A Discussion Mainly concerning the Contributions by Hutchinson and by Baker

D. G. Roberts

Phil. Trans. R. Soc. Lond. A 1970 **267**, 399-405
doi: 10.1098/rsta.1970.0046

Phil. Trans. Roy. Soc. Lond. A. **267**, 399–405 (1970) [399]
Printed in Great Britain

A discussion mainly concerning the contributions by Hutchinson and by Baker

By D. G. ROBERTS
National Institute of Oceanography, Wormley, Surrey

(Written contribution received after meeting)

During this meeting, widely differing interpretations of the sense and direction of movement indicated by the geometry of the Wonji fault belt have become evident. The sinistral sense and direction of movement (Gibson & Tazieff, this volume, p. 331, and Ambraseys in discussion) cannot be easily reconciled with the direction of movement indicated by plate tectonics (Mackenzie, this volume, p. 393). In this discussion, principally of the papers presented by Gibson & Tazieff, Baker and Mackenzie, I hope to reconcile these difficulties and additionally to emphasize existing geological and geophysical data which contribute to a more satisfactory resolution of this problem.

There are three aspects to this problem. The first concerns the correct stress field and therefore the sense and direction of motion required to produce the observed fault geometry of the Wonji fault belt. The second aspect relates to the correct relative rates and directions of spreading between the plates of the present three plate system while the third aspect relates to the evolution of this three plate system with time.

In this context, therefore, it is important to review critically the nature of faulting in the Wonji fault belt and Afar Depression. The 037° trending Wonji fault belt is constituted by NNE (027°) trending faults arranged in a right *en échelon* pattern. Gibson (1967), Mohr (1968), Gass & Gibson (1969), Gibson & Tazieff (this volume) have all considered this pattern to be indicative of sinistral shear. Additionally, the NNE trending faults are sigmoidal in form and are associated with active tensional separation. The outer parts of the sigmoidal faults lie parallel to the rift margin and increase in age away from the rift axis.

Examination of the geometry of this faulting (figure 1*f*) shows that the obtuse angle between the inner and outer parts of the sigmoidal faults is very large (*ca.* 170°) and that the angular difference between the trend of the Wonji fault belt and its constituent faults is very small. If the Wonji fault belt can be validly considered as representing the shear envelope between the Nubian and Somalian plates, these angular differences, which indicate a small conjugate shear angle, show that the confining pressure in the stress field is small and therefore that the confining pressure is negative, i.e. tension.

This interpretation is corroborated by consideration of the relevant Mohr (1882) diagram (figure 1). In figure 1, the forces acting across the shear planes have been resolved for varying conditions of compressive stress (σ_1) and confining pressure (σ_3). In cases *a*, *b*, and *c* of figure 1, the confining pressure is negative, i.e. tensional. For case *a*, where the compressive stress is zero, the Mohr circle is tangential to the Mohr envelope and tension fissures are developed perpendicular to the axis of confining pressure. In cases *b* and *c*, where the compressive stress is small and the confining pressure is negative, shear planes with very small conjugate shear angles are

