

# Mechanistic model for triple junction fracture geometry

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We show that fractures produced in an elastic, homogeneous lithospheric plate by stress generated by wedging of deepseated igneous mass(es) are comparable with the major fracture geometry and rift valley formation associated with the Red Sea, Gulf of Aden and East African Ridges; and that the formation and evolution of certain triple junction fracture geometry (FFR to RRR types) can also be related to stress generated around an oblate magmatic body.

GEOPHYSICAL data<sup>1-4</sup> from the Red Sea and Gulf of Aden indicate the presence of large mafic mass(es) in the central trough(s). In the northern Red Sea, between 17°N and 26°N, the Bouguer gravity anomaly map shows +100 mgal over the centre of the Red Sea with +125 to +150 mgal maximum<sup>1</sup>. This positive gravity anomaly extends over the northern Red Sea south of the Sinai Peninsula and probably as far south as 14°N though the magnitude is much less (Fig. 1). From these data we assumed the presence of a vertically elongated oblate igneous mass at depth extending along the axis of the Red Sea (Fig. 2) and the Gulf of Aden, and analysed the effects of magmatic stress caused by such bodies in producing rifting and fracture geometry (especially FFR to RRR types, where F denotes fault and R denotes ridge<sup>5</sup>) in the elastic lithospheric plates.

## Basic data

We used Boussinesq's three-function method as described elsewhere<sup>6-8</sup> to obtain stress distribution(s) around fractures in an infinite and homogeneous elastic rock body. Isolated oblate magma bodies were assumed to exist in isotropic elastic lithospheric rocks in the Red Sea, Gulf of Aden-Carlsberg Ridge and along the East African Rift System. Although idealised, this assumption can be used as a first approximation, if the fractures are propagated essentially in a brittle manner. Because fractures are formed under high stress, the shape of the apex of the oblate ends and the curvature of the upwell or swell and vertical protrusions are considered more important for our theoretical analyses than points, lines or circular holes<sup>9,10</sup>. We analysed stress distributions around vertically elongated oblate igneous bodies of aspect ratios 1:10 to 1:1000, assuming that the magmatic upwell or igneous mass would continue to grow at depth in areas of asthenospheric plumes<sup>11</sup> or of partial melting. Details are presented elsewhere<sup>7,8,12</sup>. Our analyses show that the absolute magnitude

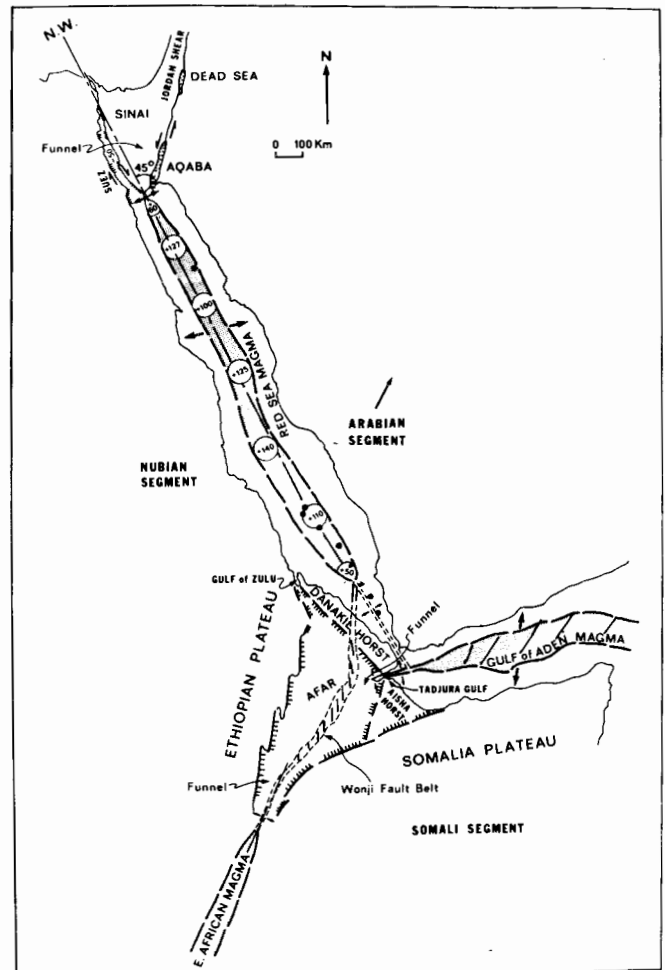
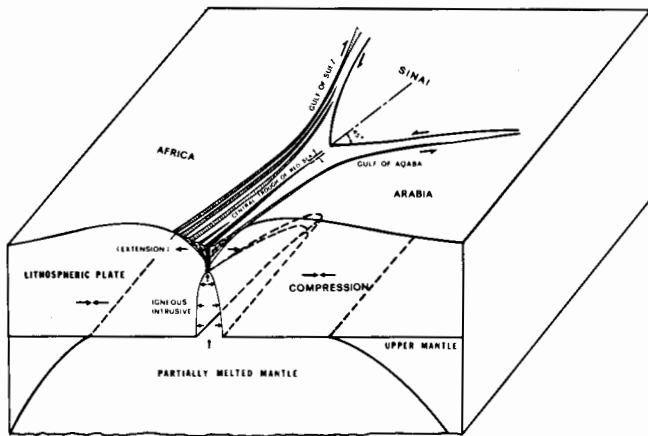


