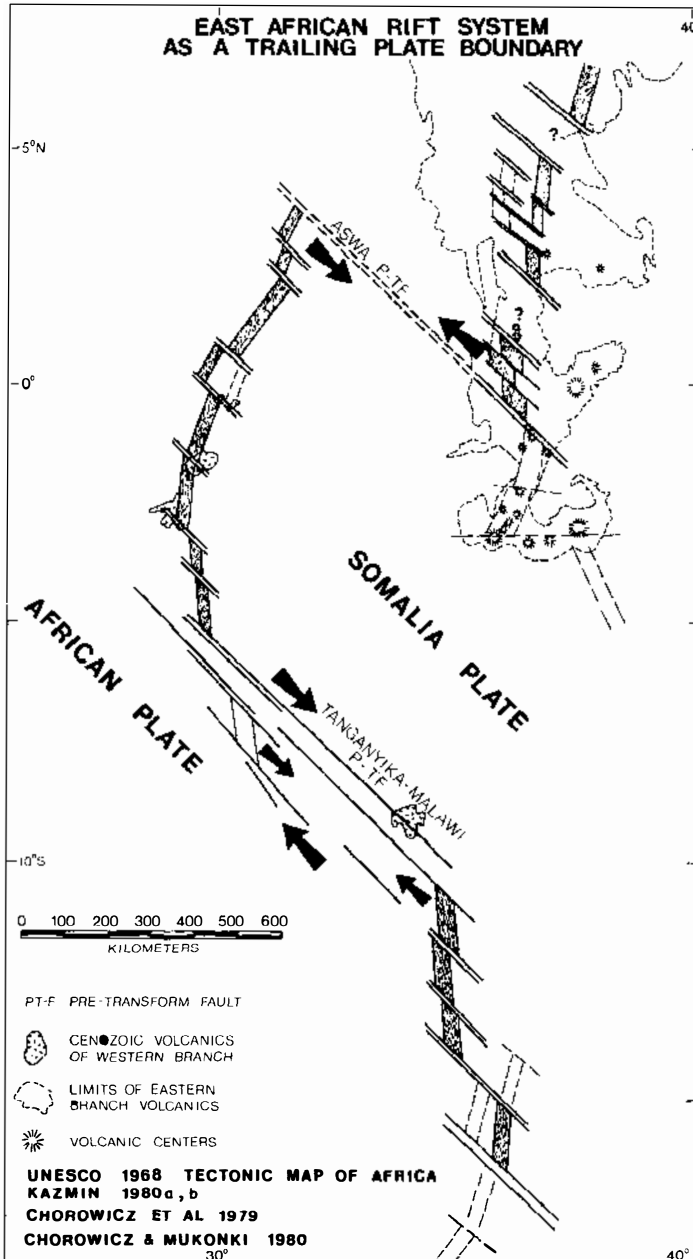

EAST AFRICAN RIFT SYSTEM
AS A TRAILING PLATE BOUNDARY
40°
5°N
0°
10°S
ASWA P-TF
SOMALIA PLATE
AFRICAN PLATE
TANGANYIKA-MALAWI P-TF
0 100 200 300 400 500 600
KILOMETERS
PT-F PRE-TRANSFORM FAULT
CENOZOIC VOLCANICS OF WESTERN BRANCH
LIMITS OF EASTERN BRANCH VOLCANICS
VOLCANIC CENTERS
UNESCO 1968 TECTONIC MAP OF AFRICA
KAZMIN 1980a, b
CHOROWICZ ET AL 1979
CHOROWICZ & MUKONKI 1980
30°
40°

Figure 1d

difference in abundance is even greater if rift-related plutonic rocks also are considered (e.g. see Ramberg & Morgan 1984).

The Malawi Rift Zone (Figure 1) forms the "trunk" of the East African rift tree and might be expected to display affinities with both branches. This does not seem to be true; thus far, our studies of the Malawi Rift Zone show that it is very similar to the other Western Branch rift zones, especially Lake Tanganyika. Hence, the Malawi Zone is included here as part of the Western Branch.

Several of the pre-Cenozoic rift remnants shown in Figure 1 could be grouped into branches, but it is difficult to prove strict genetic, or even temporal, links. Possibly the Luano, Lukusashi, Luangwa, and Ruaha rift zones (Dixey 1937a, Drysdall & Kitching 1963, de Swardt et al 1965, Drysdall & Weller 1966, Vail 1967) belong to a rift branch that originates from a bifurcation of the Kariba Rift Zone (Molyneux 1909, Guernsey 1951, Gair 1959, Tavener-Smith 1960, Drysdall & Weller 1966, Chapman & Pollack 1977, Fairhead & Henderson 1977). The other limb would be the Central Zambezi Branch (Dixey 1944a, de Swardt 1965, Vail 1967). This situation might be analogous to the bifurcation of the Tertiary African Rift System around the Tanganyika Shield.

Rift-Zone Scale

Rift branches are subdivided into rift zones in ways that are morphologically obvious but mechanically poorly understood. Usually the zonal boundaries coincide with offsets, kinks or major changes in the trends of adjacent rift zones, all of which may be associated with centers of volcanism. Such changes are obvious in Figure 1*a* but less so in Figure 1*c*. The fact that rift zones worldwide generally have lengths of 500–700 km argues that the division into zones has some genetic validity, but it appears the relationship is neither as simple nor as direct as some believe. We return to this issue in a later section. The Cenozoic rift zones of East Africa are named below, along with listings of key citations. Locations are provided in Figure 1.

MALAWI RIFT ZONE The Malawi Rift Zone includes all of Lake Malawi proper and the Shire Valley at the south end of the lake. The zone terminates at the north end in the Rungwe volcanic province (Andrew & Bailey 1910, Thiele & Wilson 1915, Dixey 1929, 1937b,c,d, 1944a, 1945a,b, 1956, 1959, Harkin 1960, Garson 1965, Lister 1967, Bloomfield 1966, 1968, Vail 1967, von Herzen & Vacquier 1967, Girdler & Sowerbutts 1970, Carter & Bennett 1973, Andrew 1974, Yairi 1977, Muller & Forstner 1973, Crossley & Crow 1980, Kaufulu et al 1980, Crossley 1982, Rosendahl & Livingstone 1983, Ebinger et al 1984, Ebinger & Rosendahl 1986).

RUKWA RIFT ZONE The Rukwa Rift Zone extends from the Rungwe volcanic province in the south, northwestward through the Rukwa trough and into the Karema gap to the east of Lake Tanganyika (Harvey & Teale 1933, Poussin 1935, Stockley 1938, Holmes 1944, 1965, McConnell 1950, Quenncll 1951, 1960b, Spurr 1954, Spence 1954a,b, Harpum 1955a,b, Harkin 1960). The northern end of the Rukwa Zone is rather ill defined, and the connection to the Tanganyika or Luama rift zones is unclear.

TANGANYIKA RIFT ZONE The Tanganyika Rift Zone consists of Lake Tanganyika plus the plain of the Ruzizi at the north end of the lake (Cornet 1905, Holmes 1916, Krenkel 1925, Teale 1932, Veitch 1935, Poussin 1935, Willis 1936, Dixey 1945a,b, 1956, 1959, Capart 1949, McConnell 1950, 1972, Wayland 1952, James 1956, Cookc 1957, Sanders 1965, Yairi & Mizutani 1969, Degens et al 1971, Bath 1975, Chorowicz & Mukonki 1980, LeFournier 1980, Patterson 1982, Rosendahl & Livingstone 1983, Lorber 1984, Burgess 1985, LeFournier et al 1985, Rosendahl et al 1986, Sander 1986). Because our structural understanding of the Tanganyika Rift Zone exceeds that of any other African rift zone, many of the examples in this paper are drawn from this zone. In many ways we consider it to be the archetypical continental rift.

ALBERT RIFT ZONE The Albert Rift Zone includes the rifted troughs from Lake Kivu in the south through the West Nile Basin in the north, including Lakes Edward, George, and Albert (Holmes 1916, 1942, Wayland 1921a,b, 1931, Combe 1930, Holmes & Harwood 1932, 1937, Boustakoff 1933, Willis 1936, Dixey 1944a, 1945a,b, 1956, 1959, Davies & Bisset 1947, Lepersonne 1949, 1956, 1970, Davies 1951, McConnell 1951, 1959, Cahen 1953, 1954, Hopwood & Lepersonne 1953, Meyer 1954, Pallister 1954, 1955a,b, Ruhe 1954, Heinzelin 1955, Harris et al 1956, Pallister & Hepworth 1956, Peeter 1959, Sahama & Meyer 1958, Barnes & Hepworth 1961, von Knorring & du Bois 1961, Hepworth 1962, Sahama 1962, Furon 1963, Bishop 1965, 1969, Gautier 1965, 1967, Bishop & Trendall 1967, de Swardt & Trendall 1969, Macdonald 1968, 1969, King 1970, Degens et al 1973, Wong & von Herzen 1974, Stoffers & Hecky 1978, Chorowicz et al 1979, Chorowicz & Mukonki 1980).

GREGORY RIFT ZONE The Gregory (Kenya) Rift Zone extends from approximately Lakes Manyara and Eyasi in the south to Lake Baringo in the north (Gregory 1896, 1920, 1921, Obst 1913, Shackleton 1945, 1951, 1955, 1978, Dixey 1945a, Baker 1958, 1963a,b, 1965, 1970, 1971, McCall 1964, 1968a,b, McConnell 1967, 1972, 1974a,b, 1979, Tobin et al 1969, Girdler & Sowerbutts 1970, King 1970, Baker & Wohlenberg 1971, Baker et al 1971, 1972, 1978, Logatchev et al 1972, 1983, Mohr 1974, 1976, Fairhead & Walker 1974, Fairhead 1976, Logatchev 1978, Long & Backhouse 1976, Maguire & Long 1976, Mohr & Wood 1976, Mboya 1983). It is convenient to include the Nyanza (Kavirondo), Utimbere, and Speke rift units with the Gregory Zone, but the temporal and mechanical relationships of these units to the zone are not well defined. In comparison to the ends of most of the Western Branch rift zones, the terminations of the Gregory Zone are relatively broad and diffuse. The southern end splays into a region called the Tanzania Divergcnce, and the northern end partially disappears beneath volcanic cover. This makes the distinction between this zone and the Turkana Zone (see below) somewhat arbitrary.

TURKANA RIFT ZONE The Turkana Rift Zone extcnds from thc Lake Baringo area in the south to the Omo River valley at the north end of Lake Turkana (von Hohnel 1894, Murray-Hughes 1933, Fuchs 1934, 1935, 1939, Dixey 1944a, Shackleton 1945, 1978, Pulfrey 1960, Dodson 1963, McCall 1964, Bishop & Trendall 1967, Howell 1968, Butzer & Thurber 1969, Walsh & Dodson 1969, Butzer 1970, Rhemtulla 1970, Baker et al 1971, 1972, Vondra et al 1971, Bowen & Vondra 1973, Mohr 1974, Behrensmeyer 1976, Mohr & Wood 1976, Truckle 1976, Vondra & Bowen 1976, 1978, Cerling & Powers 1977, Savage & Williamson 1978, Yuretich 1979, Bellieni 1981, Hopson 1982, Dunkelman 1986, Johnson et al 1986, Williamson 1986, Williamson et al 1986).

Like the ends of the Kenya Rift Zone, the southern end of the Turkana Zone is poorly constrained by any obvious surface manifestation. Volcanic cover obscures any clear line of demarcation between the northern end of the Kenya Zone and the southern end of the Turkana Zone.

The same sort of zonal distinctions can be applied to pre-Cenozoic rifting in East Africa (Figure 1). Perhaps the best example is the Luangwa Valley, which for most intents and purposes can be treated as a Karroo-aged Lake Malawi minus the water. The Kariba and Zambezi regions also are grouped into zones, although thc latter case is not as well defined as the other two.

Rift-Unit Scale

The use of the term "fundamental unit" is reserved for discrete structural basins with typical lengths of 80–160 km and length-to-width ratios of about 2–4 (Reynolds 1984). Fundamental units are the true building blocks of rifts and should not be confused with the other scales described herein. The distinction between the zone and unit scale is made clear by comparing Figures 1*a* and 1*c*. The distinction between units and smaller-scale structure is shown in Figure 2. The various half-graben identified in Figure *2a* are the rift units in the northern half of Lake Tanganyika. Other examples of fundamental units are Lakes Albert (Lake Mobutu Sese Seko) and Edward (Lake Idi Amin). Altogether, there are perhaps 70 of these fundamental units in the Tertiary System of East Africa (Figure 1*c*). A considerable portion of this article is devoted to the subject of fundamental units, particularly the ways in which they link together and the resultant structural expressions. Suffice it to say that typically these units become structurally interconnected in groups of 8 or more units. Such a genetic grouping of fundamental units creates a rift zone.

Rift units are also easily identified in the older rifting events of East Africa (Figure 1*c*). For example, the Ruhuhu and Maniamba Karroo troughs cutting across the Malawi Rift Zone (Bornhardt 1900, Andrew & Bailey 1910, Stockley 1932, Spence 1954a, Harkin 1955, McKinlay 1965, Vail 1967, Crossley & Crow 1980) are probably remnants of what were originally deeply subsided and well-developed fundamental units. Lake Mweru (de Swardt 1965, Drysdall & Weller 1966) appears to be a remnant of a single, more or less isolated fundamental unit. The Luangwa Valley is a series of well-preserved, Mesozoic-aged fundamental rift units that together formed a rift zone that bears a remarkable resemblance to the Malawi and Tanganyika rift zones (first noted by Dixey 1937a). The same can be said about the Lake Kariba area, which contains a series of fundamental units that link together to form a rift zone along the Zambia-Zimbabwe border. The Cretaceous graben of southern Sudan (J. Lambiase, personal communication) also are fundamental units linked together into a rift zone, although limitations in both rift exposures and subsurface geophysical coverage make the delineation of pre-Tertiary rift zones in Sudan uncertain at the present time. In Figure 1*c* I have identified about 55 pre-Tertiary rift units, but there are certainly many more that have gone undetected.

Rift Block Scale

The smallest structural unit of concern here is the "block." Sometimes they are expressed as ideal horst or graben, but more often they are tilted or rotated and they often change form or expression along their lengths. Johnson (1930) referred to these features as "tilt blocks, rift blocks, and step blocks"; Cotton (1950) used the term "fault-angle depression." The rotated and tilted blocks observed in the Bay of Biscay (de Charpal et al 1978, Montadert et al 1979) are synonymous with the blocks described herein. Angelier & Colletta (1983) call these structural units "first-order blocks" to differentiate them from still smaller-scale features.

