PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Structural Pattern of the Afro-Arabian Rift System in Relation to Plate Tectonics [and Discussion]

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The structural pattern of the Afro-Arabian rift system in relation to plate tectonics

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The structural pattern of the Afro-Arabian rift system suggests the influence of transcurrent faulting in the development of the main branches of the system, particularly along the Dead Sea rift, the Gulf of Suez and Red Sea, and the eastern rift of Africa.

Geophysical evidence indicates that the Red Sea and Gulf of Aden formed as a result of the separation of the Arabian and African continental blocks. Previously determined rotation poles about which the blocks separated neglect some structural features of the region. A satisfactory refit of Arabia to Africa cannot be made unless some relative movements of parts of the Africa block too place.

It is proposed that dextral strike-slip movements took place between Africa and Arabia along the Red Sea and that sinistral strike-slip movements occurred along the Dead Sea rift. In addition, rotation of the E. Kenya-Somalia block east of the eastern rift of Africa took place. Structural and palaeomagnetic evidence supports such movements. The structural model is compatible with the observed tectonic pattern and provides a genetic link between the formation of the Red Sea, Gulf of Aden and the African rifts.

Introduction

Geophysical work in the Red Sea, Gulf of Aden and Arabian Sea in the last decade has lead to the proposal of a mechanism by which Arabia could have separated from Africa (Drake & Girdler 1964; Girdler 1966; Laughton 1966; Matthews 1966). More recently the formation of the Red Sea and Gulf of Aden has been incorporated into a proposed pattern of global seafloor spreading and continental drift (Le Pichon & Heirtzler 1968; Le Pichon 1968).

In this contribution an attempt is made to reconcile knowledge of the structure of the Afro-Arabian rift system with facts and inferences resulting primarily from marine geophysical work in the region.

The structural pattern

The Afro-Arabian rift system is a series of downwarped and faulted troughs of variable width which traverse uplifted regions, the more important of which are the Ethiopian and Kenyan swell-uplifts. The system is of exceptional length and displays rectilinear sections suggestive of transcurrent faulting, but in most sections the younger and more obvious faults are normal in character.

The system extends generally southward from the Mediterranean Sea and from southern Turkey, and branches of it reach the Indian Ocean via the Gulf of Aden, at the Tanzania coastline opposite Pemba Island and at Beira on the Mozambique coast. The system separates a number of relatively stable crustal blocks—the NE Africa, Arabia, east Kenya–Somalia, north Mozambique and Lake Victoria blocks (figure 1).

The Levantine rift

The Levantine rift is relatively straight and narrow and extends from the Alpine fold belt of southern Turkey to the Red Sea. It has been interpreted as a transcurrent fault zone upon which sinistral displacements of up to 110 km have been proposed (Girdler 1966). These movements took place in distinct phases, some being possibly as old as late Cretaceous (Freund 1965), the later movements being of lower Pliocene (43 km) and Pleistocene (10 to 15 km) ages (Freund, Zak & Garfunkel 1968).

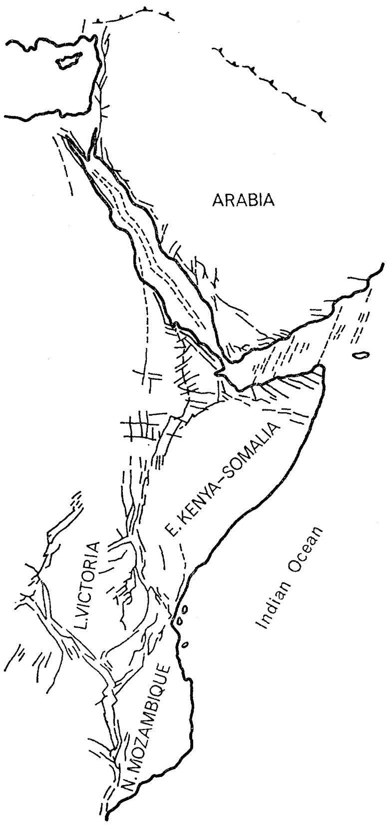

Figure 1. Fault pattern of the Afro-Arabian rift system.