Fig. 1 The Red Sea and Gulfs of Suez, Aqaba and Afar, showing gravity anomalies, major regional stress direction, the principal stress axis due to the Red Sea magmatic source, centres of volcanism ( $\blacktriangle$ ) and seismic activity ( $\bullet$ ). Southern Red Sea showing the probable formation of the Afar depression, *en echelon* normal faulting and graben, and the development of the Wonji fault belt at the axial region of the East African rift due to funnelling or bifurcation of the tensional fracture arm into strike-slip and/or *en echelon* arrays of tensile fracture zone(s) caused by stress from wedging of igneous masses into the lithospheric plate in the Gulf of Aden, Red Sea and East African ridge areas.



**Fig. 2** The mechanism of formation of the central rift in the Red Sea and the FFR type triple junction fracture geometry at the northern end caused by wedging of the dike-like igneous mass into the lithospheric plate. Graben subsidence occurs along a set of funnel-shaped normal faults in the central zone of the rift valley. The areas of compression and extension are shown by arrows; wide domal uplift and relative subsidence in the central region, as deduced from the distribution of elastic displacement vectors are shown.

of the stress contours (Fig. 3) around the apex of an oblate igneous body varies slightly with the change in aspect ratio from 1:100 to 1:1000. The effect of changing the Poisson ratio of the lithospheric plate from 0.26 to 0.4 was negligible.

These analyses indicate that: (1) elastic stress concentration is greatest around the apex of an oblate shaped igneous body (Fig. 3); and that (2) a vertically elongated oblate body is an ideal shape for the diapiric uprise of magma<sup>13</sup> because wedging of such an igneous mass into the lithospheric plate produces wide areas of lateral compression at the sides at depth but causes horizontal extension within a funnel-shaped zone above the top (Fig. 2).

When magma fluid pressure exceeds lithostatic stress, maximum stress concentration at the apex of the oblate ends may initiate fracture propagation in the elastic lithospheric plate in areas of high stress concentration, along existing lines of weakness or inhomogeneous spots. This initiates FFR type<sup>5</sup> of triple junction fracture geometry (Figs 2-4) with a tensional arm in front of the tip (where later intrusion of magmatic dikes may result in a ridge) branching into two shear zones at an angle of 30-45° with the magmatic stress axis in an homogeneous plate (as the triple junction associated with East Pacific Rise in oceanic plate) and/or *en echelon* arrays of tension fractures associated with or extending along the fracture zones (Figs 2, 3). Although one arm of the shear zone may show transcurrent movement (as left lateral in the Gulf of Aqaba), the other bifurcating arm may show *en echelon* tensile fractures which, with increasing magmatic stress, give rise to continuous normal-faulted zones (the Gulf of Suez, Figs 1, 2). Displacement along the normal-faulted zones may produce subsidence and graben (Fig. 2).

Distribution of elastic displacements above the prolate end of the elongated magma body indicates a wide domal uplift, but an area of relative subsidence and graben would occur in the centre of the domal uplift above the prolate end (Fig. 2) producing an elongated rift valley (central trough) bounded by inward-dipping funnel-shaped normal or block faults as in the Red Sea area<sup>12</sup>. Where magma from deeper levels has wedged or intruded closer to the surface, the fractures (normal faulting) produced by magmatic stress extend upward and outward as in the Red Sea and Rhine graben areas<sup>14,15</sup>. Magmas (mafic or felsic) intruding as axial dikes through such fractures in the central rift zone would produce lateral stretching, further rifting and spreading.

