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Seismic-refraction studies of the Afro–Arabian rift system — a brief review

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Abstract

The crustal and uppermost-mantle structure of major units of the Afro–Arabian rift system has been consecutively investigated by seismic-refraction surveys in the Jordan–Dead Sea rift, the Red Sea, the Afar depression and the East African rift of Kenya. With the exception of the Jordan–Dead Sea transform, the entire Afro–Arabian rift system is underlain by anomalous mantle with Pn-velocities less than 8 km/s, while under the rift flanks the velocity is clearly equal to or above 8.0 km/s. Various styles of rifting have been found. Oceanic crust floors the axial trough of the southern Red Sea rift, thinned continental crust underlies the margins of the Red Sea as well as the Afar depression and the northern Kenya rift. On the other hand, 30–35-km-thick continental crust is found both under the Jordan–Dead Sea rift, where strike-slip rifting is active and thinning towards the Mediterranean occurs, and under the central Kenya rift, where updoming is apparently the controlling feature. While the transition from thinned continental to 5–6-km-thick oceanic crust in the centre of the Red Sea appears to be more gradual, the transition from rift-related structure to undisturbed continental crust of 40 ± 5 km thickness is mostly rather abrupt. The seismic data indicate various stages of rifting evidenced by different styles of crustal structure and they imply the presence of heated uppermost-mantle under most parts of the rift system, possibly related to plume activity. Local volcanism may disrupt and/or underplate the crust in places, altering in particular the structure of the lower crust. Progressive thickening of the rifted crust away from the oceanized centres in the southern Red Sea and Gulf of Aden towards north and south may be viewed as an evolutionary sequence which, however, may be difficult to explain when viewing the Afro–Arabian rift system as an active rift controlled by plume activity.

Keywords: crust; lithosphere; seismic refraction; Afro-Arabian rift system; Red Sea; East Africa

1. Introduction

Continental rifting is one of the intraplate processes that takes place at the beginning of continental breakup. The Afro–Arabian rift system is the world's largest active continental rift system extending from Syria in the north, traversing through the Jordan valley, Dead Sea, Red Sea, Gulf of Aden, Afar, East Africa and terminating in a large number of splaying faults in southern Africa. It comprises a variety of rifting stages, starting from initial faulting, advancing through several stages of continental rifting and incipient oceanization and ending in miniature ocean

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basins. Its rift valleys split substantial domal uplifts and are accompanied by a large number of volcanic centres. The Afro–Arabian rift system is therefore the best example today for investigating the breaking of a continent in different stages.

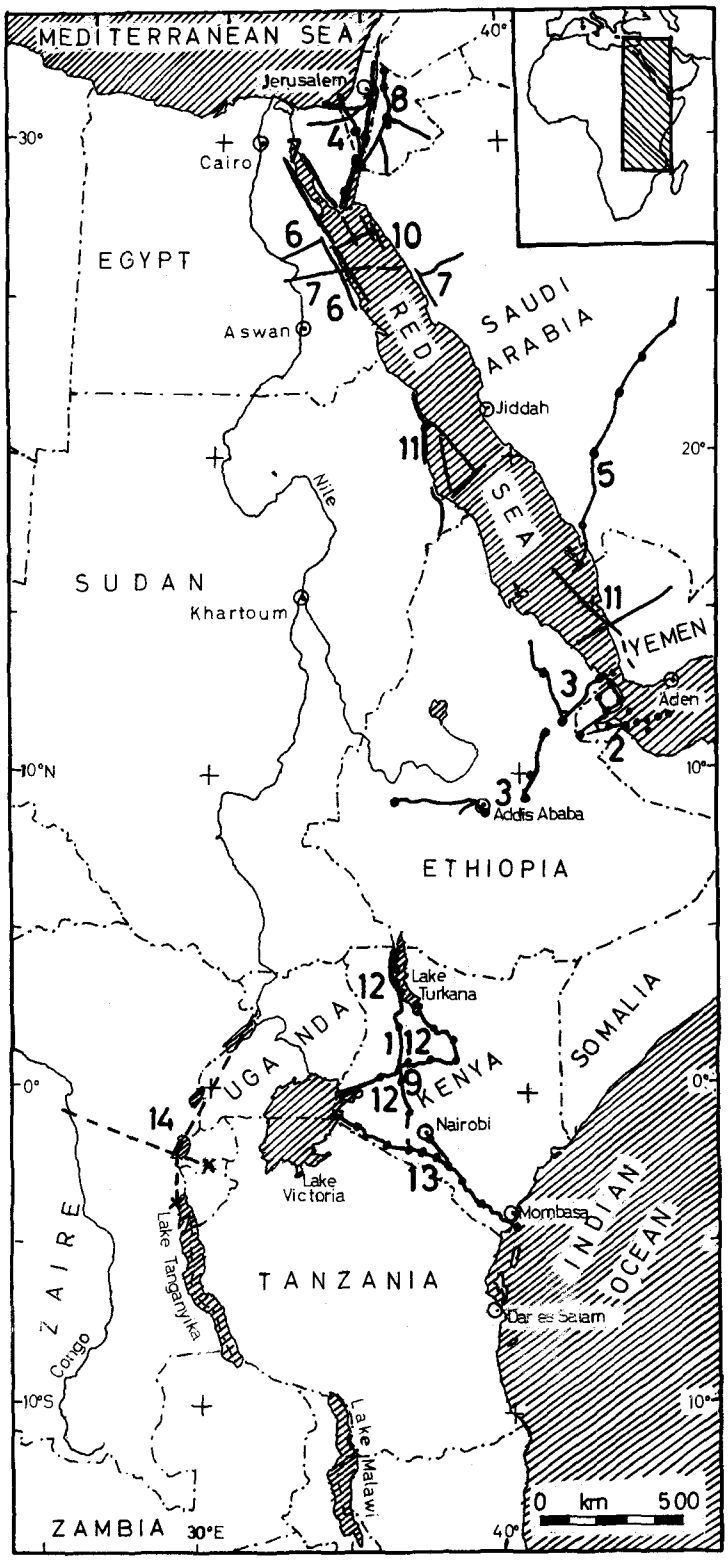
To look for mechanisms which cause the development of a continental rift during its various stages and the subsequent modification and reduction of its continental lithosphere, a 15-year interdisciplinary research programme at the University of Karlsruhe, the Collaborative Research Centre 'Stress and Stress Release in the Lithosphere', devoted a major part of its research to the investigation of the Afro–Arabian rift system. The research of the first years was concentrated on the Red Sea rift system, in particular on the Jordan–Dead Sea transform and the eastern margin of the northern and southern Red Sea (e.g., El-Isa et al., 1987; Voggenreiter et al., 1988; Bayer et al., 1989; Fuchs et al., 1990), while the second period was exclusively devoted to the eastern branch of the East African rift system inter-relating with international efforts culminating in the KRISP (Kenya Rift International Seismic Project) expeditions of 1985, 1989–1990 and 1993–1995 (KRISP Working Group, 1987, 1995; Henry et al., 1990; KRISP Working Party, 1991; Prodehl et al., 1994a; and contributions in this volume).