The Red Sea

The structural development of the Gulf of Suez may have begun as early as late Cretaceous (Said 1962), and some authors believe that the Red Sea may also have begun to develop at this time (Whiteman 1968). Facies and isopachyte maps suggest that no clearly defined 'graben' faulting took place until after the late Eocene uplift of the Red Sea margins (Swartz & Arden 1960). The development of a proto-Red Sea trough must have been complete by early Miocene times (Sestini 1965; Shata 1959). Subsequent movements were repeated upwarping of the Red Sea margin, deposition of Neogene sediments and evaporites, and several phases of faulting (Swartz & Arden 1960). The axial trough of the Red Sea developed during the later Neogene and has 'oceanic' crustal characteristics (Girdler 1966; Allan & Pisani 1966), and was accompanied by sinistral transcurrent movement on the Dead Sea rift (Freund 1965; Freund *et al.* 1968).

The scarcity of evidence of faulting along the Red Sea margins led Whiteman (1968) and Gass & Gibson (1969) to postulate that the margins are eroded monoclinal downwarps.

Transcurrent movements along Red Sea fractures was postulated by Youssef (1968) and Burek (1968).

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The Gulf of Aden

The structural development of the Gulf of Aden began with the regional late Eocene uplift of its margins and the formation of local depressions such as that occupied by the Oligo–Miocene Dufar Series of clastic sediments (Azzaroli 1968). Its main phase of development was early Miocene, leading to Miocene marine sedimentation in a proto-Gulft rough, succeeded by late Miocene and Pliocene phases of faulting and seaward warping of the Neogene sediments (Laughton 1966; Somaliland Oil Exploration Co. 1954; Beydoun 1966).

According to geophysical results almost the whole width of the Gulf is underlain by Neogene sediments and crust of oceanic type, the latter formed during Miocene and Quaternary phases of separation of Arabia from Horn of Africa (Laughton 1966).

The Afar depression

The junction region of the Red Sea, African and Gulf of Aden rifts is almost entirely occupied by the Afar depression, an extensive lowland of trapezoidal shape bounded on all sides by major faults defining the main Ethiopian plateau to the west, the Danakil and Aisha horsts to the northeast and southeast, and the northern edge of the Somalia–Ogaden plateau to the south.

The Afar depression was formed by Miocene downwarping and faulting emphasized by Quaternary uplifts of its marginal plateaux accompanied by further faulting (Mohr 1967*b*). Its floor is covered by Miocene and younger volcanic rocks, which are cut by swarms of minor, normal and transcurrent faults (Mohr 1968). The normal fault swarms trend mostly north-westward, and are crossed by a narrow northerly fault belt (the Wonji belt). The transcurrent faults trend to the northeast in the north, and to the east–southeast in the south parts of the depression.

The eastern rift of Africa

The eastern rift of continental Africa extends from the southwest corner of the Afar depression through southern Ethiopia, Kenya and northern Tanzania to the Indian ocean south of Tanga. It consists of a series of graben, asymmetrical 'graben' and step-fault zones, the greatest downthrow of the rift floor occurring in the 'graben' sectors where the marginal plateaux are highest. Although early Tertiary uplift of the region occurred the phases of faulting are of early Miocene, early Pliocene, late Pliocene and middle Pleistocene ages. Each phase was accompanied by local marginal uplifts, and the late Neogene phases produced the greatest vertical displacements.

Neglecting the westward and southwestward trending branch structures the main axis of the eastern rift describes a regular curve from the Gulf of Aden to the Indian Ocean, and its fault pattern is characterized by repeated eastward *en échelon* off-sets going northward. This pattern has been interpreted as the consequence of sinistral shear (Mohr 1967*b*; Gass & Gibson 1969).