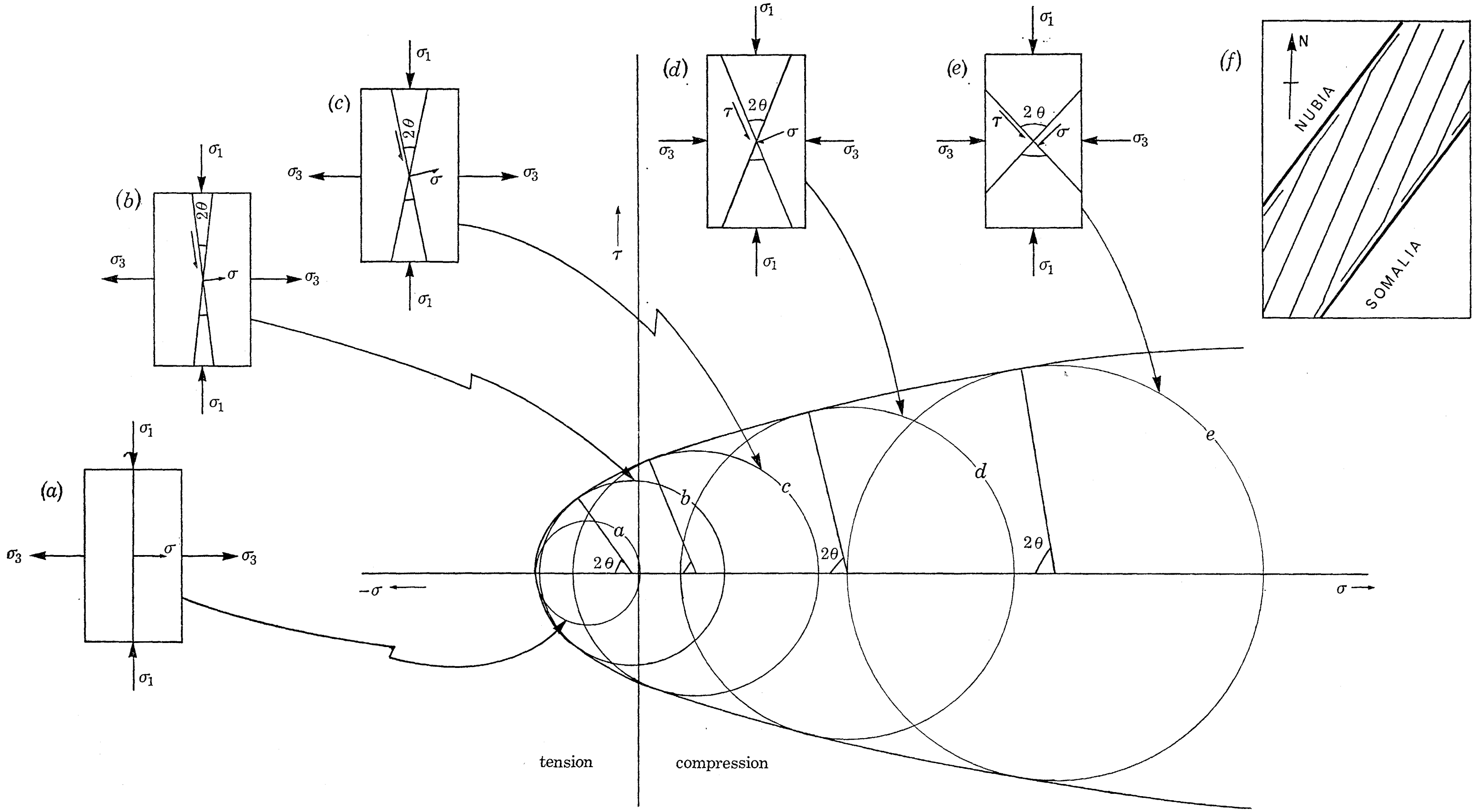


Figure 1. (*a*) to (*e*): Mohr diagram showing the resolution of forces acting across shear planes: τ, shear component; σ, normal component for varying compressive force (σ_1) and confining pressure (σ_3). (*f*): schematic of Wonji fault belt and constituent sigmoidal faults.

developed. In those cases (*d* and *e*), where the confining pressure is positive, the conjugate shear angle increases in magnitude as the stress difference ($\sigma_1 - \sigma_3$) necessary to cause movement increases. Small conjugate shear angles therefore need not be ascribed to horizontal compression because in cases *b* and *c*, shear planes separated by small conjugate shear angles have been developed under conditions of tension.

The sinistral shear interpretations of Gibson (1967), Gass & Gibson (1969), Mohr (1968), Gibson & Tazieff (this volume) are based on analogy with the classic experiments of Riedel (1929). In these experiments, *en échelon* tension fissures were developed in a clay deformed between two horizontally displaced blocks. The confining pressure used in this experiment was compression and relative movement occurred parallel to the shear envelope. In cases *a*, *b*, *c* (figure 1), although small sinistral shear has occurred, the main movement is extension in a direction close to the axis of negative confining pressure. Therefore, in the Wonji fault belt, the principal direction of relative movement is tension with small sinistral relative movement of Nubia and Somalia. The trajectory of this movement may be given by the 100° strike of lines joining conjugate offsets of the rift boundary faults (Mohr 1967*a*, *b*).

