# Palaeomagnetism and the Origin of the Red Sea and Gulf of Aden

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# Palaeomagnetism and the origin of the Red Sea and Gulf of Aden

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Palaeomagnetic data from two volcanoes of the Aden Volcanics shows 7° anticlockwise rotation of this part of Arabia relative to Africa during the last 5 Ma. On theoretical grounds this amount of deviation should not be detectable from other sources of scatter, in particular that caused by averaging the secular variation. It is suggested that this deviation is probably real as it is shown in both volcanoes, but further detailed work is necessary to distinguish between anomalous secular variation and the suggested tectonic interpretation. Studies of older rocks in both Arabia and Africa show that the Mesozoic anticlockwise rotation of Africa relative to the axis of rotation had ceased by the late Cenozoic and this movement, together with the evolution of Turkey and the Zagros Mountains, must be considered within the problem of the tectonic evolution of the Red Sea–Gulf of Aden area.

## 1. Introduction

Early palaeomagnetic results from the Aden region appeared to be highly consistent with a dilational origin of the Red Sea and Gulf of Aden (Irving & Tarling 1961), and the more recent data from both Arabia (Tarling, Sanver & Hutchings 1967) and Africa (Brock 1969*a*) appears to fully confirm this interpretation. There are, however, theoretical grounds for considering that the data so far available should be inadequate for the precise measurement of Arabia relative to Africa. It is necessary, therefore, to consider some of the principal factors affecting the accuracy of palaeomagnetic techniques before analysing the palaeomagnetic data relevant to this problem.

## 2. The accuracy of palaeomagnetic techniques

The first factor to be considered is the accuracy with which the direction of the ancient geomagnetic field can be determined. In igneous rocks, this relates to the precision of measurement of the magnetic vector associated with those ferromagnetic particles in a rock which have a characteristic relaxation time (Néel 1955) of similar or greater age than the rock itself. The techniques for isolating and defining this magnetic component are well established (Collinson, Creer & Runcorn 1967) and need not be repeated; most authorities consider that an absolute determination of the remanent vector can only be made, for a single specimen, within a few degrees. However, most sources of error in this measurement of individual vectors are random and can be considerably reduced by detailed sampling and repeat measurements, but there are systematic errors which can arise; such as anisotropic effects associated with flow-banded material and in particular with the determination of the original horizontal in a tectonically disturbed region. In sedimentary rocks, these difficulties are also present, but are generally accentuated by the complex nature of the origin of the remanence in such rocks which may be depositional, post depositional, chemical during subsequent diagenesis or chemical changes arising during the entire lifetime of the rock. It is clear, therefore, that even greater caution must be exercised in the interpretation of palaeomagnetic results from sedimentary than from igneous rocks.

The second factor to be considered is much more difficult to quantify as it involves the estimation of the accuracy of the basic assumptions involved in the interpretation of palaeomagnetic observations.

In order to establish differential movement between two land masses, some common datum must be established against which these movements can be measured. The most fundamental assumption which enables this datum to be determined is that the Earth's magnetic field, on average, is that of an axial geocentric dipole so that the *average* position of the geomagnetic pole coincides with that of the Earth's rotational pole. This means that discrepancies between the average geomagnetic field in two localities at any one time can be interpreted in terms of tectonic movements between the two areas. There are good grounds for considering that this basic assumption is generally valid as it is supported by observational evidence, for example the agreement of palaeoclimatic and palaeomagnetic latitudes in the geological past (Briden & Irving 1964) and the agreement of average palaeomagnetic directions from all areas of the world for the last few million years (Tarling 1963; Opdyke & Wilson 1968), and also by theoretical considerations of the source of the geomagnetic field which imply that the Coriolis force is a major influence on dynamo action within the Earth's core. However, while this assumption is adequate for major tectonic movements it is by no means clear if this assumption is valid on a small, precise scale (less than 5°).