Lateral extension of the crust across the eastern rift has been slight, and no crustal separation has taken place except possibly along the central section of the Gregory 'graben' in Kenya, where a sharp positive gravity ridge coincides with the centre line of the rift valley.

Interpretation of the fault pattern

The Afro-Arabian system of faults and flexures is the longest continuous structure of an extensional character known on the continents. Its northern half is characterized by a rectilinear form, and to the south a curved shape is apparent. It is difficult to imagine that a system of fractures of such length and relative straightness could develop across structurally heterogenous continental crust by extension and normal faulting alone. The conclusion of Swartz & Arden (1960) that the area is divisible into crustal blocks which moved horizontally by transcurrent movements along the main branches of the system is supported by evidence from the Gulf of Suez (Youssef 1968), the Dead Sea rift (Freund 1965; Freund *et al.* 1968) and Ethiopia (Mohr 1968).

Plate tectonics and the rifts

Recognition of the extension of the mid-oceanic ridge-rift system into the Gulf of Aden (Matthews 1966) together with the geophysical investigations in the Red Sea and Gulf of Aden has led to the view that the seafloor spreading hypothesis can also be applied to this area (Drake & Girdler 1964; Girdler 1966; Laughton 1966, Knott, Bunce & Chase 1966). More recently the concept of plate tectonics on a regional scale has also been applied (Le Pichon & Heirtzeler 1968), suggesting that the separation of Arabia and Africa was part of an extensive crustal movement pattern which can be integrated on a global scale (Le Pichon 1968). Application of the principles of plate tectonics to the Red Sea and Gulf of Aden reveals a number of problems of detail which are examined below.

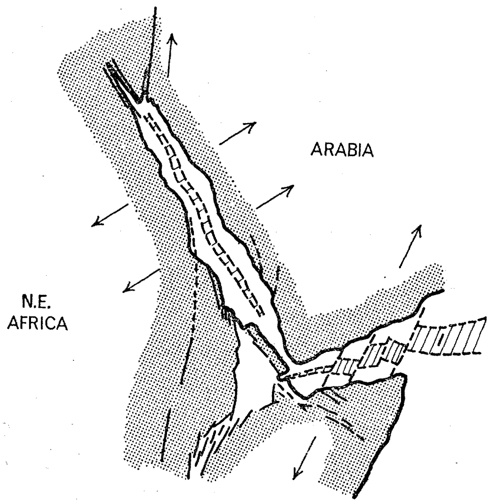

Figure 2. Main structural features of the Red Sea and Gulf of Aden. Shaded—Red Sea axial trough and Gulf of Aden zone of rough seafloor topography (after Laughton 1966). Arrows indicate inferred block movement directions in different areas.

The separation of Arabia and Africa must have been accompanied by transcurrent faulting along the Dead Sea rift and by movement on the Gulf of Aden transform faults. The orientation of these faults should represent the local direction of relative movement of the separating crustal blocks, and if the movements are opposite rotations of crustal plates about a common rotation pole, the form of the active transcurrent or transform faults should be arcs of small circles of projection about the rotation pole (Le Pichon 1968).

The transform faults of the Gulf of Aden, the Dead Sea rift and the movement trajectories of the two sides of the Red Sea inferred from their shapes do not fall on parts of small circles of projection about any single rotation pole (figure 2). The pole of rotation computed from the orientation of the Gulf of Aden transform faults and of the Owen fracture zone is located in southeast Libya (Le Pichon 1968), and is consistent with the relative motions of southern Arabia and Somalia during the opening of the Gulf of Aden. It is inconsistent with the movement trajectories of Arabia and northeast Africa during the opening of the Red Sea.