It is pertinent to emphasize here that the sinistral sense of movement given by application of the Riedel analogy to the East African rift system is entirely different from the extension indicated by earthquake mechanisms (Isacks, Oliver & Sykes 1968). A similar application of the Riedel analogy to Iceland by Einarrson (1967, 1969) indicates a N–S relative movement which is in total disagreement with the directions of movement indicated by earthquake mechanisms (Sykes 1969) and geodetic observations (Tryggvason 1968).

Finally, in terms of the plate tectonics of this area, to be compatible as a shear with the Le Pichon & Heirtzler (1968) pole, the Ethiopian rift system must lie on a small circle whose strike is locally greater than 035° (045° at 11° N and 42° E). The trends of both the Wonji fault belt (037°) and its constituent faults (027°) are therefore inconsistent with shear about the Le Pichon pole, so implying a separate pole of rotation for the Nubian and Somalian plates.

This interpretation of general east–west extension across the Ethiopian rift system must be reconciled with the data of plate tectonics. It is therefore important to review the criteria from which the relative rates and directions of movement of the Arabia–Somalia and Arabia–Nubia have been derived and also the development of the present three-plate system with time.

The principles of plate tectonics have been developed by Mackenzie & Parker (1967), Morgan (1968), Le Pichon & Heirtzler (1968), Le Pichon (1968) and Mackenzie (this volume, p. 393). For the NW Indian Ocean, Le Pichon & Heirtzler (1968) showed that the relative movement of Arabia and Africa could be illustrated as a rotation about a pole at 26° N and 21° E. The close agreement of this pole position, obtained from the aximuths of fracture zones in the NW Indian Ocean and Gulf of Aden, with the pole position obtained by Mackenzie (this volume) from a fit of the 200-fathom (366 m) contour in the Gulf of Aden implies that this pole has been static since the initiation of rifting in the Gulf of Aden during the Late Eocene (Laughton 1966*a*). Properly this pole position is only representative for the rotation of the Arabia–Somalia plates.