The dimensions of blocks seem to vary from one rift unit to another,

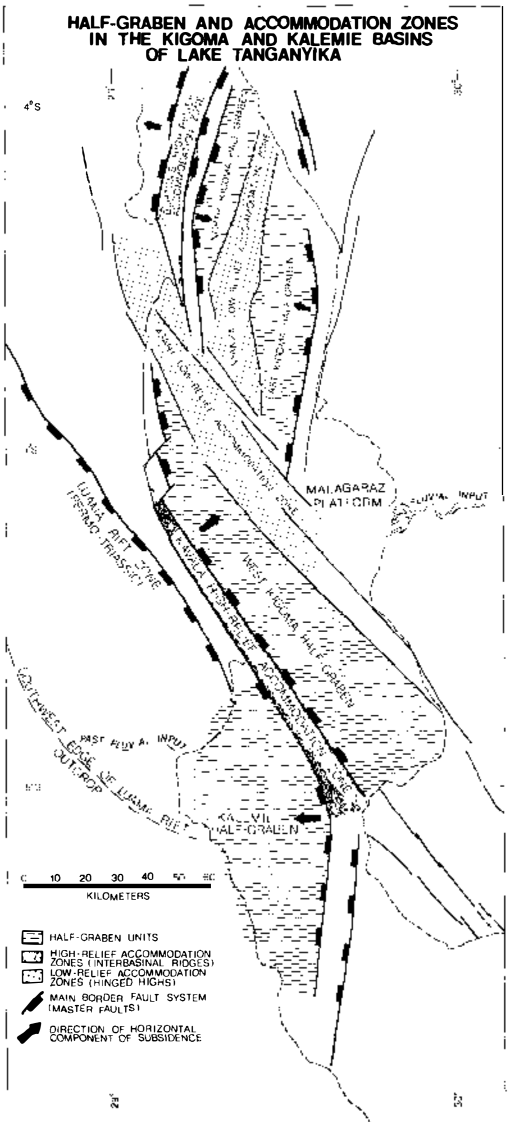


Figure 2 Structure of the northern half of Lake Tanganyika. Figure 2*a* (*above*) shows the basic architecture of half-graben and accommodation zones, Figure 2*b* (*over*) the infrastructure. Actual lengths of individual faults in Figure 2*b* are probably less than shown because of inability to discern small-scale transverse features, but widths and spacings are accurate. Note that low-relief accommodation zones are enclosed by high-relief zones.


INFRASTRUCTURE OF THE KIGOMA
AND KALEMIE BASINS OF LAKE TANGANYIKA
29°
30°
MALAGARAZI PLATFORM

Figure 2b

but widths of 10 km are typical. It is not uncommon for blocks to display apparent length-to-width ratios of up to 10, but these ratios rarely exceed 4 where data density is adequate to delineate transverse block terminations (cf. Aydin & Nur 1982). The problem in deciphering length-width relations of blocks is illustrated by the beautiful block termination shown in a photograph in McGill & Stromquist (1979). Here the Devil's Lane block is terminated by an offset that would be almost impossible to delineate from any subsurface geophysics such as seismics. The significance of blocks lies in the recognition that they represent the infrastructure of rift units, not the fundamental rifting unit of Rosendahl & Livingstone (1983). Good examples of this scale of fracture in African rifts can be found in Ebinger et al (1984) and Figure 2*b* of this review.

ON THE ARCHITECTURE OF AFRICAN RIFTING

The Historical Perspective

The distinctive morphology of the East African Rift System is, of course, the very thing that attracted researchers to it in the first place. Suess (1891), de Martonne (1897), Gregory (1896, 1921), and de Lapparent (1898) were perhaps the first to recognize the basic structure of the African Rift—bounding normal faults, down-dropped wedge-blocks, broad arching, and horizontal extension. The term rift valley was used by Gregory to denote a long strip of Earth bounded by normal faults. In fairness to his predecessors, both this term and the roots of some of Gregory's ideas are owed to earlier efforts, mainly in the Rhinegraben by workers such as de Beaumont (1827, 1830, 1844, 1847), Suess (1891), de Lapparent (1887, 1898), and Neumayer (1887). H. Cloos (1939) is usually credited with establishing the mechanical validity of the tensile origin of rifts, but again some of the incentive and groundwork for Cloos' clay modeling can be traced back to the ideas espoused by de Beaumont (1827), Suess (1880, 1891), Gregory (1896), de Martonne (1897), de Lapparent (1898), Uhlig (1907, 1912), Obst (1913), Verweke (1913), Krenkel (1922), and Willis (1928, 1936). The term taphrogenesis was used by Krenkel (1922) in ascribing a tensile origin to the East African Rift. Nowadays, the term is essentially synonymous with rifting.

Almost every major geological precept or problem related to the East African Rift can be traced back to these early rift pioneers. These include the present-day controversy between "active" and "passive" rifting mechanisms [e.g. compare de Beaumont (1827) with Suess (1891, 1909)], the issue of fault behaviors at depth, and even the idea that the East African Rift is the outstanding example of a tear between two separating continents (e.g. Krenkel 1922, Willis 1936). Wegener (1912) described the East African

Rift System as the initial stage of continental breakup. Those who doubt how much wc owe our early predecessors would benefit from a reading of the syntheses of Suess (1891, 1909), Gregory (1896, 1920), and Krenkel (1922, 1925).

Holmes (1944, 1965) synthesized much of the earlier work and formulated not only the basic picture of the East African Rift that is used today, but also many of the research problems that subsequent workers have pursued. No listing of African rift pioneers would be complete without mention of Dixey, McConnell, and Baker. Much of what is known about the geomorphology of the Western Branch, especially south of Lake Kivu, is owed to Dixey (1944a,b, 1945a,b, 1956, 1959). McConnell has published a long succession of papers dealing mostly with pre-existing structures and their influences on subsequent rifting (e.g. McConnell 1967, 1972, 1974a,b, 1978). Baker, of course, has played the modern keynote role in unraveling the chronology of the Eastern Branch, particularly the Gregory Rift Zone (e.g. Baker 1970, 1971, Baker & Wohlenberg 1971, Baker et al 1971, 1972, 1978).

Data recently acquired by the author and his associates provide an opportunity to update and to some extent revise the morphologic picture of rifting that has emerged from the above studies. We begin with the cross-sectional form of African rift units.

Cross-Sectional Morphology

The traditional morphologic picture of the African rift is one of approximate bilateral symmetry and strong two-dimensionality. This picture is not so much incorrect as it is misleading. Our studies in East Africa (Rosendahl et al 1982a,b, Rosendahl & Livingstone 1983, Patterson 1982, Ebinger et al 1984, Lorber 1984, Reynolds 1984, Reynolds & Rosendahl 1984, Sander et al 1986) demonstrate that asymmetry is the rule, not the exception; the archetypical cross-sectional form of African rift zones is a scalene to obtuse triangle. The steep side represents the major bounding fault system, and the ramping side is characterized by monoclines, steps, or flexures (Rosendahl et al 1986). Bally (1982) has made a similar deduction for the rift zones that he has examined. Hereafter, we use the terms "half-graben" and "full graben" to distinguish asymmetric cross-sectional forms from approximately symmetric cases.

It might be surprising to some workers that half-graben geometries predominate in African rift zones, but the existence of such forms is not an entirely new discovery. Careful readings of Gregory (1921), Krenkel (1925), Dixey (1929, 1956), Baker (1970), Baker et al (1972), Logatchev (1978), Crossley & Crow (1980), and Mohr (1982), among others, reveal that the existence of asymmetric geometries in East African rift zones has been known for many years. Half-graben forms in other rift environments have been described or implied by Florensov (1969), Mueller (1970), Illies (1971), de Charpal et al (1978), Kumarapeli (1978), Harding & Lowell (1979), Bally (1980, 1982, 1983), Bally & Snelson (1980), Weiblen & Morey (1980), Chenet & Montadert (1981), Effimoff & Pinezich (1981), Chenet et al (1982), Nunn (1982), Gibbs (1984), Lillie (1984), and Skilbeck & Lennox (1984). As noted by Bally (1982), the key to recognizing the preponderance of half-graben morphologies in rift zones lies with proper seismic reflection coverage. Hence, it should come as no surprise that some petroleum companies made the above discovery long ago.

Curiously, most experimental modeling of rift structures, whether done with clay (H. Cloos 1928, 1931, 1939, Wunderlich 1957, Oertel 1965, E. Cloos 1955, 1961, 1968, Elmohandes 1981), centrifuges (Ramberg 1963, 1967, 1971, 1978, Mulugeta 1985), wax (Oldenburg & Brune 1972, McGill & Stromquist 1979), cement (Freund & Merzer 1976), glass bottles (Bahat 1979, Bahat & Rabinovitch 1980), plaster (Sales 1976), or more theoretical means (Bott 1976, 1981, 1982a,b, Bott & Kusznir 1979, Withjack 1979, Artyushkov 1981, Neugebauer & Temme 1981, Bott & Mithen 1983, Keen 1985, Rowley & Sahagian 1986, among many others) usually emphasize full graben forms, or at least deformational symmetry. Sometimes this reflects a bias with regard to which "runs" an author chooses to emphasize. Other times it is an outgrowth of boundary constraints, materials, or other experimental parameters, assumptions, or limitations. In cases where the experimental full graben are both "real" and dominant, they usually occur as an end product, or at least late in the experimental rifting cycle. When available, the initial or early fracture expressions are often asymmetric. This is especially apparent in the studies of Stewart (1971), Ramberg (1971), Sales (1976, and shown in Stewart 1978), McGill & Stromquist (1979), and Mulugeta (1985).

Because half-graben seem to be the "type" morphology of African rift zones, whereas youthful ocean basins display grossly symmetric forms, we can conclude that the evolution from continental rift to oceanic spreading center must involve a progression toward symmetric cross-sectional morphologies. This conclusion is supported by our observation (see below) that full graben are a result of the linking together of half-graben (i.e. half-graben must exist first for linking to occur). A way around this conclusion is to postulate that the East African rift zones are not a precursory stage of successful spreading (cf. Fairhead & Browne 1981), but this is difficult to accept. Our group has now examined data from many rift zones that achieved partial or complete success, and in every case where subsurface data are adequate to resolve original geometry, half-graben forms predominate. This supports a similar contention by Bally (1982). We can take this to mean that regardless of their ultimate fate (successful spreading or eventual fossilization), there is nothing morphologically peculiar about the East African rift zones. It also means that half-graben morphologies must evolve into full-graben forms if successful spreading is to be achieved. Before pursuing the details of this evolution, we need a firmer understanding of the dimensional parameters of rifting.

Dimensionality of Rifting: Branch and Zone Scales

A few workers have given special attention to the issue of the third dimension of rifting (e.g. Illies 1972, Bally 1982, Gibbs 1984), but the matter usually has received only passing reference in the African rift literature. Onc reason is that activc normal faults scar thc landscape to a much greater extent than transverse fault systems, which are dominated by strike-slip motions. An exception may occur where volcanic features are associated with inferred cross-cutting structures (e.g. Fairhead 1980). A more fundamental reason is that relatively little is known about the length dimensions of rifting outside of a few well-surveyed areas, such as the North Sea and Rhinegraben. (The subsurface reflection data from these areas are largely proprietary.)

Virtually all geophysical and most dynamic models assume that rifts are strongly two dimensional on the larger scales, especially for the system, branch, and zone designations used here (e.g. Girdler et al 1969). Nonetheless, even on these larger scales the length dimension is not limitless. Consider that the distinction made here between Eastern and Western rift branches or between different rift zones implies the existence of terminations along strike, be they loss or change of surface expression, cross-cutting structures, or offsets. Perhaps the most impressive terminations in the Africa System are those at the northern end of the Western Branch, in the vicinity of the West Nile Basin (Pallister 1971), and at the southern end of the Eastern Branch, somewhere in north-central Tanzania (James 1956, Dundas 1965, Pallister 1965). The Aswa mylonite belt [also termed the Aswa shear belt, Aswa Lineament, Aswa Dislocation Zone, and Assousa Lineament (Hepworth & MacDonald 1966, Hepworth 1966, Almond 1969, Macdonald 1968, de Swardt & Trendall 1969, King 1970, McConnell 1972, Mohr 1974a)] can be connected with the Nandi fault (Shackleton 1951) and the Mozambique front (Sanders 1965) to form a quasi-continuous connection between the two branches (Figure 1). The studies by Wohlenberg & Bhatt (1972) are taken by McConnell (1972) as additional evidence for an interconnection.

Some authors have suggested the existence of a transform fault offset along the Aswa trend (Chorowicz & Mukonki 1980, Kazmin 1980a,b). The use of transform faults to explain meanders and offsets in continental rifts is an established procedure (e.g. King & Zietz 1971, Chase & Gilmer 1973). However, in the case of the Aswa connection it raises a host of complications. Some of these problems includc (*a*) the age of the Aswa Lineament (Precambian); (*b*) the great length of the proposed offset (500–600 km); (*c*) the paucity of seismicity aligned along the proposed offset (e.g. Shudofsky 1985); (*d*) the scarcity of surfacc exprcssion, especially recent dislocations, along the proposed offset; (*e*) the continuation of Eastern Branch rift morphology south of the proposed transform-rift intersection; and (*f*) the apparcnt continuation of transform-aligned structures past the rift-branch intersections. For example, the work of Vail (1972), McConnell (1972), and Browne & Fairhead (1983) points to a probable continuation of the Aswa Lineamcnt northwestward, possibly along the Abu Gabra Rift to Darfur, Sudan. McConnell (1972) continues this lineament southeastward past the intersection with the Eastern Branch to the Pangani Rift (termed the Pangani-Aswa Lineament or Pangani–Nandi–Aswa–Jebel Marra line by McConnell) and suggests a further continuation to the Lindi fault zone of Kent et al (1971). We might take note that the volcanic centers of Kilimanjaro and Elgon lie along the lineament as defined by McConnell (1972).

Evidently, the Aswa structures predate the East African Rift System, extend beyond its intersections with the Western and Eastern branches, and cross at least the Eastern Branch without creating any noticeable lateral displacement. It is possible that a transform fault has rejuvenated the central portion of this trend, but if so it is remarkably asymptomatic. A more plausible proposal is that the offset region between the two branches is a transform waiting to be born, not one that has actually happened yet to any significant degree. The term "pretransform" might be more appropriate for such cases.

Transform faults also have been used to connect rift zones. For example, both Chorowicz & Mukonki (1980) and Kazmin (1980a) have proposed a major transform fault zone connecting the north end of Lake Malawi and the middle section of Lake Tanganyika. In effect, thcse authors arc using the Rukwa Rift Zone and the southern half of the Tanganyika Rift Zone to connect the adjacent rift zones. Under this tectonic scheme, the creation of both the Rukwa trough and the southern half of Lake Tanganyika presumably would be due to pull-apart mechanisms. Chorowicz & Mukonki (1980) also terminate the Malawi Rift Zone at its south end with another large transform fault (termed the Zambezi Lineament by these authors). In an earlier paper, Chorowicz et al (1979) connected Lakes Tanganyika and Kivu with what is implied to be an imperfect, 40-km-long transform fault. Recently, Williamson (1986) proposed a Mesozoic transform offset in the southern part of Lake Turkana. These hypothesized "zone-offsetting" transforms might be analogous to those proposed for the Mid-Continent Rift System (or Keweenawan System) in the southeastern corner of Nebraska (e.g. Van Schmus & Hinze 1985).