A rotation pole consistent with the orientation of the active faults alone can be found and is located in northwest Algeria. Such a pole location is inconsistent with the shape of the Red Sea coasts, however, and because of its distance from northeastern Africa produces an exceedingly poor refit of the sides of the southern Red Sea and Gulf of Aden. The maximum permissible angular rotation about such a pole is between 2 and 3°, the constraining factor being the narrow north end of the Red Sea, where the maximum possible widening along the Gulf of Aqaba line is 150 km. A rotation of 3° about an Algerian pole would account for half the width of the southern Red Sea and Gulf of Aden. Expressed in another way a rotation apart of crustal blocks of only 3° about a distant pole is incompatible with the mean rates of widening of the Red Sea and Gulf of Aden, which are 6 and 8° respectively.

In addition to the apparent impossibility of finding a rotation pole consistent with the geometry of the structural elements, there is the problem of the dissimilar shapes of the axial trough of the Red Sea and of the ridge-trough central zone of the Gulf of Aden. The former is parallel sided and the latter is narrow in the west and widens rapidly eastward. Both these areas are interpreted as oceanic crust formed simultaneously (Girdler 1968), but their shapes are incompatible with any of the rotation pole locations that have been proposed (figure 2).

The nature and origin of the Afar depression is critical for the hypothesis for it requires that the greater part of the region of Afar was previously occupied by the southwestern tip of Arabia (Laughton 1966). The existence of the Danakil horst may be explained by anticlockwise pivoting during the widening of the southern part of the Red Sea, but the Aisha (Ali Sabiet) horst is a projection of the continental plateau and extends to within 40 km of the Gulf of Tajura. Its existence renders a close original fit of the two sides of the Gulf of Aden impossible (Azzaroli 1968). Nevertheless, the geophysical data from the Gulf of Aden indicate that it is underlain by oceanic crust across almost its whole width (Laughton 1966).

Swartz & Arden (1960) concluded that eastern Africa is divisible into stable blocks which moved horizontally relative to each other, and evidence in support of transcurrent movements on the main sectors of the rift system has already been given (Freund 1965; Youssef 1968; Gass & Gibson 1969).

The regular curve of the eastern rift of Africa, the consistent *en échelon* offset of the faults and the greater rate of widening of the Gulf of Aden by comparison with the Red Sea suggests that the Horn of Africa rotated clockwise during the formation of the Gulf of Aden. The original position of the Aisha horst would have been in the southwest corner of the Afar depression, and this obstacle to the satisfactory fit of the two sides of the Gulf of Aden rift would thus be removed.

This variation of Laughton's (1966) hypothesis of the formation of the Gulf of Aden helps to explain the structure of the Afar depression. It seems probable that both the Danakil and Aisha horsts were originally located close to the eastern margin of the main Ethiopian plateau. Rotation of the Horn of Africa and of the Aisha horst which has remained attached to it could have resulted in torsional forces that created a crustal paar and a subsidiary crustal spreading axis in western Afar. This axis dies out northward and is replaced by the main axis of the Red Sea During the opposite rotations and eastward movements of the Danakil and Aisha horsts they would separate and the Gulf of Aden spreading axis would penetrate into the Gulf of Tajura (figure 3).

The transcurrent faults of the floor of the Afar depression trend northeast in the north and

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east–southeast in the south, and in their relation to the main marginal faults of the rift they have the character of transform faults (Mohr 1968). They represent the trajectories of the later stages of movement of the Danakil and Aisha horsts away from the main Ethiopian plateau.

The Afar depression is characterized by Free Air anomalies near zero (Gouin, this volume, p. 339) and earthquake surface wave dispersion studies indicate that the crust is intermediate between oceanic and continental in character (Jones 1968). Provisionally the crust in Afar may