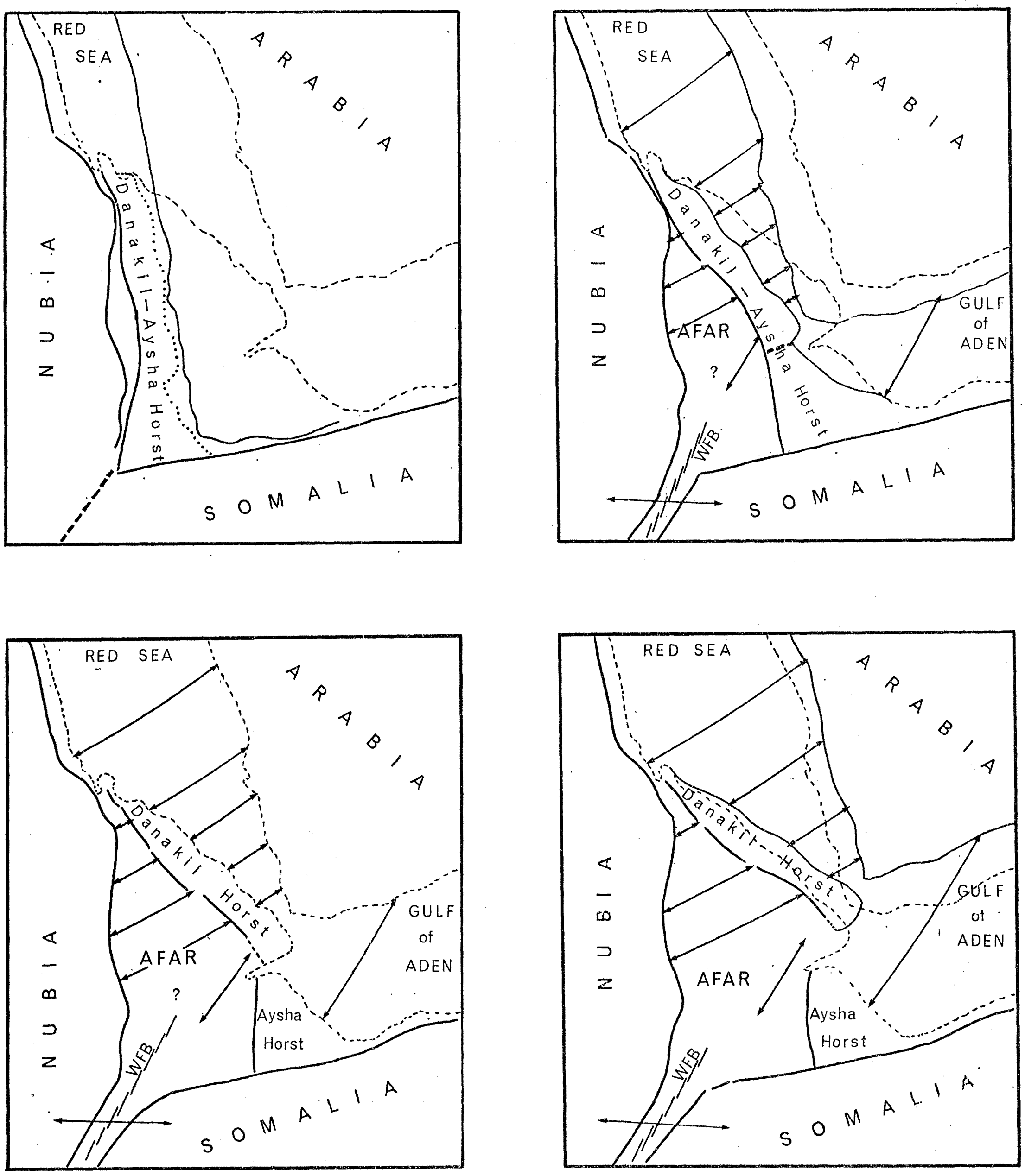
In the Red Sea, however, the aximuths of fractures zones are poorly known and are themselves controversial. Nevertheless, known rates of movement along the Dead Sea rift (Freund, Zak & Garfunkel 1968; Freund, this volume, p. 107) impose severe constraints on possible pole positions for Arabia–Nubia. The post-early Pliocene movement of 40 to 45 km quoted by Freund *et al.* is the total relative movement of Arabia and Nubia across the Dead Sea rift. Since the Dead Sea rift can be regarded as a ridge–arc transform fault, this total rate of movement must be halved before it can be correctly compared with spreading rates computed from magnetic anomalies by the Vine–Matthews hypothesis. The correct value for comparison with values of about 1 cm a^{-1} per limb quoted by Vine (1966), Roberts (1969), Allan (this volume, p. 153), Phillips *et al.* (this volume, p. 143) is therefore 0.3 cm a^{-1} per limb (base of the Pliocene 7 Ma ago). The rapid decrease in spreading rate northward along the Red Sea implies that the pole position for Arabia–Nubia must be located relatively close to the Dead Sea rift and cannot therefore be located in Italy as suggested by Mackenzie (this volume, p. 393). The cut off in seismicity (Fairhead & Girdler, this volume, p. 49) and the absence of any well-defined linear magnetic anomalies in the northern part of the Red Sea (Phillips, this volume, p. 205) may be caused by the rapid decrease in spreading rate. A third implication of a pole position located close to the Dead Sea rift is that the tectonics of this rift north of Galilee may not be representative of a simple plate boundary.