Since the previous reviews of Mechie and Prodehl (1988) and Prodehl and Mechie (1991) summarizing our knowledge of crustal structure underneath the Afro–Arabian rift system, considerable knowledge has been added. While Keller et al. (1994) and Braile et al. (1995) concentrate on the research carried out in the eastern branch of the East African rift system and Makris and Rihm (1991) offer a new model for the Red Sea, at the closure of our Collaborative Research Centre a comprehensive, up-to-date summary of our present knowledge of the entire rift system seems appropriate. This contribution, however, will only review the results of deep seismic sounding research from seismic-refraction surveys within the Afro–Arabian rift system. For the results of other disciplines and comprehensive discussions of more general results, the reader is referred to Fuchs (1997), Zeyen et al. (1997) and other related contributions of this volume. As many of the results and their implications are discussed in much detail in the earlier publications cited above and other contributions of this volume, here only a brief description of the seismic sections shown will be given.

2. Crustal seismic investigations of the Afro–Arabian rift system

Fig. 1 shows the location of all major seismic long-range lines recorded from 1967 to 1994 which covered the whole crust and partly penetrated into the uppermost mantle. The various crustal cross sections, which were published by the individual groups as crustal columns, cross sections, fence diagrams, and/or contour maps in due time after the corresponding field work, were re-inspected and redrawn at a unified scale (distance : depth = 1 : 2) in a map of the Afro–Arabian rift system (Fig. 2). The cross sections have approximately been placed in the regions for which they are representative. The map contains the majority of the crustal cross sections reaching to the crust–mantle boundary which have been published during the last 15 years. It does not include any gravity cross sections and tomographic results for which the reader is referred to the corresponding publications. References for the following brief summary of the main features of crustal structure are given in the corresponding captions of Figs. 1 and 2.

Fig. 1. Map of long-range seismic lines in the Afro–Arabian rift system. Continuous lines: seismic-refraction surveys, dots mark shotpoints where locations were published. Dashed lines: approximate lines through epicentres of local earthquakes, crosses represent IRSAC (Institut pour la Recherche Scientifique en Afrique Centrale) network stations used by Bram (1975). *1* = Kenya rift 1968 (Griffiths et al., 1971); *2* = Djibouti 1971 (Ruegg, 1975); *3* = Afar depression 1972 (Berckhemer et al., 1975); *4* = Jordan–Dead Sea–Gulf of Aqaba transform system 1977 (Ginzburg et al., 1979a); *5* = Arabian Shield 1978 (Mooney et al., 1985); *6* = northern Red Sea 1978 (Rihm et al., 1991); *7* = northern Red Sea 1981 (Makris et al., 1983; Rihm et al., 1991); *8* = Jordan 1984 (El-Isa et al., 1987); *9* = Kenya rift 1985 (KRISP Working Group, 1987); *10* = northern Red Sea (Gaulier et al., 1988); *11* = southern Red Sea (Egloff et al., 1991); *12* = Kenya rift 1990 (Prodehl et al., 1994a; Mechie et al., 1997); *13* = southern Kenya 1994 (Prodehl et al., 1997); *14* = western rift — local earthquakes recorded at two stations UVI and BTR (marked by crosses) of the IRSAC network near Bukavu, evaluated as seismic profiles UVI-N and BTR-WNW (Bram, 1975; Bram and Schmeling, 1976; see Fig. 2).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The flanks of the entire Afro–Arabian rift system are underlain by mantle with Pn-velocities of 8.0–8.2 km/s at about 40 ± 5 km depth. Continental crust that is 30–35 km thick and a mantle with velocities of 8.0 km/s are interpreted under the Jordan–Dead Sea rift, where strike-slip rifting is active and thinning towards the Mediterranean occurs. Thinned continental crust with a velocity less than 8 km/s underlies the northern Red Sea as well as the Afar depression and the northern Kenya rift. Oceanic crust floors the axial trough of the central and southern Red Sea rift and the Gulf of Aden (Fig. 3). However, oceanization has not yet replaced the thinned continental crust under their margins and coastal plains of the central and southern Red Sea as well as under the southern outlet of the Red Sea towards the Gulf of Aden. While the transition from thinned continental to 5–6-km-thick oceanic crust appears to be gradual, the transition from rift-related structure to undisturbed crust is mostly rather abrupt. The change from 15- to 18-km-thick transitional crust under the southeastern Red Sea margin to the 40-km-thick continental crust of the Arabian Shield occurs over a limited distance range of less than 50 km and is the major lateral change in structure in this region.

In the northern Afar depression the crust is only 12–15 km thick, but thickens gradually to more than 25 km in the southern Afar depression, the whole region being underlain by anomalous mantle with velocities between 7.0 and 7.4–7.5 km/s. However, an abrupt change to a 40-km-thick shield crust of the Ethiopian plateau with a mantle velocity of 8.0 km/s is evident from seismic and gravity data.