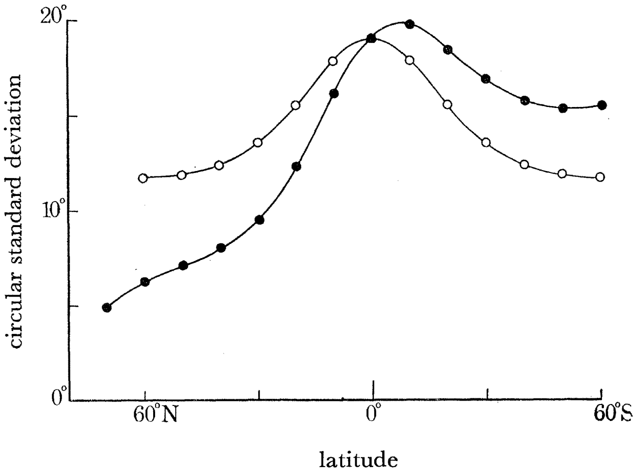

FIGURE 1. The latitudinal distribution of the scatter of geomagnetic vectors for the 1965 field. The curve with solid dots is that of the observed circular standard deviation of geomagnetic vectors, taken every 10° around lines of latitude. The curve with circles shows the variation with latitude of the scatter averaged between northern and souther hemispheres.

However, irrespective of the precise validity of the assumption of an average axial geocentric dipole, we must always be left with the problem of determining the average direction from a set of observations which have an intrinsic scatter caused by secular variations of the geomagnetic field. The information on the magnitude of secular variation during the last 50 a is rather sparse and of variable reliability so that it is extremely dangerous to extrapolate this data back through geological time. We can, however, establish models of the magnitude of secular variation which can be tested against the evidence for recent times, by direct measurement, and for geological times by palaeomagnetic observations. The simplest model consists of the magnitude of scatter of geomagnetic vectors around different lines of latitude for any one time (Creer 1961). This procedure means that secular variation is attributed entirely to a westward drift of the non-axial geocentric dipole components of the geomagnetic field. This is somewhat unrealistic in terms of the known behaviour of the Earth's field, but, by averaging the magnitude of scatter in the northern and southern hemispheres, we produce a model of scatter (figure 1) which agrees moderately well with palaeomagnetic observations for past epochs, particularly in showing a marked latitudinal dependence. The two most detailed palaeomagnetic studies—the Hawaiian Islands (Doell & Cox 1964) during the last few million years, and the Faeroe Islands (Tarling 1969) during the Eocene (55 to 60 Ma)—show respectively a slightly less and slightly greater magnitude of scatter than this model, while most other observations appear to confirm the magnitude and latitudinal dependence of scatter.

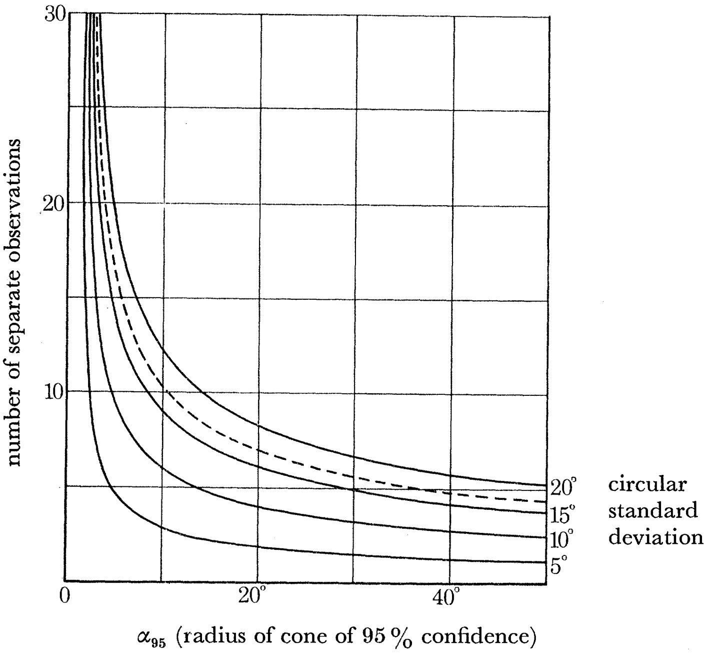

Figure 2. The relation between the number of geomagnetic vectors observed, their scatter and the precision of the mean direction. The curves are for given values of circular standard deviation as expected to be present in palaeomagnetic analyses as a function of the latitudinal variation of secular variations (see figure 1). The dashed line is for a circular standard deviation of 17° which is the scatter expected for the palaeolatitude of Aden. This implies that ten separate observations, with an intrinsic scatter of 17° circular standard deviation, would allow the mean direction to be determined, with a 95 % probability, to within 10° in the absence of all other effects and assuming perfect sampling of a 'normal' secular variation cycle.