The very rapid increase in spreading rate southward down the Red Sea indicates that in the critical junction area of Afar, the rate of opening of the Nubia–Arabia plates will be very much higher (1.4 ± 0.3 cm a^{-1} per limb; Roberts 1969) than the rate of 0.9 cm a^{-1} per limb given by Laughton, Whitmarsh & Jones (this volume, p. 227) for the western part of the Gulf of Aden. The trajectories of relative movement of Nubia–Arabia and Somalia–Arabia in this critical junction area will therefore be highly critical in determining the rate and direction of opening of the Somalian–Arabia plates.

In the Afar area, the azimuth of movement of Arabia–Somalia computed from the Le Pichon pole is 045°. In the case of the Red Sea, the trajectory of Arabia–Nubia cannot be precisely determined on the available data. It is worth noting here that movement along the N–S fracture zones of Phillips would, allowing for azimuthal change with distance from a pole located near the Dead Sea rift, result in unacceptable compression along the Ethiopian rift system. The fault plane solution of Fairhead & Girdler (this volume) is generally compatible with the azimuth of the bathymetric scarp at the foot of the Sinai peninsula, the azimuths of transform faults postulated by Girdler (1969) and with a pole position located close to the Dead Sea rift. An analysis by Roberts (1969) on this basis indicates that the trajectory of opening of Nubia–Arabia in Afar is 065° at 11° N and 42° E. The approximate relative movement of Nubia and Somalia predicted using these data is slow east–west extension with small sinistral shear.

In any discussion of the plate tectonics of this area it is highly important to consider the evolution of the present-day-three plate system through time. There is widespread evidence in this general area of a renewal in spreading beginning in the late Miocene to early Pliocene which was preceded by a hiatus. In the Gulf of Aden and NW Indian Ocean, a marked topographic break coupled with a change in character of the oceanic magnetic anomalies occurs at a point corresponding to this time (Le Pichon & Heirtzler 1968, Laughton *et al.*, this volume). A distinctive change in sediment thickness occurs at this point in the NW Indian Ocean (Ewing & Ewing 1967). Major evaporite deposition in the Red Sea ended in the Miocene (Heybroek 1965). Phillips & Ross (this volume, p. 143) indicate deformation of a presumed Miocene reflector in the Red Sea. The major phase of taphrogenesis occurred in the Kenyan and Ethiopian rifts in the early Pliocene (Baker 1965, this volume, p. 383; Gibson & Tazieff, this volume). Freund (this volume), Freund *et al.* (1968) have shown that a post-Cenomanian–pre-Pliocene movement of 80 km followed by a post-Pliocene movement of 40 to 45 km has occurred along the Dead Sea rift.

It is important to recognize that the post-Cenomaian–pre-Pliocene movement along the Dead Sea rift is contemporaneous with the pre-Pliocene development of the Gulf of Aden. Partial opening of the Red Sea had therefore occurred before the latest post-Pliocene phase. This pre-Pliocene opening occurred at a time when there was no major expression of the East African rift. Before the Pliocene therefore, when there was no major expression of the Ethiopian rift system, spreading of the two crustal plates of Arabia and unrifted Nubia–Somalia occurred



(*a*) pre-Miocene

(*b*) late-Pliocene

(*c*) present day

(*d*) 10 Ma from now

Figure 2. Schematic evolution of the Afar depression. – – – –, present-day coastline; ——, major rift boundary faults; – – – –, incipient rifting; ←——→, trajectories of relative movement of crustal plates. W.F.B.: Wonji fault belt.

about the Le Pichon pole, resulting in opening in the Red Sea and shear along the Dead Sea rift.

The development of a three-plate system from a two-plate system in the early Pliocene and the lack of contemporaneity of a part of the Red Sea with the Ethiopian rift system therefore places in error any attempt to derive the pole position for Nubia–Arabia from a best fit of Red Sea coastlines. This type of reconstruction involves a further error in the arbitrary assumption of oceanic crust throughout the width and length of the Red Sea. The width of the northern Red Sea, south of Sinai, is approximately 200 km. If the Red Sea is underlain by oceanic crust, this width must be reconciled with the post-Cenomanian movement of 100 km (Freund 1965) along the Dead Sea rift. Closure of the Gulf of Suez is inadequate to compensate for this large inconsistency which must, therefore, be attributed to attenuated continental crust.