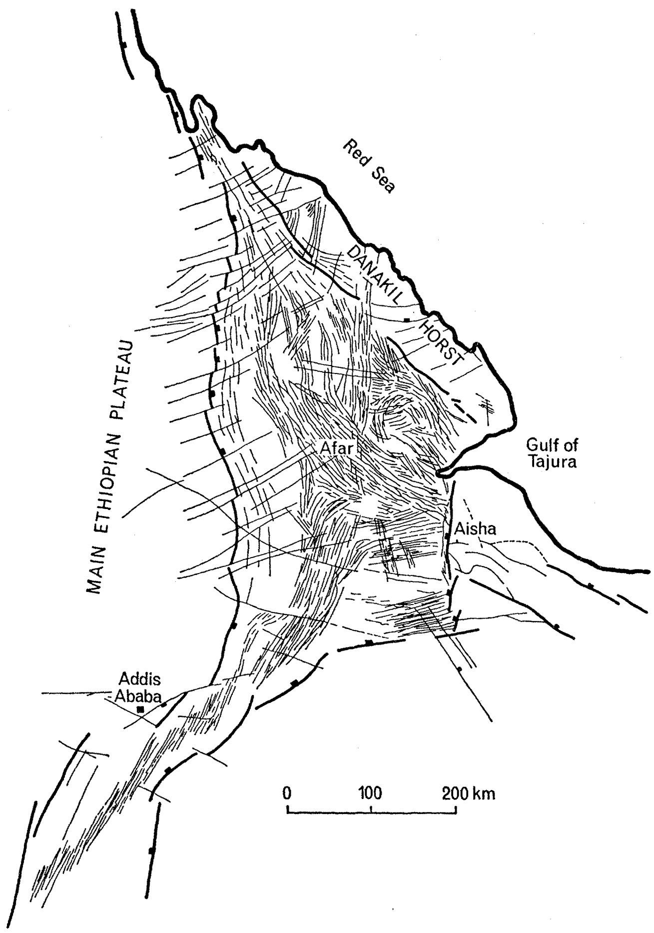

FIGURE 3. Fault tectonics of the Afar depression (after Mohr 1967).

be regarded as extended and thinned, fragmented and intruded continental crust overlain by Neogene volcanics and evaporites.

Comparison of all available palaeomagnetic data for the Cenozoic rocks of eastern Africa shows that the mean palaeoazimuth of the groups of sites east and west of the eastern rift valley differ by 13.6°, and the data are consistent with the clockwise rotation of the block east of the rift relative to the block in the west. This difference does not provide statistically conclusive evidence of the rotation of the Horn of Africa relative to the remainder of the continent, for the confidence limits of the data overlap considerably (Dr A. Brock, personal communication).

Evidence of dextral transcurrent movement along the Gulf of Suez and the western side of the Red Sea has been given by Youssef (1968) and was proposed by Swartz & Arden (1960).

A component of dextral movement of northeast Africa relative to Arabia helps to explain the northeast southwest movement vectors of the sides of the Red Sea (figure 2), which without such an explanation would be in conflict with the orientation and shape of the Dead Sea rift.

Conclusion

The structural and kinematic model of the formation of the Afro-Arabian rift is given by figure 4, which shows the principal, secondary and resultant vectors of movement of the crustal blocks relative to the main spreading axis of the central Red Sea and Gulf of Aden. The principal relative movement is the separation of Arabia and Africa about a rotation pole located approximately in the Mediterranean Sea in the vicinity of Crete. The secondary movement