The continental transform perspective of three-dimensionality treats rifts as the geometric equivalent of the ridge-transform-ridge geometries of oceanic spreading systems. The natural outcome of such a philosophy is a breakup model such as that shown in Figure 1*d*. We might consider this to be the possible boundary arrangement in East Africa if rifting continues. Although Figure 1*d* uses the rift-unit concept discussed below, this sort of model still oversimplifies and understates the true architecture of African rifts. This brings us to the subject of the geometry of half-graben units.

Geometry of Simple Fundamental Units

As stated above, rift zones are composed of fundamental units. The intrinsic geometry of an isolated unit is a half-graben whose major bounding fault is arcuate in plan view (Rosendahl et al 1986). The ideal half-graben is depicted in Figure 3. Anisotropy and heterogeneity of prerift structural

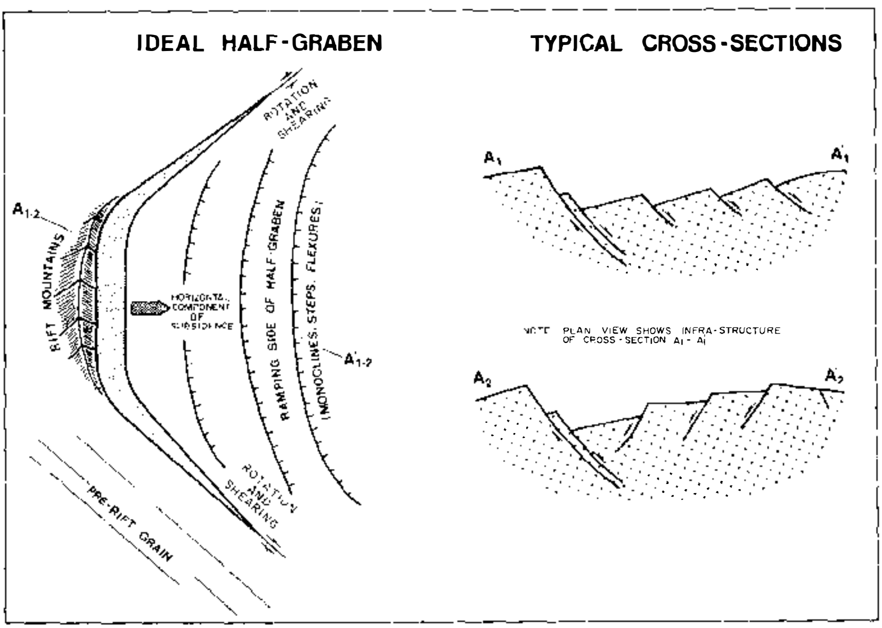


Figure 3 Plan view and hypothetical cross sections of an ideal half-graben. Note that the geometry of subsidence produces oblique-slip faulting along ends of units. Isolated half-graben tend to display synthetically faulted infrastructure (i.e. top cross section).

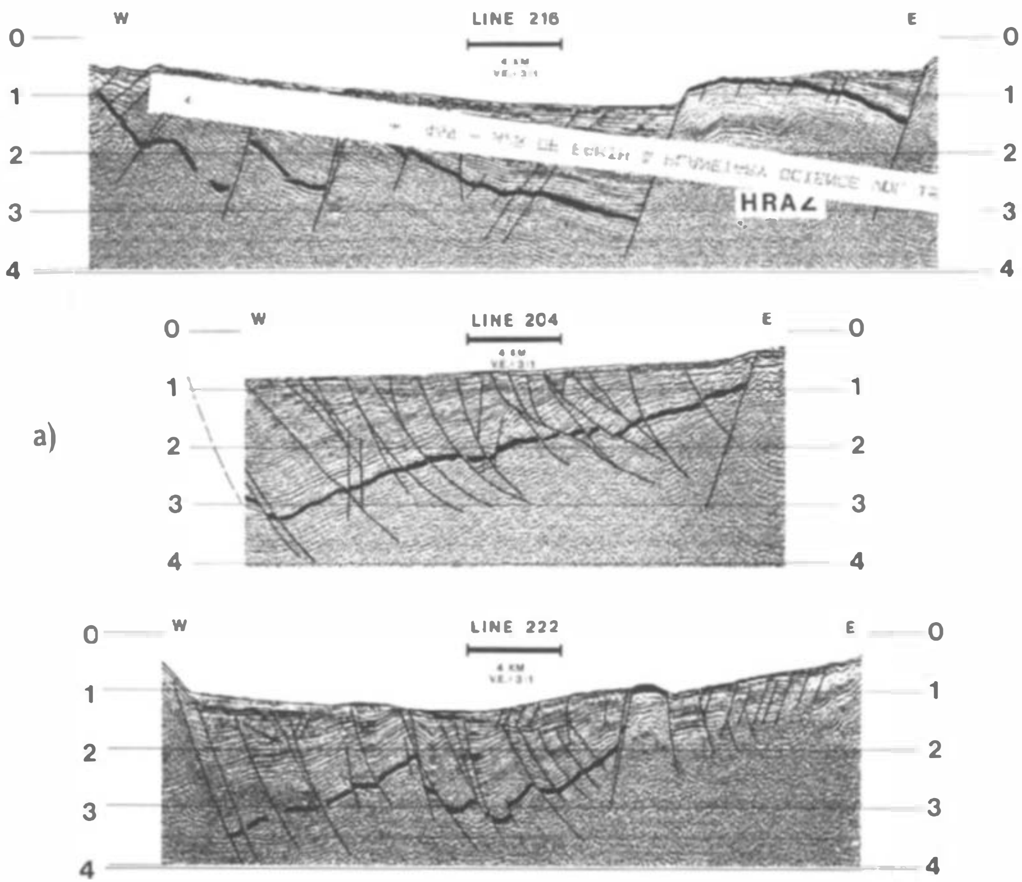
fabrics make it unlikely that the ideal case will occur in nature. Also, the linking together of units to form a rift zonc creates structural modifications to the original geometry, as discussed below.

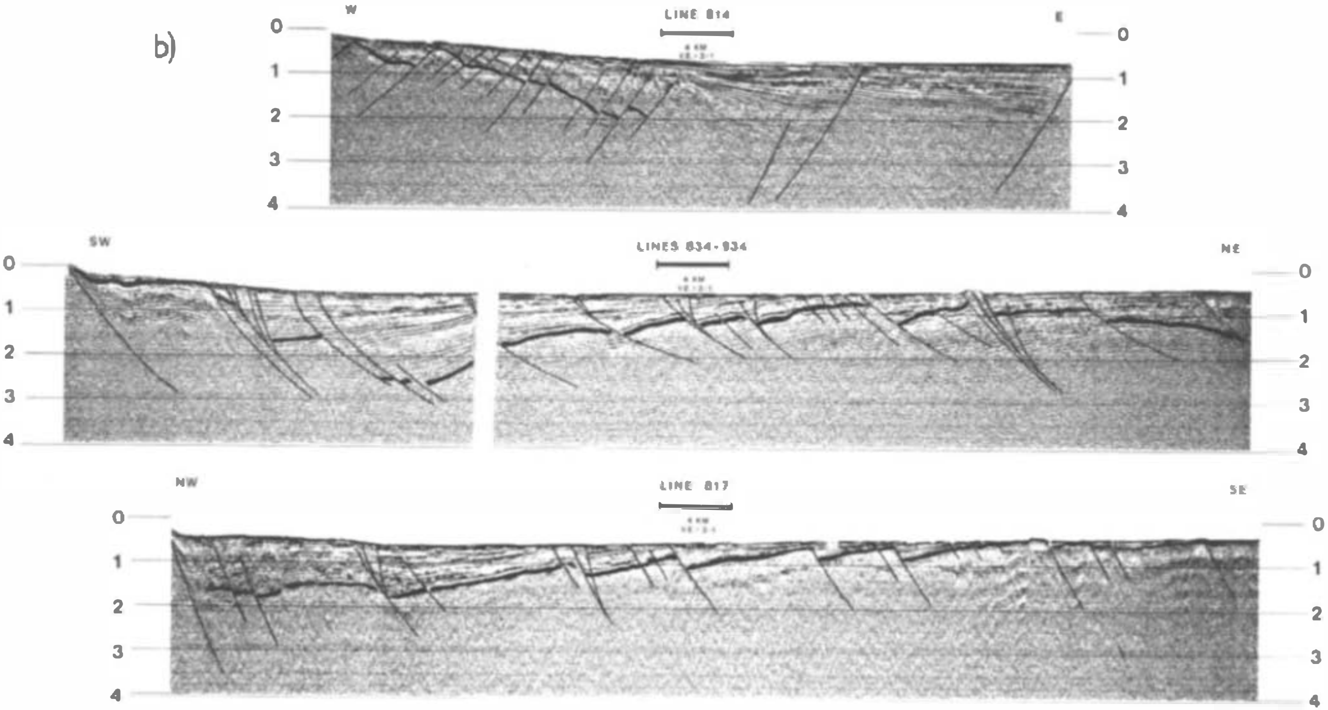
The closest approximations to the ideal case seem to occur where linking interferences are minimal. This happens at the ends of rift zones, where the terminating fundamental unit is linked only on one side, and where half-graben units alternate polarities along the strike of the rift zone without overlapping. Four seismic sections across relatively simple half-graben units in the Lake Tanganyika and Malawi Rift Zones are shown in Figure 4. Although the basic expressions are the same in these examples, the fracture spacing of the infrastructure is markedly different, ranging from 2 to 15 km. This is about the range we observe throughout the African rift zones, and it is close to the 5–15 km width range reported by Angelier & Colletta (1983) for other regions. De Charpal et al (1978) quote a range of 10–30 km for block spacing in the Bay of Biscay, but examination of their data and other proprietary seismics indicates that this range may be too high by as much as a factor of two. It should be noted that very high-resolution seismics (e.g. ccho-sounder data) tend to show smaller fracture spacings, but the dimensions of the major blocks remain the same.

Inspection of the profiles shown in Figure 4 also reveals that the variation in spacing of internal faults on any given profile (i.e. the width of blocks) is considerably less than the variation range between different rift units. For example, the ranges on lines 204, 216, and 222 from Lake Tanganyika are 2–4, 4–8, and 1–6 km, respectively. The block width ranges on lines 814, 834–934, and 817 from Lake Malawi are 7–12, 9–15, and 8–12 km, respectively. Many simple half-graben seem to show a tendency toward decreasing internal fault spacings moving toward the ramping sides of the half-graben. In some cases, the decrease in spacings follows exponential decay relations.

It can be reasoned that relatively simple half-graben also should occur during the initial development of a rift zone, provided that the fundamental units of a rift zone are not strictly contemporaneous. This means that the occurrence of isolated half-graben units should be an early stage of evolution of rift zones.

The seismic profiles in Figure 4 all show infrastructures that are mainly synthetically faulted with respect to the master border fault system. The picture is one of tilted blocks rotated in the same direction along faults that parallel the border fault systems, rather than the alternating horst and graben morphology often associated with continental rifts. The picture is very reminiscent of the tilted "pack-of-cards" geometries of Le Pichon & Sibuet (1981), Wernicke (1981), Bally (1982), Wernicke & Burchfiel


W
LINE 216
E
0
1
2
3
4
HRA2
W
LINE 204
E
a)
W
LINE 222
E
4 KM



with arrangements where half-graben overlap and face one another (e.g. Figure 7*a*). Lines 814, 834–934, and 817 are from the Karonga, Nkotakota and Nkhata provinces of Lake Malawi, respectively. All profiles represent 24-fold sections. Tanganyika lines are migrated; Malawi lines are not. See Rosendahl et al (1986) for Tanganyika line locations, and Ebinger et al (1984) for Malawi province locations. Heavy solid line represents acoustic basement, which usually can be taken as the base of the synrift.

(1982), and Angelier & Colletta (1983). It is also similar to the Bay of Biscay morphology described by de Charpal et al (1978). Our studies to date indicate that this geometry is typical of relatively simple, isolated half-graben. It is not necessarily the case, however, for half-graben that link together in ways that create structural interferences (see later discussion).

The sinuosity of the Western Branch of the East African Rift System has been recognized by virtually every worker since Gregory's time, and it is now universally attributed to a deflection of rifting around the Tanganyika Shield. A similar proposition has been made by Van Schmus & Hinze (1985) to explain a lateral offset in the Mid-Continent Rift System that Chase & Gilmer (1973) attributed to a transform fault. In contrast to this large-scale sinuosity, the arcuate forms of half-graben units in plan view are a relatively new development. Agreement on the causes of the curvature is divided between three schools of thought within our research group. One school argues that the true geometry is an orthorhombic fracture pattern, such as that produced in clay models by Oertel (1965) and convincingly explained by Reches (1978, 1983). The asymmetric half-graben form is attributed to unequal development of the four sets of faults that make up the orthorhombic geometry, and the arcuate character of the border fault systems is a consequence of trackline aliasing (Figure 5). The rhomb-shaped basins shown by Thompson & Burke (1974) in the Basin and Range Province could be cited as another example of the same process. The second school also uses trackline aliasing but begins with composite pull-apart fracture geometries such as those proposed by Aydin & Nur (1982). The fact that the infrastructure of rift units tends to be strongly linear, including the individual faults that comprise border fault systems, lends credence to both of these schools of thought. The third school argues that the arcuate forms are real, albeit perhaps not as simple or stylized as indicated in Figure 3. The support for this case comes from both the observational and fault mechanical fronts. Normal faults that curve in map view have been observed in virtually all extensional environments, including the North Sea (e.g. Ziegler 1978), the Gulf of Suez (Robson 1971), the Ethiopian Rift (Figure 1*c*; Juch 1980), the Gregory Rift (Baker et al 1972), the Rhinegraben (Hirlemann 1974), and the Basin and Range (Wright & Troxel 1966). Such patterns also have been reproduced in laboratory model experiments (e.g. Figure 2 of Bahat 1979, Figure 7 of McGill & Stromquist 1979). Satellite imagery suggests that the prevalence of curvilinear fault patterns has been grossly understated. Another line of evidence comes from a consideration of what happens to bounding rift faults with depth. If these faults flatten with depth, as suggested by many workers (e.g. Proffett 1977, Bally et al 1981, Harding 1984), then they should curve in map view as well. These three schools of