The crust under the Kenya rift is thickest (about 35 km) near the apex of the Kenya topographic dome where updoming is apparently the controlling feature and where the rift valley floor is at its maximum elevation and the amount of extension across the rift is small. To the north, the crust thins dramatically to about 20 km near Lake Turkana at the northern end of the domal uplift, where the amount of extension is higher and the elevation of the rift floor is at its lowest. Although there is evidence of underplating in the form of a relatively high-velocity lower crustal layer, there are no major seismic velocity anomalies in the middle and upper crust which would suggest pervasive magmatism. Under southern Kenya, relatively thin crust (less than 35 km) was found under the rift valley and the areas extending westward to Lake Victoria. The most interesting feature, however, is an unusually thick crust (up to 44 km) extending eastwards from the rift for over 300 km towards the continental margin near the Indian Ocean where a more normal thickness of 25–30 km is reached. Weak supercritical reflections from the Moho suggest a transitional boundary in the region of the Chyulu Hills volcanic field, a major Quaternary feature.

Detailed teleseismic tomography studies were only carried out in central and southern Kenya. The south-central Kenya rift is clearly associated with sharply defined lithospheric thinning and very low upper mantle velocities down to depths of over 150 km (Achauer et al., 1994). There the lithospheric mantle has been thinned much more than the crust. To the north, under the Turkana region, high-velocity layers detected in the upper mantle appear to require the presence of anisotropy with preferred orientation of olivine crystals (Keller et al., 1994).

3. Discussion and conclusions

Summarizing the characteristics of crust and upper mantle structure shown in Fig. 2 for the entire Afro–Arabian rift system and its flanks, the following physical parameters may be regarded as typical.

(1) Internal crustal structure variations in the rift zone are significant in all parts of the Afro–Arabian rift system.

(2) Strong crustal thickness variations occur along the entire rift system, reaching from less than 10 km to more than 35 km.

(3) Rift and flank crusts may differ substantially both in structure and velocities.

(4) The crust–mantle boundary in rift areas is usually not a sharp boundary, but a transitional zone.

(5) The uppermost-mantle (Pn) velocity in the rift zone is always less than 8 km/s, the only exception being the Jordan–Dead Sea-transform.

(6) The uppermost-mantle (Pn) velocity under the flanks is always equal to or greater than 8 km/s, an exception being the Chyulu Hills in southern Kenya.

A sequence of crustal columns (Fig. 4) shows the different stages of the in-rift crustal structure development along the course of the Afro–Arabian rift system from Syria to southern Africa. At the cen-