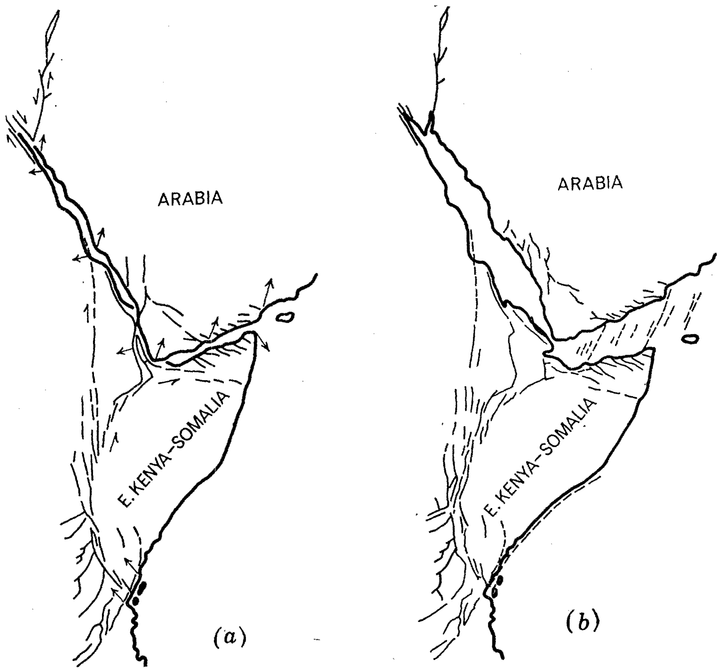

Figure 4. (*a*) Mid-Tertiary structure of the Afro-Arabian rift. Arrows indicate resultant movement vectors during the separation of Africa and Arabia. Half arrows indicate shear. (*b*) Present structure of the Afro-Arabian rift.

vectors are rotation of the Horn of Africa and northwestward movement of northeast Africa, the resultant of the two relative movements being an element of sinistral shear along the eastern rift of Africa. A virtue of this movement picture is that a rotation of the Horn of Africa of 6° can be achieved without the necessity for a large strike-slip displacement along the southern part of the eastern rift.

It is probable from a consideration of the global pattern of seafloor spreading (Le Pichon 1968) and from the relations of the African and Arabian blocks to the Alpine fold belt (Gass & Gibson 1969) that all of these blocks moved approximately northward during the Cenozoic era. Palaeomagnetic data for eastern Africa indicate a northward change in latitude of Nairobi of 18.7° during the last 70 Ma (Girdler 1968).

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References (Baker)