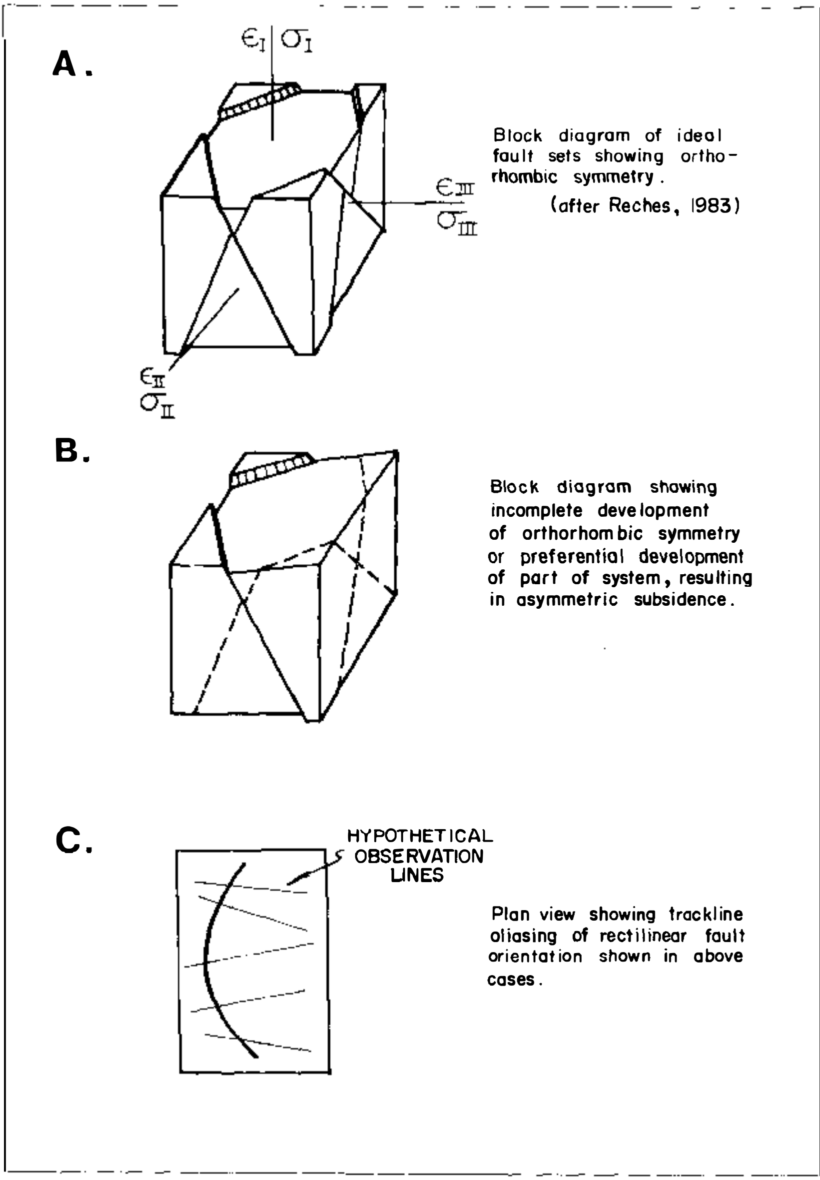


Figure 5 Creation of apparently curvilinear border faults by trackline aliasing of original orthorhombic fracture pattern.

thought are not mutually exclusive, and it is probable that all are operative to various extents in East Africa.

An important consequence of the geometry shown in Figure 3 is that strain expressions within half-graben units are spatially variable. In the ideal case, subsidence is at a maximum adjacent to the geometric center of the border fault, where the displacement is most nearly dip-slip. Toward the arcuate ends of half-graben, the total throw on the border faults decreases as the relative proportion of strike-slip motion increases. Hence, the ends of half-graben ought to be regions of rotation and oblique shearing more than regions of subsidence and pure extension. It is likely that the warping and tilting noted by Thompson & Burke (1974) near the ends of elongate basins in the Basin and Range Province are due to the same process. Much of the strike-slip faulting described in the North Sea rift zones (e.g. Ziegler 1982) also could be interpreted in the same vein. In real half-graben, the depocenters usually are not centered geometrically because half-graben are usually canted toward one end or the other. In other words, not only are half-graben asymmetric in cross section, but they also often plunge along strike as well (Burgess et al 1986). Both anisotropy of prerift structures and the orientation of the applied stress with respect to these structures may be causes of strike asymmetry. We suspect a more general cause is the interaction, or interference, of adjacent half-graben.

Geometries of Linked Half-Graben Units

The key to understanding African rift morphology and structure, including three-dimensionality on the scale of rift zones, pertains to the ways in which half-graben link together to make rift zones. Our group has recognized many different linking arrangements, but all these can be viewed as variations of the half-graben theme of rifting (cf. Rosendahl et al 1986). For the sake of discussion, it is convenient to group these variations into the families and cases shown in Figures 6*a–e*.

One linking family is created when two half-graben oppose each other, either in overlapping or nonoverlapping modes. A sensible progression of geometric possibilities is depicted in Figure 6 (cases A–F) along with idealized cross-sectional variations for selected cases.

Cases A–C in Figure 6*a* show half-graben units that overlap and face each other. If the subsiding half-graben units are contemporaneous, then a rather severe space problem seems to be created in the overlapping area. Given that subsidence involves a component of horizontal motion directed toward the ramping sides of half-graben, the facing half-graben must compete for the same piece of terrain. This can result in an antiformal

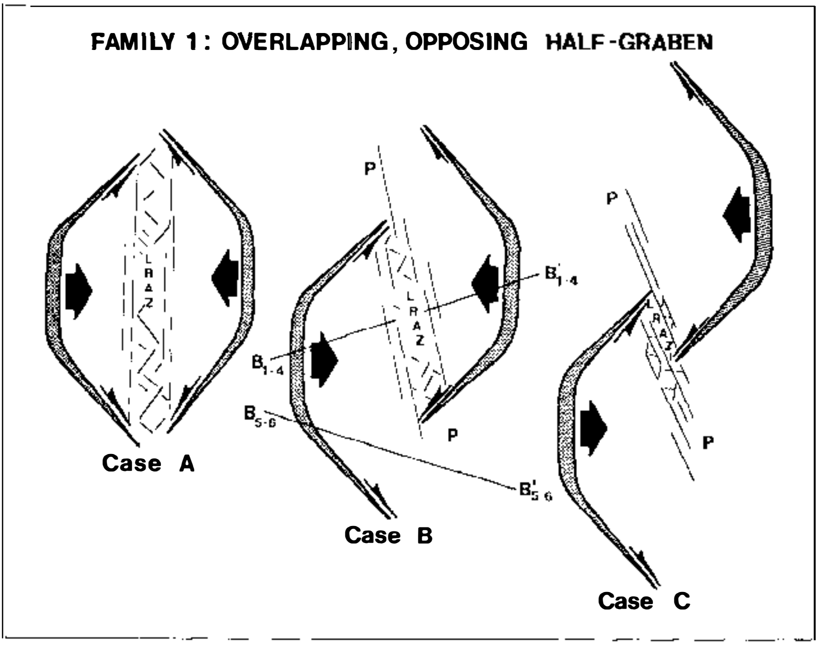


Figure 6 Examples of linked half-graben grouped into families. Opposing geometries create either low-relief or high-relief accommodation zones (LRAZ and HRAZ), depending upon the extent of overlap [compare 6*a* (*above*) and 6*b* (*over*)]. Strike-slip accommodation zones (SSAC) may be the intermediate case. Figure 6*c* shows a family of similar polarity half-graben. Hypothetical cross sections of cases B and E are shown in Figures 6*d* and 6*e*.

welt away from which the two half-graben subside in opposite directions (sections B_1 through B_4, Figure 6*d*). We have termed these welts "hinged highs," or "low-relief accommodation zones." Experimentally produced examples of hinged highs can be seen in the top one third of Figure 108 in Ramberg (1967).

The difference between sections B_1, B_2, and B_3 of Figure 6*d* relates to the cross-sectional orientations of the internal faults relative to the border fault systems. Based upon the characteristics described above for simple half-graben, one would suspect that the double synthetic arrangement shown in section B_1 should predominate. In actuality, all arrangements have been observed (e.g. Rosendahl et al 1986, Burgess et al 1986, Sander 1986). A seismic example of each is given in Figure 7. We suspect that the development of antithetic infrastructure is an offshoot of interference geometries such as those developed in family 1. Otherwise, this fracture

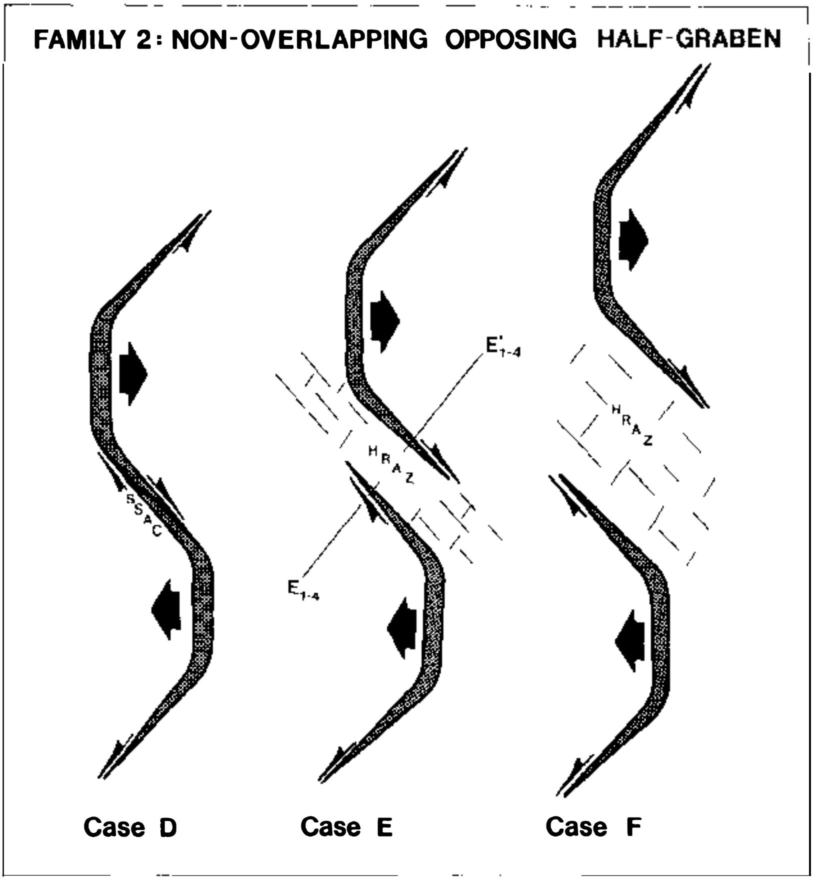


Figure 6b

arrangement should be more prevalent in simple half-graben than it appears to be.

All three of these sections (B_1 through B_3) show what appear to be full graben, but it should bc emphasized that this form is a hybrid of facing half-graben geometries, not a primary archetypical morphology. We have yet to find full graben in African rift units that cannot be explained in this fashion, nor any that do not display some type of antiformal welt. We do not deny that "true" full graben can exist, such as those shown in the clay models of H. Cloos (1939) or in profile 4 of Milanovsky (1972), but we suspect they are rare in East African rift zones. The same may be true for other continental rifts, and we believe that most full graben are actually a

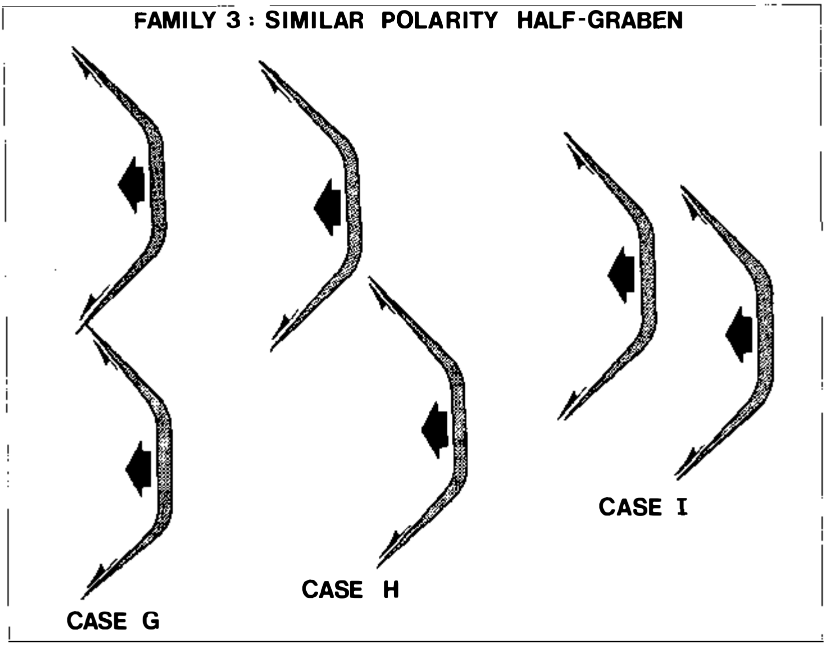


Figure 6c

result of the facing geometries described above. I draw the readcr's attention to Figure 6*a* in Eaton (1982), which looks suspiciously like section B_2, and to Figure 4 of Ghignone & Andrade (1969), which may be an example of section B_1 of Figure 6*d*. Figure 4 in Wu (1986), which shows the Albuquerque Basin of the Rio Grande Rift, also could be interpreted as facing half-graben separated by a low-relief accommodation zone.

The seismic profiles shown in Figure 7*a* indicate that subsidence of hinged highs is retarded relative to the depocenters of the facing half-graben. Nonetheless, they do eventually subside. Discussion of the evolution of these highs is taken up in a later section of this paper.