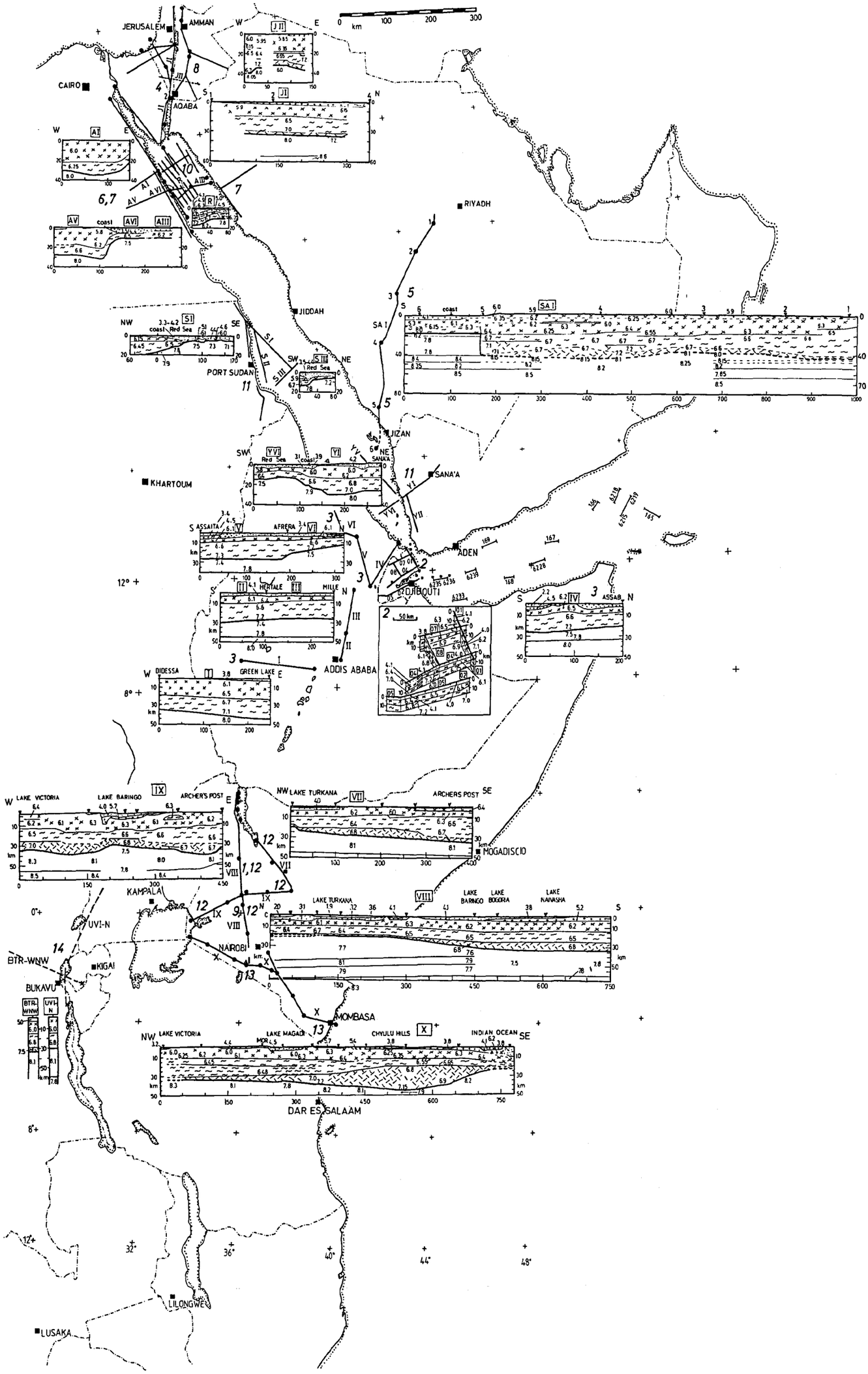

Fig. 2. Map of the Afro–Arabian rift system from the Jordan–Dead Sea transform through the Red Sea, the Gulf of Aden and the Afar depression to southern Kenya showing location of seismic lines and corresponding crustal structure sections. Location of shotpoints, if published, is marked by dots on the map, resp., by arrows along the crustal sections. In the Gulf of Aden are also shown the locations of those marine profiles which reached the Moho and which are presented as crustal columns in Fig. 3. *4* (Fig. 1): *J-I* = Dead Sea–Arava valley–Gulf of Aqaba (Ginzburg et al., 1979b). *4/8* (Fig. 1): *J-II* = Jordan–Dead Sea transform E–W section (El-Isa et al., 1987). *6* (Fig. 1): *A-I* = northern Red Sea to western flank (Rihm et al., 1991). *7* (Fig. 1): *A-III–A-VI–A-V* = northern Red Sea to western flank (Rihm et al., 1991). *10* (Fig. 1): *R* = northern Red Sea (Gaulier et al., 1988). *5* (Fig. 1): *SA-I* = Arabian Shield (Mechie et al., 1986). *11* (Fig. 1): *S-I, S-III* = southern Red Sea and southern Sudan (Egloff et al., 1991); *Y-VI–Y-I* = southern Red Sea to Yemen plateau (Egloff et al., 1991). *3* (Fig. 1): *II, III, IV, V, VI* = Afar depression (Berckhemer et al., 1975; Makris and Ginzburg, 1987); *I* = Ethiopian highland (Berckhemer et al., 1975; Makris and Ginzburg, 1987). *2* (Fig. 1): Fence diagram in quadrangle Gulf of Tadjura and Afar region of Djibouti (Ruegg, 1975). *12* (Fig. 1): *VIII* = Kenya rift between Lakes Turkana and Naivasha (Mechie et al., 1994); *VII, IX* = cross rift and flank structure of northern and central Kenya rift (Maguire et al., 1994; Prodehl et al., 1994b). *13* (Fig. 1): *X* = southern Kenya (crossing Kenya rift near Lake Magadi and traversing Chyulu Hills (Birt et al., 1997; Novak et al., 1997; Prodehl et al., 1997). *14* (Fig. 1): *UVI-N* = western rift north of Bukavu (Bram, 1975; Bram and Schmeling, 1976); *BTR-WNW* = Congo shield west of Bukavu (Bram, 1975); crosses represent IRSAC recording stations UVI and BTR of the corresponding lines.

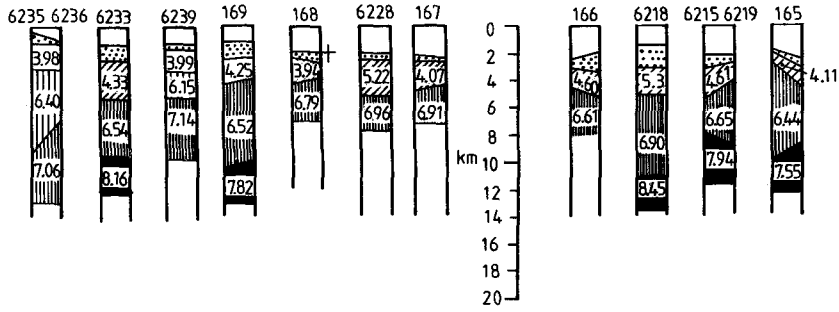

Fig. 3. Crustal columns of marine profiles observed in the western (left part) and eastern (right part) Gulf of Aden (Laughton and Tramontini, 1969). For locations, see Fig. 2.

tre thin oceanic crust is encountered in the central trough of the Red Sea and the Gulf of Aden. Moving away from the centre towards the north or south, crustal thickness increases until the thickest continental types of crust are met under the Jordan–Dead Sea transform and the domes of the East African rift system. The sequence has been updated from previous publications (Mechie and Prodehl, 1988; Prodehl and Mechie, 1991; Keller et al., 1994) by additional data which confirm and support the earlier conclusions viewing the sequence as an evolution in space.

When viewed within the context of other observations, the physical characteristics and differences illustrated in Figs. 2 and 3 lead to important conclusions concerning rift evolution in general.

(1) Internal crustal variations are often reflected in near-surface faulting, volumes and compositions of igneous activity, amount of extension, and timing of magmatic and tectonic events.

(2) All crustal sections, with the exceptions of the oceanized crusts in the Red Sea and Gulf of Aden, represent more or less stretched and thinned continental crust.

(3) Crustal thickness variation may be viewed as a function of rift development. The further the rifting process has progressed, the thinner is the crust.

(4) Following Mohr (1992), it may depend on the amount of thinning how far this thinned continental crust has been renewed by magmatic activity or whether it is still the original plateau-type crust.