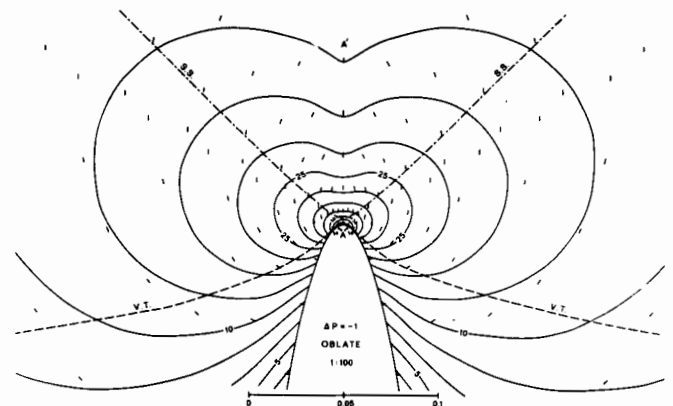
Intrusion of a wedge-shaped or slab-like mafic mass through the central normal fault zone would produce areas of relatively higher positive gravity anomaly within the trough and above the rift zone<sup>2,4,14,16</sup>.

Our analysis also indicates that stress from broad doming or upwell is not itself great enough to produce axial collapse and rift valley formation of the magnitude of the Red Sea as was proposed by Cloos<sup>17</sup> in 1939. This has also been emphasised recently by Gass and Gibson<sup>18</sup>. Mechanistically, and based on magnetic, seismic and gravity data, the formation of rift valleys and their extension and branching can be explained by dyke-like intrusions of igneous masses into the lithospheric plate below the rift valleys (Fig. 2).

An estimation of stress concentration around prolate protrusions<sup>6,7</sup> above an oblate magma body shows higher stress concentration with increasing aspect ratios from spheroidal to vertically elongated protrusions, and the development of predominantly radial, radial-concentric and concentric fracturing respectively in the lithospheric plate around such pipes, necks or volcanic centres along the axis of the rift valley or normal-faulted zone.

### Mechanistic interpretations

The bifurcation of the Red Sea rift at approximately 27°8'N into two shear zones, Gulfs of Suez and Aqaba (Figs 1, 2), the angle of about 45° of the Gulf of Aqaba shear arm with the NW-SE Red Sea axis<sup>4</sup>, and the left lateral transcurrent movement of the Gulf of Aqaba-Dead Sea-Jordan shear zone<sup>19-21</sup> are consistent with mechanistic analyses of fracture formation as a result of the Red Sea mafic intrusive mass from the upper mantle (Figs 1-3). Magnetic anomalies and high-level oceanic crust are not present in the northern part of the Red Sea (beyond 25°N), but the central trough continues as a definite bathymetric feature northward toward Sinai where it seems to terminate against the left lateral transcurrent Jordan shear<sup>4,18</sup>. Mechanistically, this part represents a tensional arm (Figs 1, 2) not yet filled by oceanic (mafic) materials at the upper level of the Red Sea crust, bifurcating into normal-faulted shear zones south of Sinai (Fig. 2). This triple junction fracture geometry at the northern end of the Red Sea is interpreted as FFR type because it relates to stress at the apex of the vertically elongated igneous mass along the rift in the Red Sea, and not RRR



**Fig. 3** Contour diagram of maximum tensile stress (in kbar) caused by an excess of magma pressure ( $P$ ) over lithostatic stress ( $\sigma_1$ ) ( $P - \sigma_1 = -1$  kbar) around the apex of the dyke-like, oblate intrusive mass. Tensile stress is indicated as positive. Only the contours around the apex (area of maximum stress concentration) are shown. Lithostatic stress should be superimposed on the stress value(s) shown. The direction of maximum stress is perpendicular to the short lines. Above the line VT induced stress due to excess magma pressure is three-dimensionally tensile although absolute tensile stress actually occurs close to the tip of the intrusive mass.

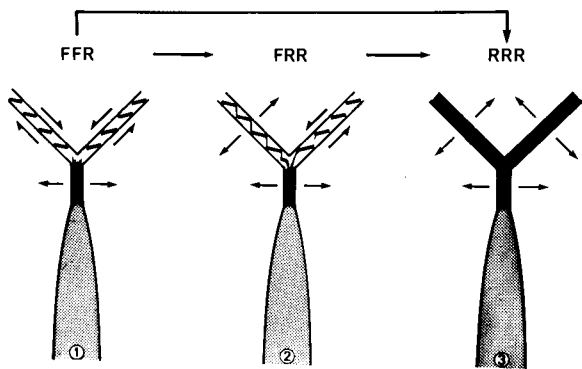


Fig. 4 Development of FFR type triple junction fracture geometry due to an oblate igneous mass and probable path of development of RRR from FFR type triple junction fracture from progressive increase of magmatic wedging and stress.