A better reconciliation with the existing geological data may result if the pole positions are recalculated making due allowance for these important factors.

A fourth problem which has caused some confusion is the overlap of the continental Aysha horst (Mohr 1967*a*; Azzaroli 1968) with the Yemen in predrift reconstructions of the Gulf of Aden by Laughton (1966*a*, *b*), Beydoun and Mackenzie (this volume, pp. 267 and 393). Baker (this volume, p. 383), following Mohr (1968), attempted to obviate this difficulty by altering the trajectory of the Somalian plate. No evidence for such a change in trajectory is indicated by the fault plane solutions (Sykes 1969) which are in complete agreement with the direction of movement of Arabia–Somalia given by the azimuths of fracture zones in the Gulf of Aden. As I have pointed out earlier in this discussion, the 065° trajectory of opening of the Arabia–Nubia plates shows that Nubia must necessarily be diverging from Somalia, thereby producing dilatation along the Ethiopian rift system. The overlap can be more simply resolved by considering the Aysha Horst to have integrally rotated with the Danakil Horst (figure 2), to which it is structurally similar (Mohr 1967*a*), in post-Miocene time (Laughton 1966*b*). A rotation of the integral Danakil–Aysha Horsts implies that the E–W rift boundary fault which forms the southern side of the Aysha Horst and the Afar Depression was a region of transcurrent faulting, until the rifting apart of the Danakil and Aysha Horsts in the Gulf of Tadjura (figure 2) (Roberts & Whitmarsh 1968). The rotation of the Danakil–Aysha Horsts is probably at hinge points in the Gulf of Zula and Straits of Bab-el-Mandeb. This type of hinged rotation, which transforms the active-spreading axis of the Red Sea into the Afar Depression, theoretically should result in NNW–SSE trending magnetic anomalies in Afar. The theoretical NNW trend disagrees with the E–W trend of the observed magnetic anomalies (Girdler, this volume, p. 359). The cause of this discrepancy is not clear and may be better understood when detailed studies are made of the geometry of spreading and the timing of the relative movements of the plates in Afar.

References (Roberts)

Allan T. D. 1970 Magnetic and gravity fields over the Red Sea. (This volume.)

Azzaroli, A. 1968 On the evolution of the Gulf of Aden. 27*th Int. Geol. Cong.* **1**, 125–134.

Baker, B. H. 1965 The rift system in Kenya. In East-African Rift System, pp. 82–85, UMC–UNESCO Seminar, Nairobi, University College.

Baker, B. H. 1970 Tectonic problems of drift applied to the Afro-Arabian rift. (This volume.)

Beydoun, Z. R. 1970 Southern Arabia and Somalia: comparative geology. (This volume.)

Einarrson, T. 1967 The Icelandic fracture system and the inferred causal stress field. In *Iceland and mid-ocean ridges* (Bjornsson, S., ed.), chap. C, pp. 128–139. Reykjavik, Prentsmidjan Leiftur H.F.

Einarrson, T. 1969 Submarine ridges and stress fields. *J. geophys. Res.* **73**, 7561–7576.

Ewing, J. & Ewing, M. 1967 Sediment distribution on the mid-ocean ridges with respect to spreading of the sea floor. *Science, N.Y.* **156**, 1590–1592.

Fairhead, J. D. & Girdler, R. W. 1970 Seismicity of the Red Sea, Gulf of Aden and Afar triangle. (This volume.)

Freund, R. 1965 A model of the structural development of Israel and adjacent areas since Upper Cretacous times. *Geol. Mag.* **102**, 189–206.

Freund, R., Zak, I. & Garfunkel, Z. 1968 Age and rate of the sinistral movement along the Dead Sea Rift. *Nature, Lond.* **220**, 253–255.

Gass, I. G. & Gibson, I. L. 1969 The structural evolution of the rift zones in the Middle East. *Nature, Lond.* **221**, 926–930.