(5) The flanks may be highly influenced by rifting in those parts which are close to the rift. Broad up-

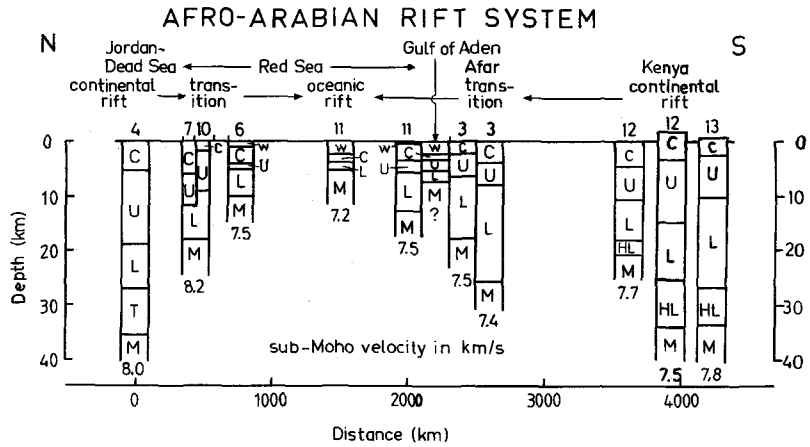

Fig. 4. Evolutionary sequence (for locations see Fig. 1) illustrating the variation in crustal thickness under the Afro–Arabian rift system from the Jordan–Dead Sea transform system through the Red Sea, Gulf of Aden and Afar triangle to the southern end of the Kenya rift. Key: W = water, C = cover rocks, U = upper crust, L = lower crust, HL = high-velocity lower crust, T = crust–mantle transition rocks, M = Moho. Depths refer to sea level. Numbers of crustal columns refer to Figs. 1 and 2.

warping and/or a transitional crust–mantle boundary may be signs of approaching rifting.

(6) Recent volcanic activity may disturb crustal interfaces; as well it may disrupt the Moho as evidenced particularly in the Chyulu Hills.

(7) The entire rift system, except the Jordan–Dead Sea transform, appears to be underlain by a heated upper mantle as evidenced by low Pn-velocities and the observed heat flow anomalies (Makris et al., 1991; Wheildon et al., 1994). Under parts of the rift zone which are narrow in their surface expression, the width of the heated upper mantle zone is also relatively narrow (Achauer et al., 1994; Braile et al., 1995).

(8) The presence of hot mantle material beneath the Kenya dome since the onset of volcanism 15–20 Ma ago is compatible with the abrupt change of Pn-velocities at the rift boundaries (Mechie et al., 1997).

(9) From xenolith investigations of alkali plateau basalts in western Saudi Arabia showing unusually high geothermal gradients within the mantle underlying the Arabian plate, evidence is derived that hot mantle wells up beneath the rift axis and flows laterally outward, cooling beneath the Arabian plate (McGuire, 1988). Temperatures in the mantle beneath western Saudi Arabia appear to be much higher than predicted by the surface heat flow suggesting that surface heat flow has not yet equilibrated with mantle temperatures.

(10) Petrological interpretations of the seismic velocities beneath the Kenya rift indicate that the lower crust beneath the rift probably consists of a mix of high-grade metamorphic rocks, mafic intrusives, and an igneous mafic residuum accreted to the base of the crust during differentiation of a melt derived from the upper mantle (Mooney and Christensen, 1994; Hay et al., 1995). The upper mantle may contain up to 5% basaltic melt, except within the high-velocity layers under the northern Kenya rift which can only be explained by some crystal orientation (anisotropy) (Mechie et al., 1997).

The sequence of crustal columns (Fig. 4) may also be thought of as an evolutionary progression in terms of intensity of rifting (see also Girdler, 1983), but this would seem most applicable to a stretching (passive) component of rifting. Various models have been developed for the Red Sea rift system which postulate different geodynamic processes as driving forces of rifting: (1) seafloor spreading during its entire evolution (e.g., Girdler, 1991); (2) diffuse extension and continental stretching; or (3) simple lithospheric shear. In contrast to Girdler (1991) who argues that the entire Red Sea is underlain by oceanic crust, the internal crustal structure of the northern Red Sea points to a highly extended continental crust, that has nearly developed to a stage where seafloor spreading initiates (Cochran and Martinez, 1988; Makris and Rihm, 1991). Makris and Rihm (1991) assume, with Arabia as the moving and Africa as the stable plate, pure shear through stretching, thinning and diffuse extension. Cochran and Martinez (1988) subdivide the Red Sea into three parts which are evidence of a certain stage of crustal development: the crust of the northern Red Sea as extended continental crust, the central Red Sea being a transition zone with punctiform seafloor spreading as demonstrated by Bonatti (1985), and finally the southern Red Sea where seafloor spreading has developed in the entire central trough.

The seismic data available today indicate that the Afro–Arabian rift development can be subdivided into six stages which are evident in six zones: (1) shearing along the Dead Sea–Jordan transform system; (2) diffuse and gradual breaking of a continent along the entire East African rift system (Strecker, 1991); (3) stretching and extension of continental crust in the northern Red Sea; (4) highly extended continental (possibly renewed) crust under Afar and the southernmost tip of the Red Sea; (5) punctiform spreading in the central trough of the central Red Sea; and (6) seafloor spreading under the Gulf of Aden and the southern Red Sea. As a seventh stage faulting in southern Africa may be regarded as a first sign of future rifting.

As is discussed further in other contributions of this volume (Volker et al., 1997; Zeyen et al., 1997), the Red Sea spreading is heavily influenced by the Afar plume. For the East African rift system, it has been debated, whether this rifting is active or passive. In other contributions of this volume another plume rising under the East African plateau is discussed as a possible cause for active rifting (Birt et al., 1997; Mechie et al., 1997; Simiyu and Keller, 1997; Zeyen et al., 1997).