There is no compelling reason why the subsidence of the two facing or adjacent half-graben should be contemporaneous or equal. This suggests another group of variations, exemplified by section B_4. Figure 7*a* (line 206) shows a seismic profile from Lake Tanganyika that displays a B_4 geometry. Note that subsidence along the "new" border fault system on the east is creating an antiformal welt that is still strongly asymmetric. One outgrowth of this arrangement is that internal faults associated with creation of the original border fault system on the west are being "pulled over" by the

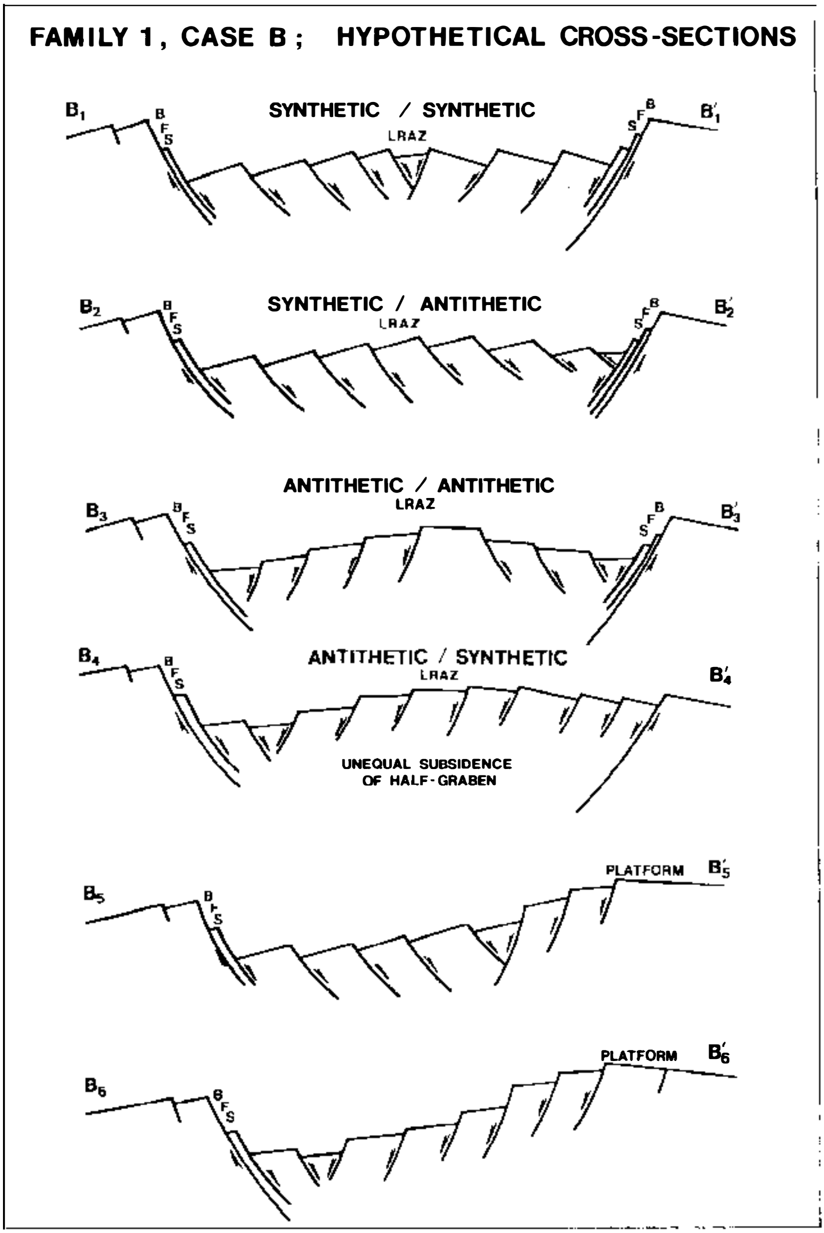

FAMILY 1, CASE B ; HYPOTHETICAL CROSS-SECTIONS
B1
B'1
SYNTHETIC / SYNTHETIC
LRAZ
B2
B'2
SYNTHETIC / ANTITHETIC
LRAZ
ANTITHETIC / ANTITHETIC
LRAZ
B3
B'3
B4
B'4
ANTITHETIC / SYNTHETIC
LRAZ
UNEQUAL SUBSIDENCE
OF HALF-GRABEN
B5
PLATFORM
B'5
B6
PLATFORM
B'6

Figure 6d

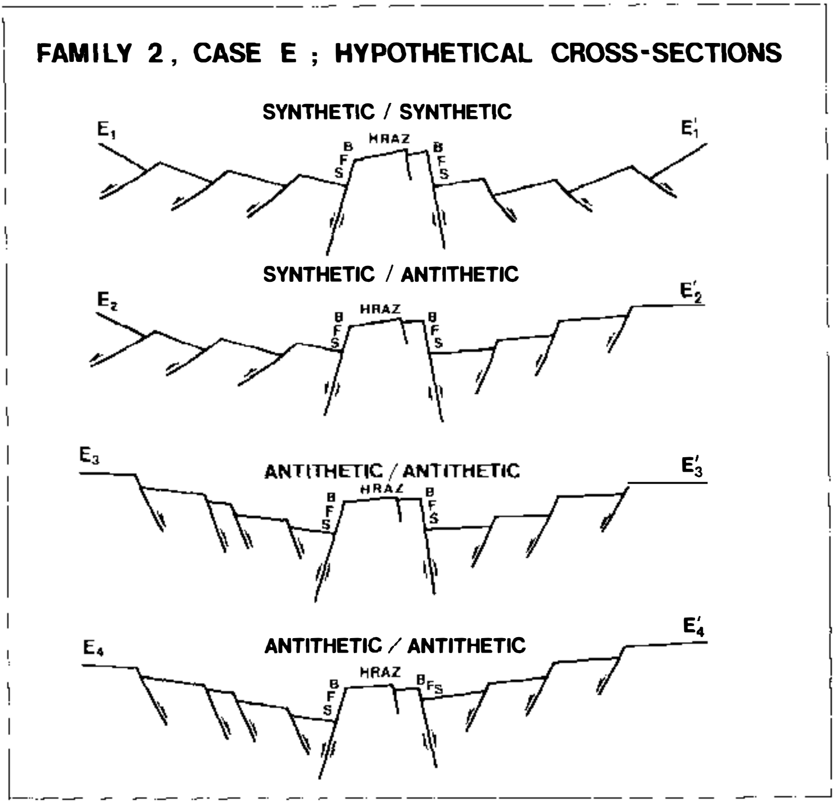


Figure 6e

new subsidence on the east. This is similar to a situation described by Gibbs (1983), and it is an alternative explanation to that of Proffett (1977) for how normal faults can change into reverse faults. Apparently, significant subsidence cannot occur along both border fault systems at the same time. At present, the activity is centered along the new border fault system.

Do morphologies such as those shown in sections B_1 through B_3 evolve from equal, simultaneous subsidence along the facing border fault systems, or rather do they evolve from subsidence that "teeter-totters" between the border faults? This question is tantamount to asking if section B_4 is a precursor of geometries such as those shown in sections B_1 through B_3. Our seismic data from the African rift lakes seem to favor the subsidence

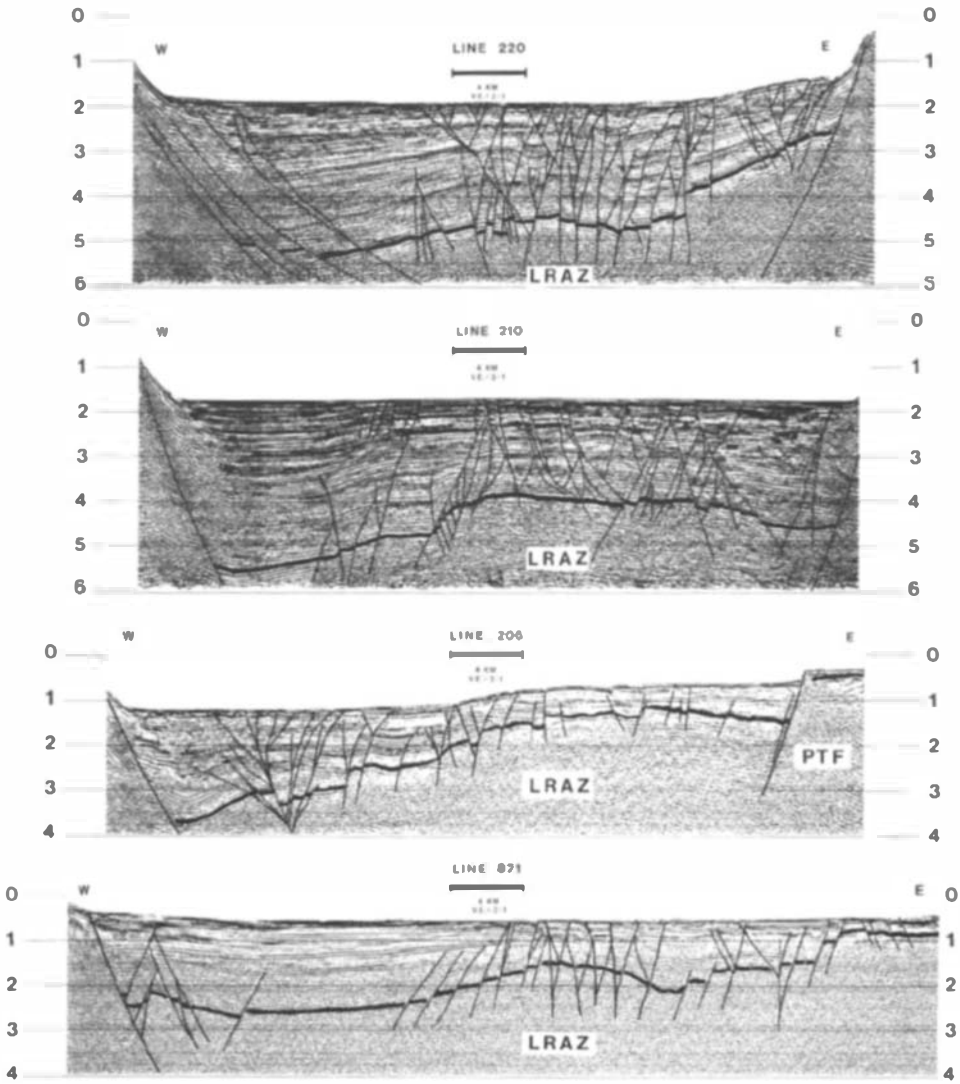


Figure 7a

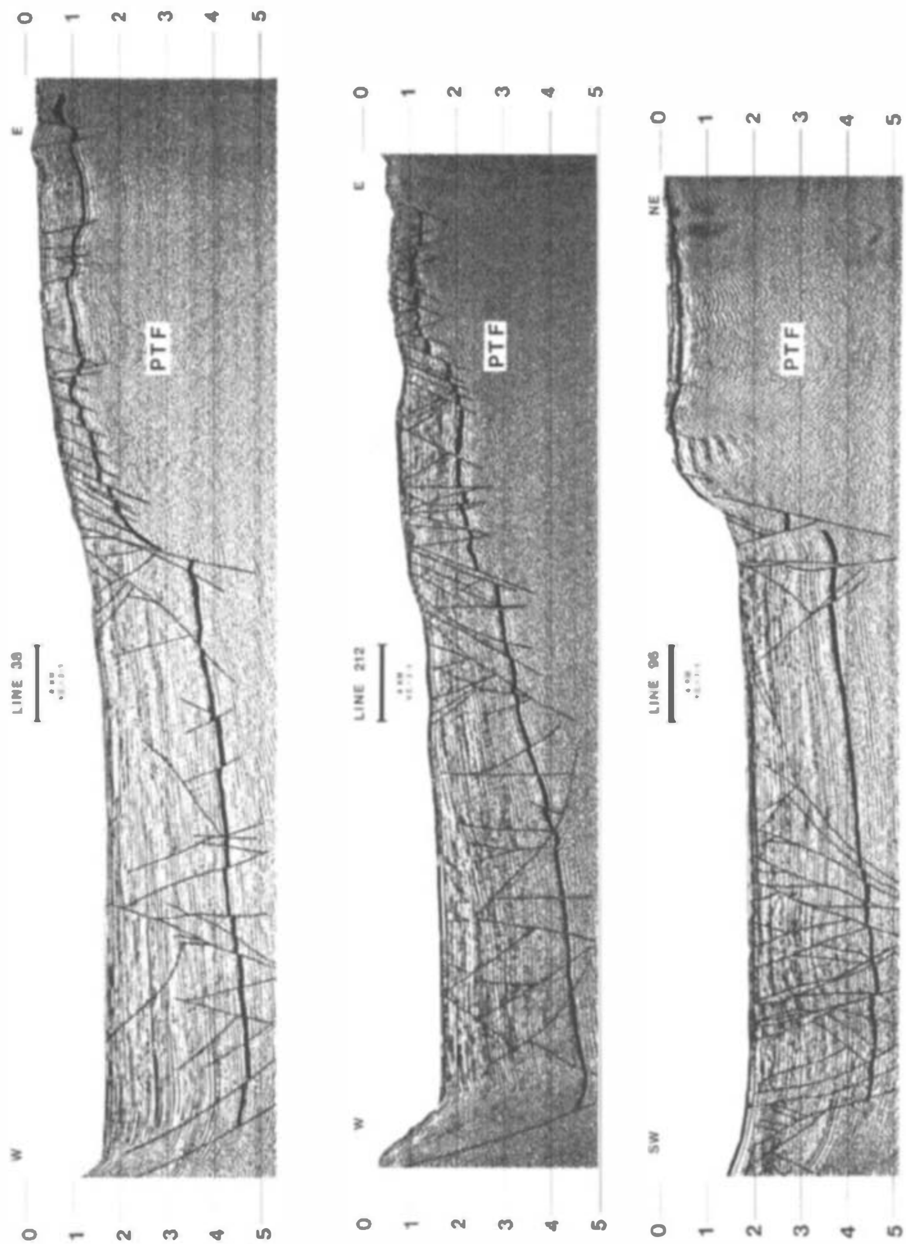


Figure 7b

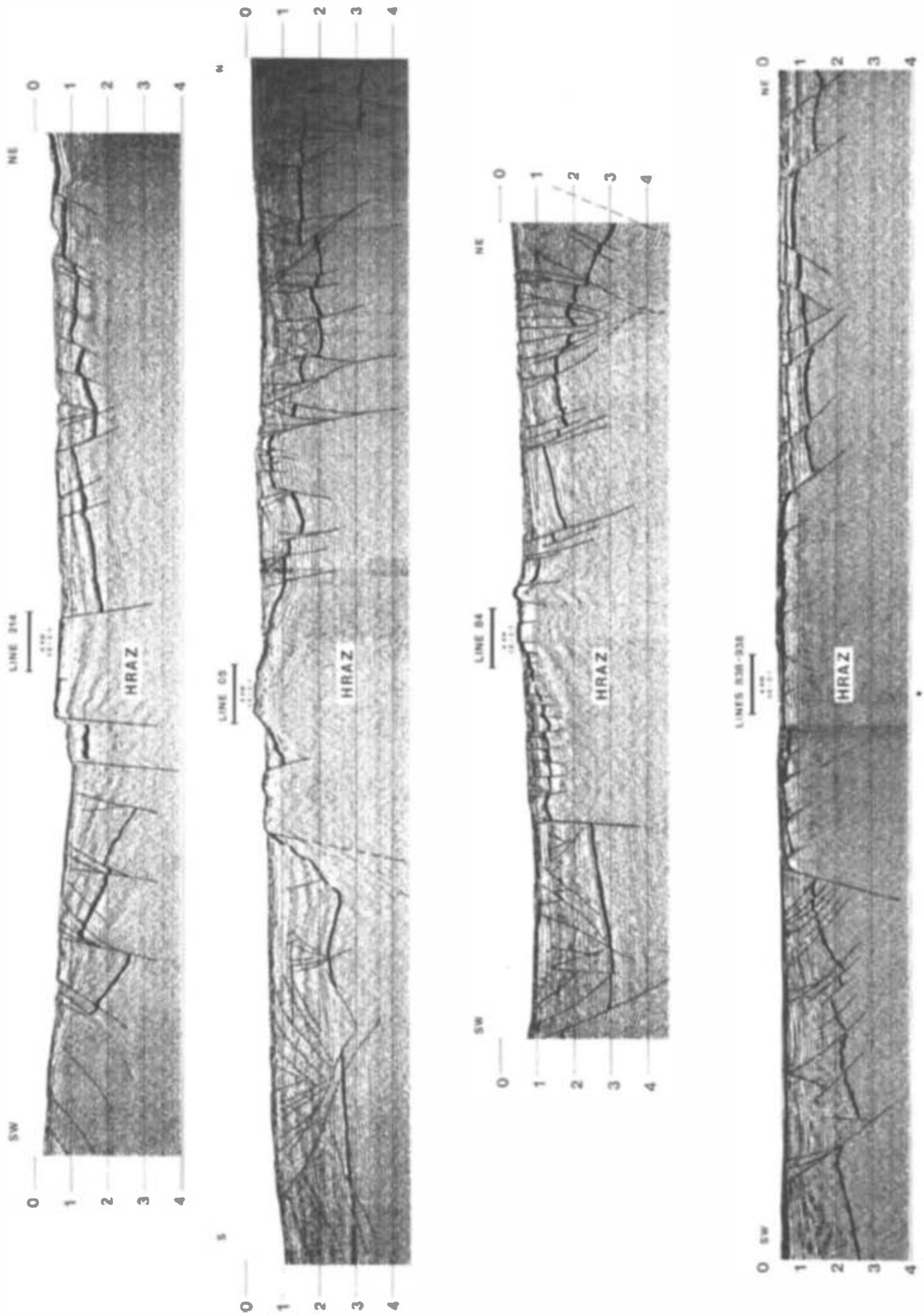

NE
SW
LINE 214
HRAZ
LINE 05
HRAZ
NE
SW
LINE 84
HRAZ
NE
SW
HRAZ
NE
SW

Figure 7 Interpreted multichannel seismic profiles showing actual examples of case B, E, and D geometries. Figure 7*a* shows several types of low-relief accommodation zones (LRAZ), or hinged highs, Figure 7*b* shows examples of platforms (PTF), Figure 7*c* shows examples of high-relief accommodation zones (HRAZ), and Figure 7*d* (*above*) shows a possible example of a strike-slip accommodation zone (SSAZ). Compare to expressions of simple, isolated half-graben (e.g. Figure 4). Lines 220, 210, 206, 38, 212, 96, 214, 05, 84 and 78 are from Lake Tanganyika. Lines 821 and 838–938 are from Lake Malawi. Correlations of seismic lines to cross-sectional geometries in Figures 6*d* and 6*e* are as follow: line 220 to case B_1; 210 and 821 to B_3; 206 to B_4; 38, 212, and 96 to B_5 and B_6; 214 and 05 to E_1; 84 and 838–938 to E_2. Line 78 correlates to case D of Figure 6*b*. All profiles represent 24-fold sections. All Tanganyika lines except 05 are migrated; Malawi lines are not. Note that profile 05 is mainly dip-line, whereas others cross accommodation zones at angles in excess of 30°. See Rosendahl et al (1986) for Tanganyika line locations.

