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The development of the Red Sea and Gulf of Aden in relation to plate tectonics† (summary only)

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The ideas of Hess and Dietz on seafloor spreading were principally concerned with the production of ocean floor on the axes of oceanic rifts. The continents were believed to move with the surrounding ocean floor, and to remain undeformed during their motion. These are also the ideas on which plate tectonics depends, though it differs from earlier theories by imposing rather severe restrictions on the possible relative motions. The basic assumption in plate tectonics is that the surface of the Earth may be divided into many rigid aseismic plates in relative motion. The boundaries of the plates are defined by the seismic zones of the world, earthquakes being the expression of the relative motion between neighbouring plates. Since the relative motion of any two plates may be completely described by a rigid body rotation of one about some axis through the centre of the Earth, all problems concerned with present-day continental drift and tectonics reduce to the problem of determining the axes of relative rotation and angular velocities of all pairs of plates in contact. There is now abundant evidence to show that the basic assumption of plate tectonics is correct (McKenzie & Parker 1967; Morgan 1968; Le Pichon 1968; Isacks *et al.* 1968).

The evolution of the Red Sea and the Gulf of Aden is a consequence of the motions of at least four plates: Arabia, the north-west Indian Ocean, Africa east of the rift and Africa west of the rift. The motion between Arabia and east Africa is well determined from observations in the Gulf of Aden, but that between Arabia and west Africa must be obtained by fitting Arabia on to Africa by closing the Red Sea. The motion on the Ethiopian rift can then be calculated.

Motion between Arabia and India causes the seismicity on the Owen fracture zone north of the Sheba ridge, and one fault plane solution shows that the motion is right lateral. Such motion must produce an offset in the ridge axis across the Owen fracture zone. The Gulf of Aden and the Red Sea also illustrate how ridges evolve as spreading continues.

Though these ridges are of considerable interest, they are not the major active features of the Middle East. These are farther north in northern Turkey and Iran, where the slip rates are probably between 1.5 and 3 nm s^{-1} (5 and 10 cm a^{-1}). Thus the complicated collision of Africa and India with Eurasia has probably caused the extension and spreading in the Red Sea and Gulf of Aden.

References (McKenzie)

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Le Pichon, X. 1968 *J. geophys. Res.* **73**, 3661.
McKenzie, D. P. & Parker, R. L. 1967 *Nature, Lond.* **216**, 1276.
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† *Nature, Lond.* (in the Press).

Discussion

I. L. Gibson (*Leeds University, written*) commented that one could not doubt the general validity of plate tectonic theory when applied to the study of the large-scale movement of mega-continental plates. However, Dr McKenzie's work involves the movements of much smaller plates over shorter distances, and therefore the results should be treated with some caution if they conflict with the geological interpretation.

Implicit in plate tectonic theory is the concept that the plates move as rigid units without internal deformation. Morgan (*J. geophys. Res.* **73**, 1959) has shown that for mega-continental plates this assumption is justified. However, in the Sinai–Arabian area deformation within these much smaller blocks may reach significant proportions. Certainly Freund (this volume) has indicated that there is internal deformation within the Sinai block on the western side of the Jordan Shear. The Arabian block also shows signs of internal deformation. Here NW trending tensional features appear, some following older structural lines (Brown, this volume). N–S tensional dykes also occur.

As these smaller plates appear to have suffered internal deformation, presumably the outline of the plates will also have been altered. As a result the pole positions calculated from the fit of adjacent deformed plates will automatically be affected. From this it can be assumed that errors will occur when the two poles for the opening of the Red Sea and the Gulf of Aden are used to calculate the rate and direction of relative motion in the Ethiopian rift. These uncertainties may explain why Dr McKenzie's interpretation of the Ethiopian rift as a zone of E–W tension is in conflict with the speakers interpretation which suggests that the rift is a region of predominantly left lateral shear (Gibson, this volume).

D. P. McKenzie replied that he expected the simple version of plate tectonics outlined by McKenzie & Parker and by Morgan to break down in some areas for the reasons outlined by Dr Gibson, but did not believe that the south end of the Red Sea was such a case. The seismic activity is restricted to the centre of the Gulf, the rift and the Red Sea, and no activity is observed within the Arabian Shield. In regions where internal deformations are important, such as Iran, the seismicity is not localized in this way. Also it is difficult to understand how the two shores could remain undeformed if the Arabian plate was being deformed during the motion. Even if these arguments are not accepted, it is still possible to show that the rifting must be dominantly in a northwest–southeast direction, though it is no longer possible to determine the pole. Laughton's maps of transform faults in the Gulf of Aden determine the direction of relative motion between Africa east of the rift and Arabia, and the displacement can be obtained from the separation of the 1000 m contours. If the motion between the two sides of the rift is required to be left lateral, the opening of the Red Sea which is required is not compatible with the distribution of basement rocks, and does not permit matching of the coastlines even at the southern end. A small component of left lateral motion, combined with about 60 km of opening normal to the rift, is consistent with the fit of the coast lines and may be the explanation of Dr Gibson's observations.

Some observations on active faults in northern Iran may also be relevant to this problem. Field studies of surface breaks of the 1 September 1962, earthquake and the shock of 31 August 1968, showed large left lateral movements and some overthrusting. Fault plane solutions, however, show that both earthquakes were dominantly overthrust, with only a small component

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of left-handed strike slip motion. Since the fault plane determined from the fault plane solutions agrees well with the field observations, and since the slip vectors are about N 20° E over the whole area, the true motion is probably given by the fault plane solutions. Thus, the vertical movements on the faults are concealed by the behaviour of the incompetent surface rocks. Less is known about the surface breaks of normal faults, since most extensional earthquakes occur beneath the sea. Somewhat doubtful evidence from normal faults in western Turkey appears to show the same effect. These observations suggest that strike slip motions on faults are much easier to observe than vertical movements, and that Dr Gibson's observations could well be compatible with the extension of 60 km in a northwest–southeast direction calculated from the motion of the three rigid plates, combined with a much smaller left lateral shear.

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