Regarding the sequence of crustal columns as an evolutionary progression in terms of intensity

of rifting, it may, however, not be a useful measure of an active component of rifting as illustrated by the southern Kenya rift. There, in the vicinity of the Kenya dome, the teleseismic results show that the lithosphere has been thinned considerably (Achauer et al., 1994) whereas the refraction results (Maguire et al., 1994; Mechie et al., 1997) and surface structural estimates (Baker and Wohlenberg, 1971; Strecker, 1991) provide evidence for modest crustal thinning and only 5–10 km extension. This situation is complicated due to the probability of magmatic additions to the crust, but active mantle upwelling seems required. The abrupt lithospheric boundaries between the flanks and the rift valley and the low heat flow on the flanks are evidence that major activity has been recent. The high surface heat flow in the rift valley, the earthquake activity and its concentration in the upper 10–12 km of the crust, and the recent volcanicity all suggest that the rift is active today. The steep-sided low-velocity zones extending deep into the mantle beneath the axis of the rift (Achauer et al., 1994) and gravity models where low-density material reaches deep into the mantle (Ebinger et al., 1989; Hay et al., 1995; Birt et al., 1997; Simiyu and Keller, 1997) are consistent with hot, convecting material from a mantle plume confined beneath the Tanzanian craton from which hot material rises to shallower depths under the outer rims formed by the western and eastern rifts of the East African rift system (Birt et al., 1997; Mechie et al., 1997). Unfortunately, for the northern part of the Kenya rift where extension of 30–40 km is being discussed, no deep-reaching teleseismic information is available. On the basis of high-resolution shallow seismic-reflection data Morley (1994) discusses the interaction of deep and shallow processes in the evolution of the northern Kenya rift. Mechie et al. (1997) discuss a possible interaction of the plumes beneath Afar and beneath the Tanzanian craton in northern Kenya. Zeyen et al. (1997), in a more generalizing concept, propose models in which large mantle plumes are the ultimate source for the forces leading to rift formation.

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References

Achauer, U., the KRISP Working Group, 1994. A three-dimensional image of the upper-mantle structure beneath the central Kenya rift from teleseismic investigations. In: Prodehl, C., Keller, G.R., Khan, M.A. (Eds.), Crustal and Upper Mantle Structure of the Kenya Rift. Tectonophysics 236, 305–329.

Baker, B.H., Wohlenberg, J., 1971. Structure and evolution of the Kenya Rift Valley. Nature 229, 538–542.

Bayer, H.-J., El-Isa, Z., Hötzl, H., Mechie, J., Prodehl, C., Saffarini, G., 1989. Large tectonic and lithospheric structures of the Red Sea region. In: Rosendahl, B.R., Rogers, J.J.W., Rach, N.M. (Eds.), African Rifting. J. Afr. Earth Sci. 8, 565–587.

Berckhemer, H., Baier, B., Bartelsen, H., Behle, A., Burckhardt, H., Gebrande, H., Makris, J., Menzel, H., Miller, H., Vees, R., 1975. Deep seismic soundings in the Afar region and on the highland of Ethiopia. In: Pilger, A., Rösler, A. (Eds.), Afar Depression of Ethiopia. Schweizerbart, Stuttgart, pp. 89–107.

Birt, C., Thybo, H., Maguire, P.K.H., Khan, M.A., Keller, G.R., Patel, J., 1997. The influence of pre-existing structures on the evolution of the southern Kenya rift valley—evidence from seismic and gravity studies. In: Fuchs, K., Altherr, R., Müller, B., Prodehl, C. (Eds.), Structure and Dynamic Processes in the Lithosphere of the Afro-Arabian Rift System. Tectonophysics 278, 211–242 (this volume).

Bonatti, E., 1985. Punctiform initiation of seafloor spreading in the Red Sea during transition from a continental to an oceanic rift. Nature 316, 33–37.

Braile, L.W., Keller, G.R., Wendlandt, R.F., Morgan, P., Khan, M.A., 1995. The East African Rift System. In: Olsen, K.H. (Ed.), Continental Rifts: Structure, Evolution, Tectonics (CREST). Elsevier, Amsterdam, pp. 213–232.

Bram, K., 1975. Zum Aufbau der Kruste und des oberen Mantels im Bereich des westlichen Grabens des ostafrikanischen Grabensystems und im östlichen Zaire-Becken. Ergebnisse einer Untersuchung der Raumwellen von Nah-Erdbeben, Geophys. Abh. 4, Inst. Geophysik, Freie Univ. Berlin, 65 pp.

Bram, K., Schmeling, B.D., 1976. Structure of crust and upper mantle beneath the Western rift of East Africa, derived from investigations of near earthquakes. In: Pilger, A., Rösler, A. (Eds.), Afar between Continental and Oceanic Rifting. Schweizerbart, Stuttgart, pp. 138–143.

Cochran, J.R., Martinez, F., 1988. Evidence from the northern Red Sea on the transition from continental to oceanic rifting. In: LePichon, X., Cochran, J.R. (Eds.), The Gulf of Suez and Red Sea Rifting. Tectonophysics 153, 25–53.

Ebinger, C.J., Deino, A.L., Drake, R.E., Tesha, A.L., 1989. Chronology of volcanism and rift basin propagation: Rungwe volcanic province, East Africa. J. Geophys. Res. 94, 15785–15803.

Egloff, F., Rihm, R., Makris, J., Izzeldyn, Y.A., Bobsien, M., Meier, K., Junge, P., Noman, T., Warsi, W., 1991. Contrasting styles of the eastern and western margins of the southern Red Sea: the 1988 SONNE experiment. In: Makris, J., Mohr, P., Rihm, R. (Eds.), Red Sea: Birth and Early History of a New Oceanic Basin. Tectonophysics 198, 329–353.

El-Isa, Z.H., Mechie, J., Prodehl, C., Makris, J., Rihm, R., 1987. A crustal structure study of Jordan derived from seismic refraction data. Tectonophysics 138, 235–253.

Fuchs, K., 1997. Synopsis SFB 108 — Stress and stress release in the lithosphere. In: Fuchs, K., Altherr, R., Müller, B., Prodehl, C. (Eds.), Stress and Stress Release in the Lithosphere — Structure and Dynamic Processes in the Rifts of Western Europe. Tectonophysics 275, 1–14.