Gibson, I. L. 1967 The volcanic geology of an axial portion of the main Ethiopian Rift. *IUGG U.M.C. Symposium* **8**, 38.

Gibson, I. L. & Tazieff, H. 1970 The structure of Afar and the northern part of the Ethiopian rift. (This volume.)

Girdler, R. W. 1969 The Red Sea—a geophysical background. In *Hot brines and recent heavy metal deposits in the Red Sea* (Degens, E. T. and Ross, A., eds.), pp. 38–58. New York: Springer-Verlag.

Girdler, R. W. 1970 An aeromagnetic survey of the junction of the Red Sea, Gulf of Aden and Ethiopian rifts. (This volume.)

Heybrock, F. 1965 In *Salt basins around Africa*, pp. 17–41. Institute of Petroleum, London.

Isacks, B., Oliver, J. & Sykes, L. R. 1968 Seismology and the new global tectonics. *J. geophys. Res.* **73**, 5855–5901.

Laughton, A. S. 1966*a* The Gulf of Aden. *Phil. Trans. Roy. Soc. Lond.* A, **259**, 150–171.

Laughton, A. S. 1966*b* In *The World Rift System* (Irvine, T. N., ed.). *Geol. Survey Pap. Can.* **66–14.**

Laughton, A. S., Whitmarsh, R. B. & Jones, M. T. 1970 The evolution of the Gulf of Aden. (This volume.)

Le Pichon, X. & Heirtzler, J. R. 1968 Magnetic anomalies in the Indian Ocean and sea-floor spreading. *J. geophys. Res.* **73**, 2101–2117.

Le Pichon, X. 1968 Sea-floor spreading and continental drift. *J. geophys. Res.* **73**, 3661–3697.

Mackenzie, D. P. 1970 The development of the Red Sea and Gulf of Aden in relation to plate tectonics. (This volume.)

Mackenzie, D. P. & Parker, R. L. 1967 The North Pacific: an example of tectonics on a sphere. *Nature, Lond.* **216**, 1276–1280.

Mohr, O. 1882 Über die Darstellung des Spannungzustandes eines Korpelementes. *Zwil. Ingenieure* **28**, 113–156.

Mohr, P. A. 1967*a* The Ethiopian Rift System. *Bull. Geophys. Obs. Addis Ababa* **11**, 1–63.

Mohr, P. A. 1967*b* Major volcano–tectonic lineament in the Ethiopian Rift System. *Nature, Lond.* **213**, 664–665.

Mohr, P. A. 1968 Transcurrent Faulting in the Ethiopian Rift System. *Nature, Lond.* **218**, 938–941.

Morgan, W. J. 1968 Rises, trenches, great faults, and crustal blocks. *J. geophys. Res.* **73**, 1959–1982.

Phillips, J. D. & Ross, D. R. 1970 Seismic reflexion and topography studies in the Red Sea. (This volume.)

Phillips, J. D., Woodside, J. & Bowin, C. O. 1970 Magnetic and gravity anomalies in the Central Red Sea. (This volume.)

Riedel, W. 1929 Zur Mechanik geologischer Brucherscheinungen. *Zentbl. Miner. Geol. Palaönt.* (Abt B), pp. 354–369.

Roberts, D. G. 1969 Structural evolution of the rift zones of the Middle East. *Nature, Lond.* **223**, 55–57.

Roberts, D. G. & Whitmarsh, R. B. 1968 A bathymetric and magnetic survey of the Gulf of Tadjura, western Gulf of Aden. *Earth Planet. Sci. Lett.* **5**, 253–258.

Sykes, L. R. 1969 Seismological evidence for transform faults, sea floor spreading and continental drift. In *The history of the earth's crust* (Phinney, R. A., ed.), pp. 120–150. Princeton: Princeton University Press.

Tryggvason, E. 1968 Measurement of surface deformation in Iceland by precision levelling. *J. geophys. Res.* **73**, 7039–7050.

Vine, F. J. 1966 Spreading of the ocean floor: new evidence. *Science, N.Y.* **154**, 1405–1415.