type with a hot spot at the centre of the triple junction south of Sinai as envisaged by Burke and Dewey<sup>22</sup>. Lack of igneous activity, and large negative gravity anomalies in the Gulfs of Suez ( $-50$  mgal) and Aqaba ( $-100$  mgal) support this interpretation. But continued rifting with increasing magmatic stress and filling of properly oriented fracture arms with magmatic materials can transform an FFR into an RRR type triple junction. This gradual evolution may follow the path FFR→FRR→RRR or proceed directly from FFR to RRR type (Fig. 4). The Gulf of Suez has been suggested to be a "failed arm" of a triple junction; there is no geophysical evidence<sup>4</sup> of its continuation northward in the Mediterranean. On the other hand, the Gulf of Aqaba–Dead Sea–Jordan shear zone is more extensive (600 km) and shows transcurrent movement on the order of 90 to 110 km (refs 4, 20). The  $45^\circ$  orientation of the Gulf of Aqaba–Dead Sea–Jordan shear to the principal stress axis (Figs 1, 2) of the Red Sea igneous mass is ideal for strike-slip movement providing relief of the stress resulting from magma pressure caused by continued magma generation at depth, rifting, magmatic wedging and spreading along the Red Sea central trough; it adds to the NE movement of the Arabian Plate<sup>23</sup>. This may also account for the low seismicity of the northern Red Sea. Mechanistically, the Gulf of Suez represents an *en echelon* fault zone widened (70–80 km) by normal faulting with continued rifting and increasing stress because of the growth of the Red Sea igneous mass since Miocene. The orientation at  $10$ – $15^\circ$  of the Gulf of Suez to the principal Red Sea axis (Fig. 1) makes it an extensional inactive or "failed" arm of the northern Red Sea triple junction fracture. The orientation of preexisting lineaments in the basement rocks seems to have controlled the low angle orientation of this fracture zone producing the Gulf of Suez.

At the southern end of the Red Sea, the oceanic crust and centres of volcanism within the Red Sea rift seem to extend to almost  $15^\circ$ N (refs 4, 18; Fig. 1). On the basis of seismicity<sup>23</sup>, however, the Red Sea rift has been considered as continuing further south to join with the Gulf of Aden and East African rift forming the boundary of the triple junction plates of Arabia, Nubia and Somalia. Mechanistically, the southern extension of the Red Sea central rift represents a tensional fracture arm, developed from stress resultant from further wedging and intrusion of the Red Sea igneous mass, which bifurcates into two shear-faulted tensional belts: the Gulf of Aden and the main Ethiopian rift (Figs 1 and 2). The Gulf of Aden, identified as a tensional feature<sup>24</sup>, involves the separation of the continental blocks of Africa and Arabia and the formation of new oceanic crust in between. The belt of Quaternary tensional faulting occurring along much of the axial portion of the main Ethiopian rift, termed the Wonji

fault belt<sup>25</sup>, is characterised by a series of *en echelon* fracture swarms<sup>26</sup> and is interpreted by Gibson<sup>27</sup> as open tensional faults resulting from left-lateral shear along the length of the main Ethiopian rift. This and Girdler's view<sup>28</sup> agree with our mechanistic interpretation (Fig. 1) which suggests that the origin of the Wonji fault belt is related to stress from the Red Sea igneous mass. An axial zone of relatively high Bouguer gravity values coincides with the Wonji fault belt and injection of basaltic dikes at shallow depth has been suggested<sup>29</sup>. Thus, mechanistically, the triple junction fracture geometry (FFR) at the southern end of the Red Sea is being transformed to RRR type with magmatic wedging and intrusion in the Gulf of Aden and the main Ethiopian rift.

The Gulf of Tadjura represents a tensional feature (Fig. 1) produced by rifting as a result of the Gulf of Aden's magmatic stress. If its origin is related to this magmatic stress, the Gulf of Tadjura's tensional arm should bifurcate into two *en echelon* normal-faulted tensional or shear zones. These seem to be: one, paralleling the Red Sea along the western Danakil block and extending to the Gulf of Zulu; the other extending along the western margin of the Aisha block toward the Somalia Plateau (Fig. 1). Normal faulting toward Afar along these bifurcating fracture arms would produce the Danakil and Aisha Horsts (Fig. 1). Stress caused by the igneous mass along the East African ridges would cause bifurcation or funnelling into two *en echelon* normal-faulted zones (Fig. 1). Such funnelling of the East African ridges into the Dankelina fault along the Ethiopian side and the East African rift along the Somalia side is well known<sup>30</sup>. Normal faulting along the *en echelon* tensional zones of Ethiopia, Somalia and Danakil height<sup>29</sup> (Fig. 1) would produce a depression similar to Afar with a high plateau or horst on each side of the triangle. Thus the origin of the Afar depression can be directly correlated with the stress fields generated by the wedging of the Gulf of Aden and the East African igneous masses. At the northern end of the Ethiopian plateau and the Danakil height, the normal-faulted zone(s) narrow into the Gulf of Zulu (Fig. 1) and mark it as a tensional zone. Mechanistically, all the Gulfs (Suez, Tadjura, Zulu, and so on) are tensional features. Recent active rifting, spreading, volcanism and the formation of graben along the tensional zones within the Afar depression<sup>31</sup> may result from complex interaction of stress fields and fracturing in the Afar crust caused by the East African, Red Sea and Gulf of Aden's magmatic stresses.