Fuchs, K., Altherr, R., Strecker, M., 1990. Spannung und Spannungsumwandlung in der Lithosphäre. Ein Bericht aus dem Sonderforschungsbereich 108, Universität Karlsruhe. Geowissenschaften, Mitt. XVIII der Senatskomm. Geowiss. Gemeinschaftsforschung, DFG, pp. 143–179.

Gaulier, J.M., LePichon, X., Lyberis, N., Avedik, F., Geli, L., Moretti, I., Deschamps, A., Hafez, S., 1988. Seismic study of the crust of the northern Red Sea and Gulf of Suez. In: LePichon, X., Cochran, J.R. (Eds.), The Gulf of Suez and Red Sea Rifting. Tectonophysics 153, 55–88.

Ginzburg, A., Makris, J., Fuchs, K., Prodehl, C., Kaminski, W., Amitai, U., 1979a. A seismic study of the crust and upper mantle of the Jordan–Dead Sea Rift and their transition toward the Mediterranean Sea. J. Geophys. Res. 84, 1569–1582.

Ginzburg, A., Makris, J., Fuchs, K., Perathoner, B., Prodehl, C., 1979b. Detailed structure of the crust and upper mantle along the Jordan–Dead Sea Rift and their transition toward the Mediterranean Sea. J. Geophys. Res. 84, 5605–5612.

Girdler, R.W., 1983. Processes of planetary rifting as seen in the rifting and break up of Africa. In: Morgan, P., Baker, B.H. (Eds.), Processes of Continental Rifting. Tectonophysics 94, 241–252.

Girdler, R.W., 1991. The Afro–Arabian rift system — an overview. In: Gangi, A.F. (Ed.), World Rift Systems. Tectonophysics 197, 139–153.

Griffiths, D.H., King, R.F., Khan, M.A., Blundell, D.J., 1971. Seismic refraction line in the Gregory rift. Nature 229, 69–71.

Hay, D.E., Wendlandt, R.F., Keller, G.R., 1995. The origin of Kenya rift plateau-type flood phonolites: Integrated petrologic and geophysical constraints on the evolution of the crust and upper mantle beneath the Kenya Rift. J. Geophys. Res. 100, 10549–10557.

Henry, W.J., Mechie, J., Maguire, P.K.H., Khan, M.A., Prodehl, C., Keller, G.R., Patel, J.P., 1990. A seismic investigation of the Kenya rift valley. Geophys. J. Int. 100, 107–130.

Keller, G.R., Prodehl, C., Mechie, J., Fuchs, K., Khan, M.A., Maguire, P.K.H., Mooney, W.D., Achauer, U., Davis, P.M., Meyer, R.P., Braile, L.W., Nyambok, I.O., Thompson, G.A., 1994. The East African rift system in the light of KRISP 89–90. In: Prodehl, C., Keller, G.R., Khan, M.A. (Eds.), Crustal and Upper Mantle Structure of the Kenya Rift. Tectonophysics 236, 465–483.

KRISP Working Group, 1987. Structure of the Kenya rift from seismic refraction. Nature 325, 239–242.

KRISP Working Group, 1995. Group takes a fresh look at the lithosphere underneath Southern Kenya. Eos 76, 73, 81–82.

KRISP Working Party, 1991. Large-scale variation in lithospheric structure along and across the Kenya Rift. Nature 354, 223–227.

Laughton, A.S., Tramontini, C., 1969. Recent studies of the crustal structure in the Gulf of Aden. Tectonophysics 8, 359–375.

Maguire, P.K.H., Swain, C.J., Masotti, R., Khan, M.A., 1994. A crustal and uppermost mantle cross-sectional model of the Kenya Rift derived from seismic and gravity data. In: Prodehl, C., Keller, G.R., Khan, M.A. (Eds.), Crustal and Upper Mantle Structure of the Kenya Rift. Tectonophysics 236, 217–250.

Makris, J., Ginzburg, A., 1987. The Afar depression: transition between continental rifting and sea-floor spreading. In: Ben Avraham, Z. (Ed.), Sedimentary Basins within the Dead Sea and Other Rift Zones. Tectonophysics 141, 199–214.

Makris, J., Rihm, R., 1991. Shear-controlled evolution of the Red Sea: pull apart model. In: Makris, J., Mohr, P., Rihm, R. (Eds.), Red Sea: Birth and Early History of a New Oceanic Basin. Tectonophysics 198, 441–466.

Makris, J., Allam, A., Mokhtar, T., Basahel, A., Dehghani, G.A., Bazari, M., 1983. Crustal structure in the northwestern region of the Arabian shield and its transition to the Red Sea. Bull. Fac. Earth Sci., King Abdulaziz Univ. 6, pp. 435–447.

Makris, J., Tsironidis, J., Richter, H., 1991. Heatflow density distribution in the Red Sea. In: Makris, J., Mohr, P., Rihm, R. (Eds.), Red Sea: Birth and Early History of a New Oceanic Basin. Tectonophysics 198, 383–393.

McGuire, A.V., 1988. The mantle beneath the Red Sea margin: xenoliths from western Saudi Arabia. In: Bonatti, E. (Ed.),

Zabargad Island and the Red Sea Rift. Tectonophysics 150, 101–119.

Mechie, J., Prodehl, C., 1988. Crustal and uppermost mantle structure beneath the Afro–Arabian rift system. In: LePichon, X., Cochran, J.R. (Eds.), The Gulf of Suez and Red Sea Rifting. Tectonophysics 153, 103–121.

Mechie, J., Prodehl, C., Koptschalitsch, G., 1986. Ray-path interpretation of the crustal structure beneath Saudi Arabia. Tectonophysics 131, 333–352.

Mechie, J., Keller, G.R., Prodehl, C., Gaciri, S., Braile, L.W., Mooney, W.D., Gajewski, D., Sandmeier, K.-J., 1994. Crustal structure beneath the Kenya rift from axial profile data. In: Prodehl, C., Keller, G.R., Khan, M.A. (Eds.), Crustal and Upper Mantle Structure of the Kenya Rift. Tectonophysics 236, 179–200.