teeter-totter (e.g. Burgess et al 1986, Sander 1986), suggesting that rifting energy there is insufficient for simultaneous development of two facing, overlapping half-graben.

Sections B_5 and B_6 show two hypothetical variations in the morphology across the nonoverlapping regions of facing half-graben. Several actual seismic examples are provided in Figure 7*b*. Generally, these nonoverlapping areas display a half-graben form bounded by a platform on the ramping side. The platform-basin transitions can range from relatively gradual to abrupt (compare lines 212 and 38, Figure 7*b*), depending upon the proximity to a border fault "tail." The difference between this geometry and those of simple half-graben (e.g. Figures 3 and 4) is mainly a matter of degree. Also, platforms tcnd to bc associatcd with larger areas of subdued rift shoulder topography.

Clearly, the amount of overlap between the facing half-graben in cases A–C of Figure 6*a* has a strong influence on such things as the areal size of platforms, the length and trend of hinged highs, and the ways in which the horizontal stress components of subsidence are relieved along the hinged highs. For example, negligible platform development, longitudinal hinged highs, and pronounced axial compression are more likely for case A than C. The latter geometry is more prone to show large platforms and oblique-trending hinged highs characterized by shearing. Another variable is the relative positioning of the two facing half-graben. Where oblique arrangements occur, the geometries tend to become extremely complicated, especially with regard to the expressions of hinged highs.

Cases E and F in Figure 6*b* are examples of geometries in which adjacent half-graben display opposite polarities but do not overlap to any significant extent. The "backbone" between the two half-graben is a relatively unsubsided region termed an "interbasinal ridge" by Rosendahl et al (1986) and a "high-relief accommodation zone" by Reynolds (1984) and Burgess et al (1986). We like to view these zones as remnants of prerift rock that have been excluded from significant synrift subsidence by the particular arrangement of the bounding fault systems.

Some of the possible morphologic variations for case E arc shown in sections E_1 through E_4 (Figure 6*e*). The top three sections show various combinations of synthetic and antithetic infrastructures; the bottom section shows a double antithetic arrangement where subsidence of the two half-graben is unequal. Seismic examples of sections E_1 and E_2 are provided in Figure 7*c*. This type of linking geometry is easily recognized in other continental rifts [e.g. compare section E_1 to Figure 4 in Ghignone & Andrade (1969); section E_2 to Figure 2, profile 5, in Milanovsky (1972) and to line B74–21M in Skilbeck & Lennox (1984); section E_3 to Figure

12 in Okaya & Thompson (1985)]. Geometries such as those shown in cases D–F in Figure 6*b* also could explain the switching asymmetry described by Mueller (1970) for the Rhinegraben.

The differences between cases E and F of Family 2 pertain to the relative widths, areal extents, and perhaps the elevations of the high-relief accommodation zoncs bctwccn adjacent half-graben. Hypothetically, broad zones such as case F should be subjected to the least subsidence, but the possibility of developing pull-apart terrains atop these zones may obscure this relationship. We return to this issue in the discussions concerning preexisting fabrics and mechanisms of rifting.

Case D represents the transition between overlapping and non-overlapping geometries. The "backbone" between the adjacent half-graben still should be treated as an accommodation zone (because it continues to accommodate the motions generated by opposing subsidence), but the terms low- and high-relief accommodation zones no longer apply, *sensu stricto*. Figure 7*d* shows a seismic profile that may display this type of linking arrangement. The expression of the accommodation zone is a vertical boundary across which the regional dip changes markedly. Such boundaries may display "flower structure" (Harding 1985), indicative of strike-slip faulting. For this reason, we term these zones "strike-slip accommodation zones."

Cases G through I show linking geometries in which half-graben units face in the same directions. Unless the half-graben in case G are very different in age, it would be difficult to distinguish this geometry from a single, relatively isolated half-graben, especially with synthetically faulted infrastructure. Case I demonstrates another way that structural platforms can be created. A profile taken across either half-graben to the rhomboidal-shaped platform between the units would look much like the sections shown in Figure 7*b*.

Hypothetically, the linking couplets shown in Figure 6 can be combined with each other in virtually any conceivable mode. In reality, ccrtain linking relationships tend to be repeated during the creation of African rift zones. Burgess et al (1986) have noted that geometries that generate low-relief accommodation zones generally are terminated by high-relief geometries. In other words, case A through C arrangements (Figure 6*a*) are enclosed along strike by case E or F geometries. The best example of this is the northern half of the Lake Tanganyika Rift Zone (Figure 2). This figure also points out the direct relationship between kinks or doglegs in rifts and accommodation zones. Thus far, our studies have shown that every major kink in an African rift lake correlates to a high-relief or strike-slip accommodation zone. However, not all high-relief or strike-slip accommodation zones are expressed as kinks.

APPLICATIONS AND IMPLICATIONS OF ARCHITECTURAL THEME

Relationships to Prerift Fabrics

There has been much written about the roles of preexisting structure on the development of rift patterns (e.g. Dixey 1956, Holmes 1965, McConnell 1972, 1974a, 1978, King 1970, 1978a,b, Sykes 1978, Mohr 1982, and many other authors). Most of this literature can be divided into two schools of thought. Both contend that rifts follow earlier trends, but they disagree on the genesis of the relationship. The "opportunistic" school argues that African rifts follow antecedent grains because it is mechanically convenient to do so (e.g. Dixey 1956, King 1970). This is the classic "zone-of-weakness" doctrine that has so dominated tectonic thought since Suess's time. The specification of "mechanical convenience" is not universally agreed upon, but the work of Handin (1969) suggests an angular relation of about 25° between the direction of extensional stress and the direction of antecedent lines of weakness. Angular differences greater than this presumably force extensional fractures to adopt paths that ultimately cross existing fabrics. The other school argues for genetic causality, and McConnell (1972, 1974a,b, 1978) is the most outspoken proponent of this position.

It is worth examining the role of antecedent structures in the context of the scales and architectural patterns described here. The first point we should make is that one's perspective on the quality of the coincidence between antecedent structure and rifting is very much scale dependent. On the scale of rift branches, there can be little disagreement with Sykes (1978), who contends that rifting follows the more recent tectonic pulses. Certainly the deflection of the Western Branch around the Tanganyika Shield illustrates the strong effect at this scale of rifting.

A strong correlation to preexisting fabric also occurs on the scale of rift blocks, a point raised by Mohr (1982) and verified by our seismic studies (e.g. Patterson 1982, Lorber 1984). In brief, the orientation of the infrastructure follows the local foliation of the country rock, except where foliations intersect at high angles.

The correlation of preexisting fabric to rift zones and rift units is much more complicated and, as might be deduced from Figure 8, depends largely upon which elements of rift units are considered. The orientations of high-relief accommodation zones almost always follow prerift structural trends very closely, whereas border fault systems usually do not. Low-relief accommodation zones (i.e. hinged highs) may or may not follow antecedent foliation. Figure 8 from Lake Tanganyika portrays these patterns

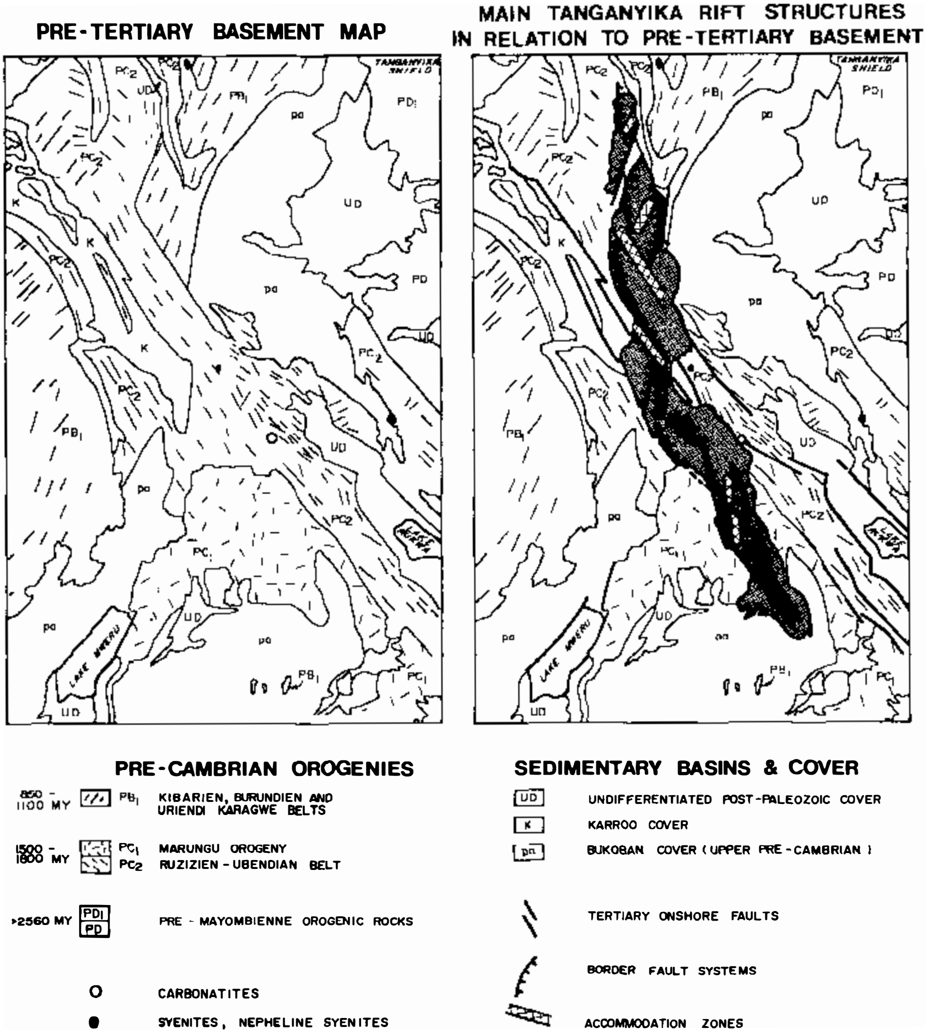


Figure 8 Relationship of Tanganyika rift structures to preexisting basement type and trends. Note the strong correlation between orientation of high-relief accommodation zones and the grain of the basement rocks. Also note that border fault systems, especially in the northern half of the zone, tend to cut across basement fabric. The overall zonal trend seems to follow the Ruzizien-Ubendian and Kibarien-Burundien belts.

quite clearly. Too few strike-slip accommodation zones are known to draw any generalities on their relation to previous structure.

The above discoveries suggest that the features that terminate rift units along strike are also those that follow preexisting grain and display the most shearing. This is equivalent to saying that the termination of rift units occurs by strike-slip faulting along prerift zones of weakness. Border fault systems "take-off" from high-relief accommodation zones and eventually cut across preexisting fabric. The data shown in Figure 8 yield the distinct impression that border fault systems are nature's way of connecting high-relief accommodation zones, not the other way around. Certainly, it is difficult to draw any other conclusion with regard to the Kavala Island and Burton's interbasinal ridges, which are mechanically coupled by the border fault systems along the western edges of the Kigoma and Nyanza-Lac half-graben (Figure 2).

Are transverse fault systems created in nature to transfer motions between offset normal faults, as implied by Bally (1982) and Gibbs (1984), or do border fault systems develop between, and in response to, discrete zones of shear, as suggested herein? The question goes beyond semantics because it strikes at the very heart of the mechanisms of rifting . . . if we are correct in our analysis, then the world's classic, archetypical rift should be treated initially as the product of pull-apart tectonics.

Because low-relief accommodation zones originate from geometries such as those shown in Figure 6*a*, it is not surprising that their relationships to preexisting fabric are complicated. On the one hand, they are part of the infrastructure of fundamental units and might be expected to behave like blocks. On the other hand, their overall orientations are strictly constrained by the asymmetric subsidence of the facing half-graben. Likely, the individual fracture patterns of hinged highs will follow older grains, but the overall trends usually will not.

Volcanism

Volcanism is the true "wild card" of rifting, especially in terms of relative abundances, compositions, and timing with respect to structural expressions. Consider that the Eastern and Western branches of the East African System are certainly genetically related, yet one branch is almost devoid of rift-related volcanics, whereas the other is virtually buried in them (Figure 1*b*). Also, it is now reasonably well established that volcanism can occur at any stage of rift evolution (Mohr 1982). Nothing in the architectural theme presented here explains the differences between the Eastern and Western branches, but the model may shed some light on the issue of where volcanism may first occur in relatively "dry" rift zones.

Within the Western Branch, rift-related volcanics are known to occur in the Rungwe belt between the Malawi and Rukwa rift zones, at the south end of the Albert Zone in the Kivu region, and between the Kivu and Edward rift units (Figures 1*b* and 1*c*). All of these known occurrences can be placed on either high-relief accommodation zones between half-graben units or on the pre–transform faults between rift zones. We also are reasonably certain that volcanic cones have been built on two high-relief accommodation zones in Lake Tanganyika. Hence, all known or inferred volcanics along the Western Branch seem to be associated with the boundaries between half-graben, not along the main portions of border faults or within units. This is in keeping with the structural setting of these zones, which suggests that high-relief accommodation zones should offer easier magmatic pathways to the surface than border fault systems, particularly if the latter sole out at relatively shallow depths. Reynolds (1984) believes that this association applies to other continental rift zones, and he cites the Cat's Hill volcanic center in the Rio Grande Rift as an example.