The analysis also suggests that one need not invoke the presence of hot spots or asthenospheric plumes<sup>22</sup> at the intersection of triple junctions to explain every example of major or minor triple junction (FFR or RRR type) fracture geometry.

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- 1 Nafe, J. E., Hennion, J. F., and Peter, G., *Int. Ocean. Congr. NY*, 42 (1959).
- 2 Drake, C. L., and Girdler, R. W., *Geophys. J. R. astr. Soc.*, 8, 473 (1964).
- 3 Girdler, R. W., *Q. J. Geol. Soc. Lond.*, 114, 79 (1958).
- 4 Girdler, R. W., in *Hot brine and recent heavy metal deposits in the Red Sea* (edit. by Degans, E. T., and Ross, D. A.) (Springer-Verlag, New York, 1969).
- 5 McKenzie, D. P., and Morgan, W. J., *Nature*, 227, 125 (1969).
- 6 Bhattacharji, S., and Koide, H., *Eos*, 55, 439 (1974).
- 7 Koide, H., and Bhattacharji, S., *J. econ. Geol.*, 70, 4 (1975).
- 8 Koide, H., *Proc. Int. Conf. Mech. Behaviour Materials*, 4, 455 (1972).
- 9 Anderson, E. M., *Proc. R. Soc. Edinb.*, 56, 128 (1936).
- 10 Robson, G. R., and Barr, K. G., *Bull. Volcanol.*, 27, 315 (1964).
- 11 Morgan, W. J., *Bull. Am. Assoc. petrol. Geol.*, 56, 203 (1972).
- 12 Bhattacharji, S., and Koide, H., *Geol. Soc. Am. Abstr.*, 6, 1024 (1974).
- 13 Koide, H., and Bhattacharji, S., *Geol. Soc. Am. Abstr.*, 6, 829 (1974).
- 14 Lowell, J. D., and Genik, *Bull. Am. Assoc. Petrol. Geol.*, 56, 250 (1972).
- 15 Illies, J. H., and Mueller, St., *Int. Upper Mantle Proj. Rep.*, 27, 10 (1970).
- 16 Baker, B. H., and Wohlenberg, J., *Nature*, 229, 538 (1971).
- 17 Cloos, H., *Geol. Rundschau*, 30, 405 (1939).
- 18 Gass, I. G., and Gibson, I. L., *Nature*, 221, 926 (1969).
- 19 Dubertret, L., *Physique Geol.*, 9, 3 (1967).
- 20 Quennell, A. M., *Q. J. Geol. Soc. Lond.*, 114, 1 (1958).
- 21 Freund, R., *Geol. Mag.*, 102, 189 (1965).
- 22 Burke, K., and Dewey, J. F., *J. Geol.*, 81, 406 (1973).
- 23 McKenzie, D. P., Davis, D., and Molnar, P., *Nature*, 226, 243 (1970).

- <sup>24</sup> Laughton, A. S., *Phil. Trans. R. Soc.*, A259, 150 (1966).  
<sup>25</sup> Mohr, P. A., *Bull. Geophys. Obs. Addis Ababa*, 3, 9 (1960).  
<sup>26</sup> Mohr, P. A., *Bull. Geophys. Obs. Addis Ababa*, 11, 1 (1967).  
<sup>27</sup> Gibson, I. L., *Tectonophysics*, 8, 561 (1969).  
<sup>28</sup> Girdler, R. W., *Nature*, 217, 1103 (1968).  
<sup>29</sup> Baker, B. H., Mohr, P. A., and Williams, L. A. J., *Bull. geol. Soc. Am.* 136, 48 (1972).  
<sup>30</sup> Abdel Gaward, M., in *Hot brine and recent heavy metal deposits in the Red Sea* (edit. by Degens, E. T., and Ross, D. A.) (Springer-Verlag, New York, 1969).  
<sup>31</sup> Barberi, F., Tazieff, H., and Varet, J., *J. Tectonophysics*, 15, 19 (1972).