Mechie, J., Prodehl, C., Keller, G.R., Khan, M.A., Gaciri, S.J., 1997. A model for structure, composition and evolution of the Kenya rift. In: Fuchs, K., Altherr, R., Müller, B., Prodehl, C. (Eds.), Structure and Dynamic Processes in the Lithosphere of the Afro-Arabian Rift System. Tectonophysics 278, 95–119 (this volume).

Mohr, P., 1992. Nature of the crust beneath magmatically active continental rifts. In: Ziegler, P.A. (Ed.), 1992. Geodynamics of Rifting, Vol. II. Case History Studies on Rifts: North and South America, Africa. Tectonophysics 213, 269–284.

Mooney, W.D., Christensen, N.I., 1994. Composition of the crust beneath the Kenya rift. In: Prodehl, C., Keller, G.R., Khan, M.A. (Eds.), Crustal and Upper Mantle Structure of the Kenya Rift. Tectonophysics 236, 391–408.

Mooney, W.D., Gettings, M.E., Blank, H.R., Healy, J.H., 1985. Saudi Arabian seismic-refraction profile: a traveltime interpretation of crust and upper mantle structure. Tectonophysics 111, 173–246.

Morley, C.K., 1994. Interaction of deep and shallow processes in the evolution of the Kenya rift. In: Prodehl, C., Keller, G.R., Khan, M.A. (Eds.), Crustal and Upper Mantle Structure of the Kenya Rift. Tectonophysics 236, 81–91.

Novak, O., Prodehl, C., Jacob, B., Okoth, W., 1997. Crustal structure of the southeastern flank of the Kenya rift deduced from wide-angle P-wave data. In: Fuchs, K., Altherr, R., Müller, B., Prodehl, C. (Eds.), Structure and Dynamic Processes in the Lithosphere of the Afro-Arabian Rift System. Tectonophysics 278, 171–186 (this volume).

Prodehl, C., Mechie, J., 1991. Crustal thinning in relationship to the evolution of the Afro–Arabian rift system—a review seismic-refraction data. In: Makris, J., Mohr, P., Rihm, R. (Eds.), Red Sea: Birth and Early History of a New Oceanic Basin. Tectonophysics 198, 311–327.

Prodehl, C., Keller, G.R., Khan, M.A. (Eds.), 1994a. Crustal and Upper Mantle Structure of the Kenya Rift. Tectonophysics, 236, 483 pp.

Prodehl, C., Jacob, B., Thybo, H., Dindi, E., Stangl, R., 1994b. Crustal structure of the northeastern flank of the Kenya rift. In: Prodehl, C., Keller, G.R., Khan, M.A. (Eds.), Crustal and Upper Mantle Structure of the Kenya Rift. Tectonophysics 236, 271–290.

Prodehl, C., Ritter, J.R.R., Mechie, J., Keller, G.R., Khan, M.A., Jacob, B., Fuchs, K., Nyambok, I.O., Obel, J.D., 1997. The KRISP 94 lithospheric investigation of southern Kenya—the experiments and their main results. In: Fuchs, K., Altherr, R., Müller, B., Prodehl, C. (Eds.), Structure and Dynamic Processes in the Lithosphere of the Afro-Arabian Rift System. Tectonophysics 278, 121–147 (this volume).

Rihm, R., Makris, J., Möller, L., 1991. Seismic surveys in the northern Red Sea: asymmetric crustal structure. In: Makris, J., Mohr, P., Rihm, R. (Eds.), Red Sea: Birth and Early History of a New Oceanic Basin. Tectonophysics 198, 279–295.

Ruegg, J.C., 1975. Main results about the crustal and upper mantle structure of the Djibouti region (T.F.A.I.). In: Pilger, A., Rösler, A. (Eds.), Afar Depression of Ethiopia. Schweizerbart, Stuttgart, pp. 120–134.

Simiyu, S., Keller, G.R., 1997. An integrated analysis of lithospheric structure across the East African plateau based on gravity anomalies and recent seismic studies. In: Fuchs, K., Altherr, R., Müller, B., Prodehl, C. (Eds.), Structure and Dynamic Processes in the Lithosphere of the Afro-Arabian Rift System. Tectonophysics 278, 291–313 (this volume).

Strecker, M.R., 1991. Das zentrale und südliche Kenia-Rift unter besonderer Berücksichtigung der neotektonischen Entwicklung. Habil. Schrift, Universität Karlsruhe, 182 pp.

Voggenreiter, W., Hötzl, H., Mechie, J., 1988. Low-angle detachment origin for the Red Sea rift system? In: Bonatti, E. (Ed.), Zabargad Island and the Red Sea Rift. Tectonophysics 150, 51–75.

Volker, F., Altherr, R., Jochum, K.P., McCulloch, M.T., 1997. Quaternary volcanic activity of the southern Red Sea: new data and assessment of models on magma sources and Afar plume–lithosphere interaction. In: Fuchs, K., Altherr, R., Müller, B., Prodehl, C. (Eds.), Structure and Dynamic Processes in the Lithosphere of the Afro-Arabian Rift System. Tectonophysics 278, 15–29 (this volume).

Wheildon, J., Morgan, P., Williamson, K.H., Evans, T.R., Swanberg, C.A., 1994. Heat flow in the Kenya rift zone. In: Prodehl, C., Keller, G.R., Khan, M.A. (Eds.), Crustal and Upper Mantle Structure of the Kenya Rift. Tectonophysics 238, 131–149.

Zeyen, H., Volker, F., Wehrle, V., Fuchs, K., Sobolev, S., Altherr, R., 1997. Styles of continental rifting: crust–mantle detachment and mantle plumes. In: Fuchs, K., Altherr, R., Müller, B., Prodehl, C. (Eds.), Structure and Dynamic Processes in the Lithosphere of the Afro-Arabian Rift System. Tectonophysics 278, 329–352 (this volume).