The regular spacing of volcanic centers along the Kenya (Gregory) and Ethiopian (Figure 1*c*) rift zones (average about 43 km according to Mohr & Wood 1976) and Turkana Rift Zone (about 50 km according to Dunkelman 1986) could be interpreted in the same vein as above. The occurrence of transverse volcanic trends in the southern Kenya Zone (Figure 1*d*) also could be associated with accommodation-zone volcanism (Figure 1*c*). However, the volcanic "wild card" reappears with regard to the only definitive Eastern Branch test of this correlation. Our recent seismic surveys of the Turkana Rift Zone suggest that North, Central, and South islands, along with an unnamed volcanic plug between Central and South islands, occur in the middle of half-graben units (Dunkelman 1986). This is exactly the opposite of what seems to occur along the Western Branch rift zones, and it suggests that egress of magmas in "wet" rift zones must be governed by different mechanical rules. It is interesting to note that volcanism in the Oslo graben (e.g. Ramberg & Larsen 1978) occurs in association with both a high-relief accommodation zone (Reynolds 1984) and in the middle region of the southern half-graben. B. T. Larsen (personal communication) believes that the latter occurrences predate the former.

Active or Passive Rifting?

There are nearly as many proposed mechanisms of rifting as there are rift researchers. Most recent reviewers of this subject (e.g. Fischer 1975, Ramberg & Neumann 1978b, Baker & Morgan 1981, Bott 1981, 1982a,b, Illies 1981, Mohr 1982, Morgan & Baker 1983, Turcotte & Emerman 1983, Ramberg & Morgan 1984) have divided propositions into what are now known as the "active" and "passive" modes of rifting (Şengör & Burke

1978). According to the proponents of active rifting, rifts are a tensile response to doming, arching, and/or uplift on a regional scale (e.g. Gregory 1896, 1921, H. Cloos 1939, Dainelli 1943, Holmes 1944, 1965, Quennell 1960a, Gass 1970, 1973a,b, Le Bas 1971, Burke & Whiteman 1973, Lowell et al 1975, Burke 1976a,b, 1977, Bailey 1978, Ramberg & Spjeldnaes 1978).

Variations and elaborations on the active theme concern such issues as the role and timing of volcanism, the causes of doming (e.g. compression of the African plate versus plumes and hotspots), the scales of doming, episodicity, and the interrelations of aulacogens, failed arms, and triple junctions. One interesting African variation is that raised by Le Bas (1971) and Gass (1975), who use different domes to make different parts of the East African Rift System. Mohr (1982) argues that the number of these variations are so great that they render the active mechanism useless as a general thcorcm of rifting.

The passive mechanism argues that subsidence, not uplift, is the first expression of rifting, and that any doming that occurs is a consequence of later thermal events (e.g. Baker et al 1972, Hutchinson & Engels 1972, Blundell 1978, de Charpal et al 1978, King 1978a,b, Illies 1978, Ramberg & Larsen 1978, Chapin 1979, Faller & Soper 1979). Most passive rifters agree that subsidence is an expression of stretching and thinning of the lithosphere induced mainly by horizontal plate separations. Variations in the passive mode pertain to the physics of lithospheric attenuation and the roles and timing of thermal events, including volcanism.

Some workers take a more noncommittal stance by discussing subsidence and uplift in a quasi-contemporaneous sense (e.g. Logatchev 1978), or else they place them after initial episodes of volcanism (e.g. Williams 1978). Although many workers often favor one or the other modes, they seem willing to accept the premise that different modes are possible for different rifts (e.g. Baker & Morgan 1981). However, the argument goes beyond geography because some authors disagree on individual rifted systems [e.g. Hutchinson & Engels (1972) vs Lowell et al (1975) on the Red Sea; Baker et al (1972) vs Gass (1970) on the Gregory Rift].

Certainly the architectural patterns described here are symptoms of the causative agents of African rifting, but are the symptoms unique enough to diagnose the type of malady? Does the architectural theme constrain the above models? The problem we face is that the symptoms mainly relate to brittle fracture, whereas the mechanisms also involve the ductile portion of the plates. As de Charpal et al (1978) point out, behavior in the brittle crust should not be used to measure necking in the underlying ductile zone. Thinning in the latter can both precede and exceed that in the former. In view of these difficulties, we limit our discussion to a few key points.

The first concerns thc issuc of subsidence, shcaring, and high-relief accommodation zones. Relations to preexisting fabric seem to argue that subsidence is a by-product of shearing along high-relief accommodation zones, not the other way around. If so, then perhaps we ought to concentrate our search for rift mechanisms on situations or conditions that give rise to relatively large-scale intraplate shear stresses. This would argue for a variation of the passive rifting theorem for the same reasons that the Dead Sea rift is classified as passive.

The second point to consider is that nothing in the synrift histories of the African rift zones we have studied requires regional uplift or doming concurrent with extensional deformation. Some of our seismic profiles show unconformities and even some evidence of subaerial erosion, but these events can be explained adequately by facing half-graben geometries with the subsidence teeter-totter, or by climatic changes. It is not so easy to discount the possibility of early or prerupture uplift. Unlike the Bay of Biscay, the rotated fault blocks in the African rift lakes do not display enough internal stratigraphy to prove the existence of prerift sags. Indeed, the lack of such internal stratigraphies could be used to support the active-rifting theorem. Acoustic basement in Lakes Tanganyika, Turkana, and Malawi has the same basic seismic character and is probably the acoustic signature of deeply eroded, prerift crystalline rocks mantled with soils, perisols, laterites, etc (Burgess et al 1986). If the hiatuses across these boundaries prove to be large, as we suspect they will, then the possibility of regional, prerift uplift cannot be discounted.

The third point concerns the issue of volcanism. It has been suggested or implied by some workers (e.g. Williams 1978) that volcanism is the first symptom of rifting, at least in some rift zones. Unfortunately, this is almost impossible to prove. On the other side of the coin, it is certain that subsidence has preceded significant volcanism in the Malawi, Tanganyika, and Albert rift zones. If volcanism and doming are contemporaneous, this relation might argue that subsidence precedes uplift.

The uncertainty regarding the chronology, sequencing, and timing of rifting events in East Africa is deeper than might be ascertained from the active-passive controversy alone. The situation also is further clouded by a certain degree of circularity. For example, those who are especially impressed with regional erosional surfaces (e.g. Dixey 1956) tend to be proponents of active rifting and date the onset of rifting from one or another of these surfaces. In this fashion Dixey placed the initiation of the Malawi Zone in the Miocene. Crossley & Crow (1980), on the other hand, date the onset of Malawi fault activity at the Pliocene. Where volcanics are associated with rifting, such as in the Kenya Rift Zone, it is tempting to correlate the onset of rifting with the first appearance of some particular volcanic event (e.g. Williams 1978). It might be said that the rifting sequence one derives for East Africa is strongly influenced by the criteria one uses to define the onset of rifting.

In Figure 9 I have attempted to construct an evolutionary scheme of rifting that is compatible with our seismic results from African rift zones and with the major points raised in this paper. Some of the more attractive features of previously published models also have been retained. The work of Lowell & Genik (1972) needs specific mention because the model they derived for the southern Red Sea has strongly influenced the conceptualization of the last two stages of Figure 9. It might be noted that Lowcll & Genik's study contains many of the elements that now, 15 years later, are the highlights of the more popular extensional models.

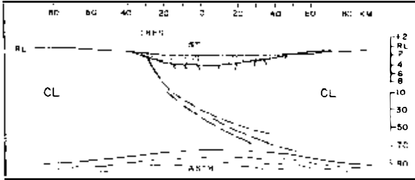
Comments on the Development of Passive Margins

When researchers attempt to fit conjugate margins back together, the backtracking usually begins with magnetic anomalies and ends with matching some bathymetric contour (e.g. Talwani & Eldholm 1977). The final fits are never truly clean, and they often leave overlaps, gaps, or misfits that resemble continental rift zones. Another complication of passive-margin rift sequences relates to dip; some appear to dip toward the adjacent continents, whereas others dip away. In some places this change in dip direction occurs over relatively short distances along the same margin. Several authors have addressed these specific problems [initially Lowell & Genik (1972) and more recently Bally (1982)], but satisfactory explanations have proven elusive. We think the architectural theme described here provides some elegant, yet simple answers, and we use the Tanganyika Rift Zone as a case in point.

The first point is that there is little yet to fit back together with regard to the Tanganyika Rift Zone, or to any of the other rift zones south of Ethiopia. The maximum extension we compute across any Tanganyika fundamental unit is 8%, and values of 5–7% are more typical. Although stretching and consequent separation in the ductile portion of the lithosphere could be much greater (cf. Wright & Troxel 1966), it clearly has not reached a stage of significant lithospheric separation. This means that if ocean basins such as the Red Sea and the Norwegian-Greenland Sea began as Tanganyika-like rift zones, then closing the basins by removing the oceanic crust should result in overlaps and misfits that resemble the

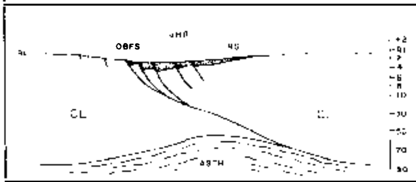
Figure 9 Possible stages in the evolution of continental rifts. Stages correspond to cross-sectional snapshots of a hypothetical rift basin. Volcanism is treated as a "wild card" in the rifting process because it can occur at any stage. Note that abandonment also can happen at any stage.

POSSIBLE STAGES IN THE EVOLUTION OF RIFTS



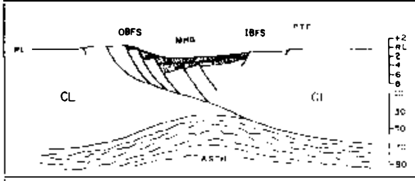
STAGE 1: STRETCH TROUGH (ST)

INITIAL STRETCHING AND THINNING OF CL, CREATING RELATIVELY BROAD SURFACE DEPRESSION. UPPERMOST CRUST MAY SHATTER, BUT FAULT THROWS GENERALLY BELOW RESOLUTION LIMITS OF SEISMICS. TYPICAL AMOUNT OF SUBSIDENCE IS 10 TO 15 KM. SEDIMENT INFILL DOMINATED BY FLUVIAL OR EOLIAN SANDS SHOWING MUCH REWORKING. SYSTEM WILL APPEAR TRANSGRESSIVE WITH VARIABLE AND COMPLICATED INPUT PATTERN. COMPARE TO STAGE 1 OF KAZMIN (1980a).



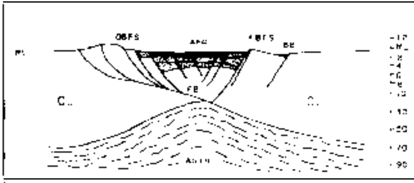
STAGE 2: JUVENILE HALF-GRABEN (JHG)

DEVELOPMENT OF ASYMMETRIC GRABEN COMPOSED OF FAULT BLOCKS THAT TILT MAINLY IN THE SAME DIRECTION. OBFS DIVIDES REGION OF SHOULDER UPLIFT FROM REGION OF CONTINUED SUBSIDENCE, BUT ACTUAL SUBSIDENCE MORE OR LESS EQUALLY DISTRIBUTED AMONG FAULTS THAT DEFINE TILTED BLOCKS. TYPICAL NUMBER OF ACTIVE BLOCKS RANGE FROM 3 TO 6, WITH TYPICAL WIDTH OF 10 KM. REGION OF ACTIVE SUBSIDENCE GENERALLY NARROWER THAN WIDTH OF ST. STRATIGRAPHY CONTROLLED BY WEDGE-BLOCK STYLE OF DEPOSITION OF FLUVIAL CLASTICS, WHICH CAN ENTER FROM EITHER SIDE OF HALF-GRABEN. SEDIMENT LITHOLOGY DEPENDENT ON POSITION WITHIN WEDGE-BLOCK AND DISTANCE FROM SOURCE. ANGULAR UNCONFORMITY OFTEN DIVIDES STAGE 1 AND STAGE 2, SUGGESTING THAT ONSET OF BLOCK ROTATION IS RELATIVELY ABRUPT. ONSET OF STAGE 2 PROBABLY RELATES TO CREATION OF DETACHMENT ZONE THROUGH CL.



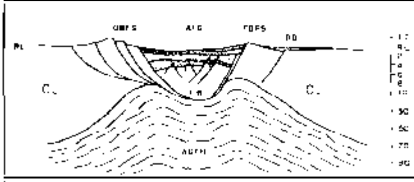
STAGE 3 MATURE HALF-GRABEN (MHG)

DEVELOPMENT OF STRONGLY ASYMMETRIC GRABEN WITH MOST OF SUBSIDENCE TAKEN UP ALONG OBFS. CONTINUED UPLIFT AND ROTATION OF SHOULDER USUALLY CREATES BACK-TILTED RIFT MOUNTAINS, RESULTING IN CESSATION OF SIGNIFICANT SEDIMENT INPUT FROM STEEP SIDE OF HALF-GRABEN. MOTIONS ALONG INTERNAL FAULTS SLOW OR CEASE, BUT OVERALL RATE OF SUBSIDENCE MAY ACCELERATE. SUBSIDENCE GENERALLY OUTPACES SEDIMENTATION, EXCEPT WHERE AXIAL DELTAS OCCUR. WITH SWITCH FROM DISTRIBUTED TO LOCALIZED MASTER FAULT SYSTEMS, WEDGE-BLOCK STYLE OF DEPOSITION GIVES WAY TO CONSTRUCTION OF BROAD FANS ORIGINATING FROM RAMPING SIDE OF HALF-GRABEN. COMPARE TO WERNICKE (1981).



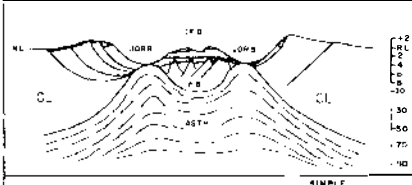
STAGE 4 FACING HALF-GRABEN

ACTIVATION OF FBFS CONCURRENT WITH RETARDATION OR CESSATION OF SUBSIDENCE ALONG OBFS. GEOMETRY EVENTUALLY PRODUCES APPARENT FULL-GRABEN WITH AXIAL HIGH, OR "HINGE ZONE". CENTRAL REGION MAY BECOME A FREE BLOCK. BACK-TILTED RIFT MOUNTAINS CAN DEVELOP ON BOTH SIDES OF BASIN, WHICH RESULTS IN CUTTING OFF FLUVIAL SEDIMENT SUPPLY AND CREATION OF DEEP, STARVED LAKES. ONSET OF ACTIVITY OF FBFS USUALLY MARKED BY ANGULAR UNCONFORMITY AND CREATION OF A NEW GENERATION OF FAULTS. SEDIMENTATION DOMINATED BY BIOGENIC RAIN AND LOCAL BORDER FAULT FANGLOMERATES. COMPARE TO STAGE III OF LOWELL AND GENIK (1972).