Azzaroli, A. 1968 On the Evolution of the Gulf of Aden. *23rd Int. Geol. Congr., Prague* **1**, 125–134.
Beydoun, Z. R. 1966 Geology of the Arabian Peninsula. *U.S. Geol. Surv. Prof. Pap.* 560-H.
Burek, P. J. 1968 Tectonic effects of sea-floor spreading on the Arabian Shield. Contrib. no. 81, Geosciences Div., S.W. Center Adv. Studies, Dallas, Texas.
Dixey, F. 1956 The East African Rift System. *Bull. Overseas Geol. Min. Res.* **1**.
Drake, C. L. & Girdler, R. W. 1964 A geophysical study of the Red Sea. *Geophys. J.* **8**, 473–495.
Freund, R. 1965 A model of the structural development of Israel and adjacent areas since Upper Cretaceous times. *Geol. Mag.* **102**, 189–205.
Freund, R., Zak, I. & Garfunkel, Z. 1968 Age and rate of sinistral movement along the Dead Sea Rift. *Nature, Lond.* **220**, 253–255.
Gass, I. G. & Gibson, I. L. 1969 Structural evolution of the rift zones of the Middle East. *Nature, Lond.* **221**, 926–930.
Geukens, F. 1966 The geology of Yemen. *U.S. Geol. Surv. Prof. Pap.* 560-B.
Girdler, R. W. 1958 The relationship of the Red Sea to the East African rift system. *Q. Jl geol. Soc. Lond.* **114**, 79–105.
Girdler, R. W. 1966 The role of translational and rotational movements in the formation of the Red Sea and Gulf of Aden. *Geol. Surv. Pap. Can.* **66–14**, 65–77.
Girdler, R. W. 1968 Drifting and rifting of Africa. *Nature, Lond.* **217**, 1102–1106.
Greenwood, J. E. G. W. & Bleakley, D. 1967 The geology of the Aden Protectorate. *U.S. Geol. Surv. Prof. Pap.* 560-C.
Hamilton, W. & Myers, W. B. 1966 Cenozoic Tectonics of the western United States. *Geol. Surv. Pap. Can.* 66–14, 291–306.
Jones, P. B. 1968 Surface wave dispersion and crustal structure between the Gulf of Aden and Addis Ababa. *Bull. Geophys. Obs. Addis Ababa* **13**, 19–26.
Knott, S. T., Bunce, E. T. & Chase, R. C. 1966 Red Sea seismic reflection studies. *Geol. Surv. Pap. Can.* **66–14**, 33–61.
Laughton, A. S. 1966 The Gulf of Aden. *Phil. Trans. Roy. Soc. Lond.* A **259**, 150–171.
Le Pichon, X. 1968 Sea-floor spreading and continental drift. *J. geophys. Res.* **73**, 3661–3697.
Le Pichon, X. & Heirtzler, J. R. 1968 Magnetic anomalies in the Indian Ocean and sea-floor spreading. *J. geophys. Res.* **73**, 2101–2117.
Mathews, D. H. 1966 The northern end of the Carlsberg Ridge. *Geol. Surv. Pap. Can.* **66–14**, 124–134.
McConnell, R. B. 1967 The East African Rift System. *Nature, Lond.* **215**, 578–581.
Mohr, P. A. 1967*a* The Ethiopian rift system. *Bull. Geophys. Obs. Addis Ababa.* **11**, 1–65.
Mohr, P. A. 1967*b* Major volcano-tectonic lineament in the Ethiopian rift system. *Nature, Lond.* **213**, 664.
Mohr, P. A. 1968 Transcurrent faulting in the Ethiopian rift system, *Nature, Lond.* **218**, 938.
Said, R. 1962 *The geology of Egypt*. New York: Elsevier.
Sestini, J. 1965 Cenozoic Stratigraphy and depositional history, Red Sea coast, Sudan. *Bull. Am. Ass. Petrol. Geol.* **49**, 1453–1472.
Shata, A. 1959 Structural development of the Sinai Peninsula, Egypt. *XX Int. Geol. Congr. Mexico, Proc. Ass. African Geol. Surveys*, pp. 225–249.
Somaliland Oil Exploration Co. Ltd. 1954 *A geological Recconnaissance of the sedimentary deposits of the Protectorate of British Somaliland*, 41 pp. London: Crown Agents.
Swartz, D. H. & Arden, D. D. 1960 Geologic history of the Red Sea area. *Bull. Am. Ass. Petrol. Geol.* **44**, 1621–1637.
Whiteman, A. J. 1968 Formation of the Red Sea Depression. *Geol. Mag.* **105**, 231–246.
Youssef, M. I. 1968 Structural pattern of Egypt and its interpretation. *Bull. Am. Ass. Petrol. Geol.* **52**, 601–614.

Discussion

Dr R. B. McConnell (this question and reply were written) drew attention to a well-known alinement of NNE SSW faulting which can be followed from the centre of Lake Malawi through eastern Tanzania to line up with the straight NNE SSW line of the coast of north-eastern Tanzania and southeastern Kenya on which the ports of Tanga and Mombasa lie. Could Mr Baker explain how the apparent straightness of this lineament could be reconciled with the recent rotation of the Kenya–Somalia block north of Tanga which he was proposing?

Mr B. H. Baker replied as follows: The line of faults to which Dr McConnell refers—the Tanzania 'fall' line, is an important fault zone separating the interior plateau of eastern Tanzania and Kenya from the belt of sedimentary basins of Karroo, Mesozoic and late Tertiary ages which lie to the east. The Neogene movement pattern that is proposed involves clockwise rotation of the E. Kenya–Somalia block relative to the rest of northeast Africa together with northwestward movement of northeast Africa relative to Arabia. At the southeastern extremity of the eastern rift the Pangani 'graben' and the Usambara and Pare horsts have a northwest–southeast structural trend, parallel to the trend of the Red Sea. In this region the local relative movement vectors on either side of the Pangani graben were both northwestward, and little or no strike-slip movement need be postulated in this sector of the eastern rift. Nevertheless, there is some imperfect evidence for left lateral displacement of the western limit of Karroo and later Mesozoic sediments immediately west of Pangani amounting to not more than 25 km.

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