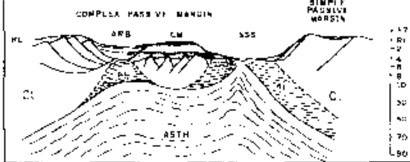
STAGE 5 SUBSIDENCE TEETER-TOTTER

ALTERNATION IN BOUNDARY FAULT ACTIVITY BETWEEN FBFS AND OBFS, POSSIBLY SEVERAL TIMES. ALTERNATIONS APPEAR TO BE RELATIVELY SUDDEN, RESULTING IN CREATION OF ANGULAR UNCONFORMITIES. ABANDONED SITE OF AFG MAY BE UPLIFTED AND ERODED, SOMETIMES EXTENSIVELY. OVERALL PATTERN IS A TEETER-TOTTER, ALBEIT WITH A COMPLICATED AND SPATIALLY CHANGING HINGE LINE. MOST OF SHALLOW PROCESSES EXPLICABLE IN TERMS OF FB TO RISING ASTH. IF ASTH RISES ALONG MAJOR DETACHMENTS, PLUME MAY SPLIT INTO EDDIES. DEPOSITIONAL PATTERNS DURING THIS STAGE MAINLY CONTINUATION OF PREVIOUS STAGE.



STAGE 6 JUVENILE OCEANIC RIFT BASIN (JORB)

DEVELOPMENT OF ONE OR MORE JORB. DRAWING SHOWS SITUATION OF SIMULTANEOUSLY ACTIVE JORB SEPARATED BY FB. CENTRAL BLOCK CAN BECOME COMPLETELY ISOLATED IF BOUNDED BY TRANSFORMS IN OTHER PLANE. IFB PROBABLY UPLIFTED RELATIVE TO LEVEL IN STAGE 4, RESULTING IN REDEFORMATION OF BLOCK AND EROSION AND REWORKING OF SEDIMENT PILE ON TOP OF FB. COMPARE TO STAGE IV OF LOWELL AND GENIK (1972).



STAGE 7 SUCCESSFUL SPREADING SYSTEM (SSS)

CONTINUED OPENING OF ONE JORB AND EVENTUAL ABANDONMENT OF OTHER(S). ABANDONMENT CAN OCCUR AT ANY TIME FROM STAGE 4 ONWARD. SITUATION DEPICTED HERE SHOWS SMALL ARB, BUT FEATURES CAN BE LARGE, THICKLY SEDIMENTED BASINS UNDERLAIN BY BROAD ZONE OF AL. MECHANICALLY, FB BECOMES ATTACHED TO ONE OF PLATES BUT GEOPHYSICALLY AND PETROLOGICALLY IT WILL APPEAR AS A CONTINENTAL "MARSHMALLOW" RIDDLED WITH RIFT-TYPE STRUCTURES. IF BOTH JORB REMAIN ACTIVE FOR LENGTHY PERIOD, IFB MAY BECOME A MICROCONTINENT.

AFG = APPARENT FULL-GRABEN
AL = ACCRETED LITHOSPHERE
ARB = ABANDONED RIFT BASIN
ASTH = ASTHENOSPHERE
BB = BACK BASIN
CL = CONTINENTAL LITHOSPHERE
CM = CONTINENTAL "MARSHMALLOW"
FB = FREE BLOCK
FBFS = FACING BORDER FAULT SYSTEM
IBFS = INCIPIENT BORDER FAULT SYSTEM
IFB = ISOLATED FREE BLOCK
JHG = JUVENILE HALF-GRABEN
JORB = JUVENILE OCEANIC RIFT BASIN
MHG = MATURE HALF-GRABEN
OBFS = ORIGINAL BORDER FAULT SYSTEM
PTF = PLATFORM
RL = REFERENCE LEVEL
RS = RAMPING SIDE OF HALF-GRABEN
SSS = SUCCESSFUL SPREADING SYSTEM
ST = STRETCH TROUGH

Tanganyika Rift Zone. We might say that continental rift zones are the "leftovers" of backtracking plates to their times of opening (but not to their times of rifting).

If the Tanganyika Rift Zone werc to evolve into a successful oceanic rift, it could not possibly do so in any symmetric conjugate sense. Indeed, it is impossible to produce biaxial symmetry by splitting the map of Tanganyika (Figure 8) along strike. Bally (1982) flirted with the same conclusion, but the "fitting-together" problem is even more complicated than he imagined because the original fracture patterns are usually not orthorhombic. Let us continue by imagining the hypothetical conjugate margin that would result from the spreading of Figure 8. For the same reason that the fracture margins of high-relief accommodation zones are possible loci of early volcanism, they are also the preferred track of an incipient plate boundary. In a sense, the plate boundary partially exists in the vicinity of the high-relief accommodation zones. The next step is connecting these incipient boundaries together. The connections almost certainly must occur within the half-graben units, either along low-relief accommodation zones or border fault systems. Where both elements exist (e.g. cases A–C, Figure 6*a*), mechanical decoupling is probably easier along low-relief accommodation zones. Where the connection must occur through a simple half-graben, the border fault system is the convenient choice. Even so, there are no compelling reasons why the interconnections need to follow the surficial trace of the border fault systems, especially if the border fault systems flatten out with depth and intersect the ductile zone within the upper 15–20 km of crust. Figure 10 shows two possible geometries after successful splitting. Simple cross-sectional examples at various positions along the margins of Figure 10*b* are provided in Figure 10*c*. These hypothetical cross sections are comparable to those postulated for various passive margins, and they also provide a ready explanation for the variability observed along most passive margins.

Which elements of the fundamental unit become spreading centers and which transform faults? Our intuition would argue that high-relief accommodation zones should be the prototransforms, and a rather compelling case could be derived for situations where the orientation of the stress field remains relatively constant from the onset of rifting through successful splitting. If the stress field changes orientation significantly at the time of successful splitting and our suppositions regarding volcanism are correct, then it is conceivable that border fault systems occasionally could evolve into transforms rather than spreading centers. The breakup scheme in Figure 10 assumes the former case, but it is obvious that either case would result in very asymmetric conjugate margins.

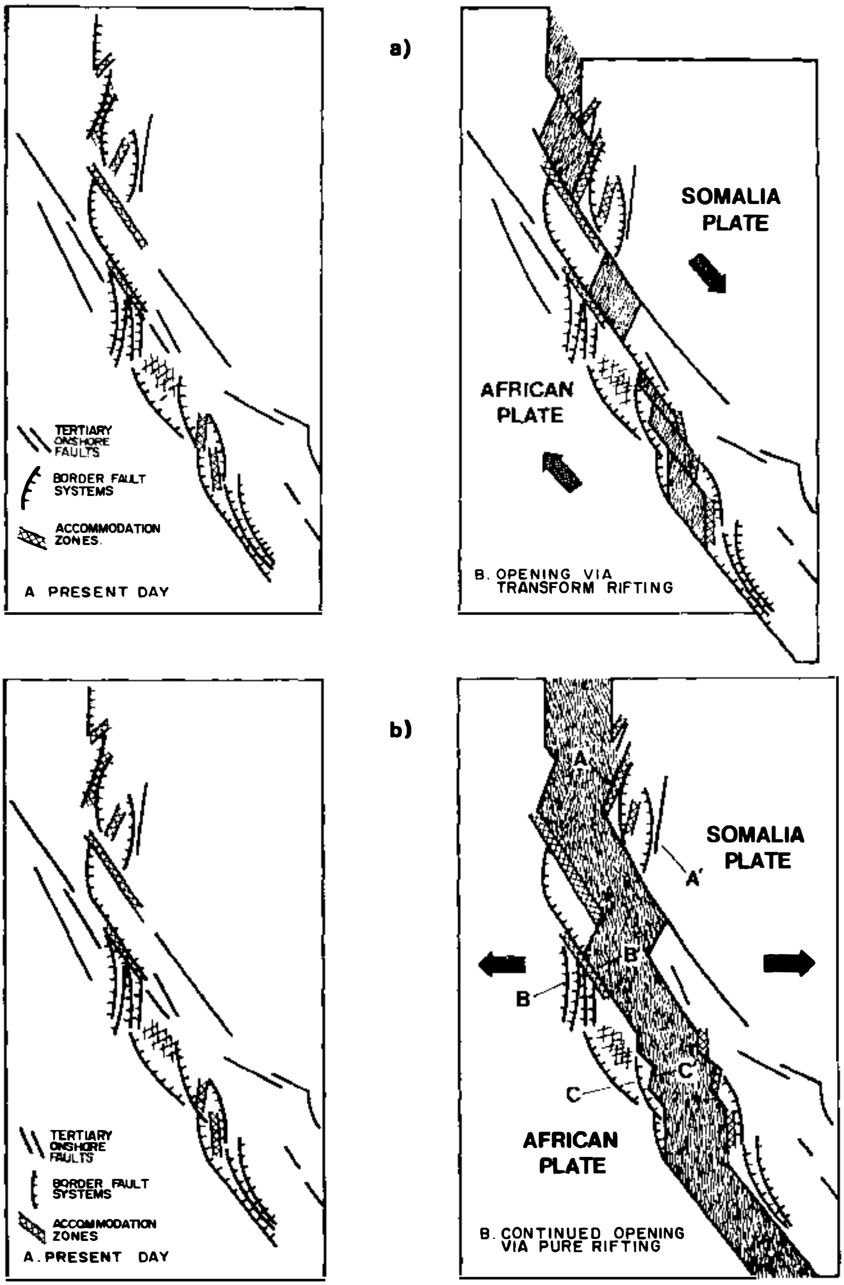
A related issue concerns the proposition that oceanic ridge-ridge transforms can be extended across passive margins and into continental lineaments. This idea began with Wilson's (1965) suggestion that mid-ocean ridge offsets should mimic changes in continental margin orientations. The idea gained popularity from efforts such as Hayes & Ewing (1970) and Arens et al (1971). Extensions into continental zones of weakness have been proposed by Snelgrove (1967), Girdler (1968), Garson & Mitchell (1970), Fail et al (1970), Fuller (1971), Garson & Krs (1976), Fletcher et al (1978), and Sykes (1978), to name just a few. The above discussion, along with Figure 10, suggests that such extensions are possible only where the following circumstances prevail: (*a*) High-relief accommodation zones follow preexisting structural grains of regional extent; and (*b*) high-relief accommodation zones evolve into transforms, which maintain the same orientation. This requires that the stress field not undergo any significant deviation between the continental rifting phase and the spreading phase.

Given these circumstances, especially the unlikelihood of the last condition, it is difficult to accept that a majority of ridge-ridge transforms maintain pole-of-rotation trajectories across hundreds of kilometers of continent. The usual case is probably closer to what Reynolds (1984) has described and what I have shown here in Figure 10. This implies that transform continuations such as those shown in Figures 5 and 7 of Garson & Krs (1976) may be incorrect.

If ridge-ridge transform faults ultimately owe their existences to high-relief accommodation zones (interbasinal ridges), which is probably the general case, then we could conclude that the geometry of trailing plate edges is largely implanted at the onset of the continental rifting phase. Presumably, this applies to such parameters as transform-fault spacing and perhaps even spreading-center placements. It seems likely that the regularities in spacings described by Schouten & Klitgord (1982a,b) are inherited from the regularities in spacings of high-relief accommodation zones. Another consequence of the breakup theme described herein is the prediction that seismic traverses parallel to passive margins ought to show basin-swell-basin morphology. The first-order wavelength should be the average distance between high-relief accommodation zones—about 120 km for the East Africa System. The strike profiles from offshore Brazil (e.g. Asmus & Guazelli 1981) seem to support such a prediction, as do many proprietary lines from petroleum companies.

Concluding Statement

I have molded this review around the idea that African rift morphology has a measure of architectural stability, repeatability, and even predictability with regard to certain parameters. The key to understanding the architectural patterns lay in recognizing the various ways in which rift


a)
TERTIARY ONSHORE FAULTS
BORDER FAULT SYSTEMS
ACCOMMODATION ZONES.
A PRESENT DAY
SOMALIA PLATE
AFRICAN PLATE
B. OPENING VIA TRANSFORM RIFTING
b)
TERTIARY ONSHORE FAULTS
BORDER FAULT SYSTEMS
ACCOMMODATION ZONES
A. PRESENT DAY
A
A'
B
B'
C
C'
SOMALIA PLATE
AFRICAN PLATE
B. CONTINUED OPENING VIA PURE RIFTING

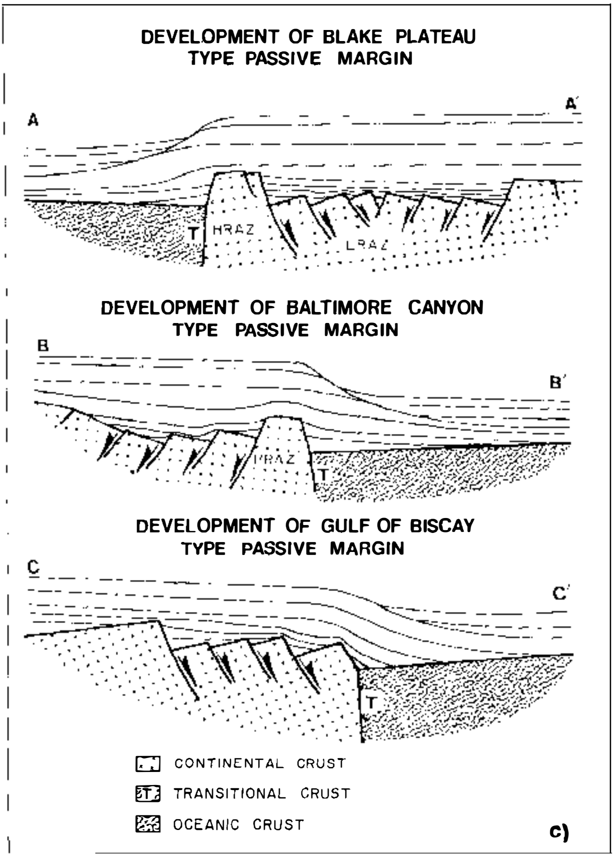


Figure 10 Hypothetical splitting of the Tanganyika Rift by transform (Figure 10*a*) and pure orthogonal (Figure 10*b*) rifting. Figure 10*c* shows passive-margin settings along the traverses shown in Figure 10*b*. Note that the profiles in Figure 10*c* also apply to Figure 10*a*.

units tend to link together. The impact of this geometric theme on our understanding of continental rifting, in Africa and elsewhere, could be very significant. Given what is at stake, perhaps it is fitting to close this paper on a cautionary note. I use the same admonition that Suess used to close his famous treatise on African rifts (Suess 1891):

> In all representations of this kind we have, however, to guard against the assumption of a general arrangement of any kind: indeed, considering the almost incomprehensible variety of the occurrences, a systematic search for regularity is not without danger, because the inquiring mind is so easily led astray from the path of sound synthesis.

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