The magnitude of scatter is usually expressed in terms of the circular standard deviation (c.s.d. = $\cos^{-1}(R/N-1)$, where $N$ is the number of observations and $R$ is the length of vector sum of the observations). The simple model of secular variation adopted above suggests that the circular standard deviation varies from about 7° near the poles, to about 19° at the Equator. The precision with which the mean direction is measured, $\alpha$, is also defined (Fisher 1953) in terms of the number of observations ($N$) and the length of the resultant vector ($R$)

$$\cos\alpha = 1-\frac{N-R}{R}\left\{\left(\frac{1}{P}\right)^{1/(N-1)}-1\right\},$$

where $P$ is the probability (usually 0.05). Assuming both perfect measurement and perfect sampling of the secular variation cycle, we can therefore relate the precision of the mean direction, the number of observations and the scatter attributed to the secular variation model (figure 2). It is clear from this comparison that extremely detailed sampling must be undertaken to detect small-scale tectonic movements if this model of secular variation is even approximately realistic. This does not mean that large-scale tectonics, such as continental drift or even moderate intra-continental movements cannot be studied, but in examining the palaeomagnetic evidence for very small scale rotations, such as associated with the formation of the Gulf of Aden and Red Sea, then the palaeomagnetic data must be very carefully scrutinized.

## 3. Palaeomagnetic results relative to the origin of the Red Sea and Gulf of Aden

3.1. The first palaeomagnetic results from this area were from Aden itself (Irving & Tarling 1961). This volcano, now known to be about 5 Ma old (Dickinson, Dodson, Gass & Rex 1969), was originally sampled in 1959 to investigate the magnitude of secular variation in low latitudes. The rocks were found to be extremely stably magnetized and characterized by extremely tight grouping of directions both between different samples and different sites. The completely unexpected result was that the mean declination was 7° west of north, while the mean inclination was exactly that of the diploe field, 24°, with a high precision, $\alpha_{95} = 2.7°$. The data are excellent from all respects and the deviation appears to be real. The largest source of undetected error could be in assuming that there has been no tectonic tilt since the eruption but the evidence of raised sea beaches suggests that this is a reasonable assumption, and even if small tectonic tilts ($< 6°$), known to occur in much older rocks along the coast, are assumed, these are generally southerly and would affect the inclination to a far greater extent than the declination. The possibilities appear to be: (1) that the average ambient magnetic field in which the rocks cooled was not an axial geocentric dipole field, (2) the secular variation cycle had an entirely different magnitude than our model, (3) the secular variation cycle was not adequately sampled, or (4) Aden has rotated relative to a geocentric dipole field along the Earth's present axis of rotation. Most palaeomagnetic evidence suggests that the Earth's average magnetic field is, for at least 95% of geological time, an axial geocentric dipole and the samples from Aden appear to cover at least a few thousand years as they include material from lavas and the plugs which displace them and also include normally and reversely magnetized rocks. This time range suggests that the observed consistency would not arise by sampling during either a period of predominantly non-dipole field or within a very brief part of a secular variation cycle. The tectonic rotation hypothesis would appear to be a more realistic interpretation, but it was thought necessary to obtain further samples from South Arabia in order to test this interpretation.

It was therefore very fortunate that the Royal Society should organize an expedition to study the volcanoes in this area. (I am very grateful for the assistance of Dr I. Gass in allowing a student to accompany this expedition to collect samples for palaeomagnetic studies.) Unfortunately most of the samples, from three volcanoes, including Aden, were of little value for normal palaeomagnetic studies as it was necessary to eliminate much of the data on grounds of instability or the effects of lightning (Tarling *et al.* 1967) so that not much reliability could be placed on the remaining material. However, the samples from the oldest of the volcanoes, Jebel Khariz, now dated as 10 Ma old (Dickinson *et al.* 1969), had a mean inclination of axial dipole direction but the declination was west of north by between 6 and 15°, depending on the method of selection of the more reliable data, and this deviation was statistically significant despite the much larger scatter.

Two separate volcanoes in Arabia, therefore, show a small but statistically significant deviation in declination which can be attributed to an anticlockwise rotation of some 6 or 7° about a point near the Dead Sea. Unfortunately the data are still inadequate to distinguish between this tectonic interpretation and the possibility of either a non axial geocentric dipole field or inadequate sampling of the full secular variation cycle. However, new results from Africa (table 1) do suggest that the Earth's magnetic field was not abnormal in this region at this time.

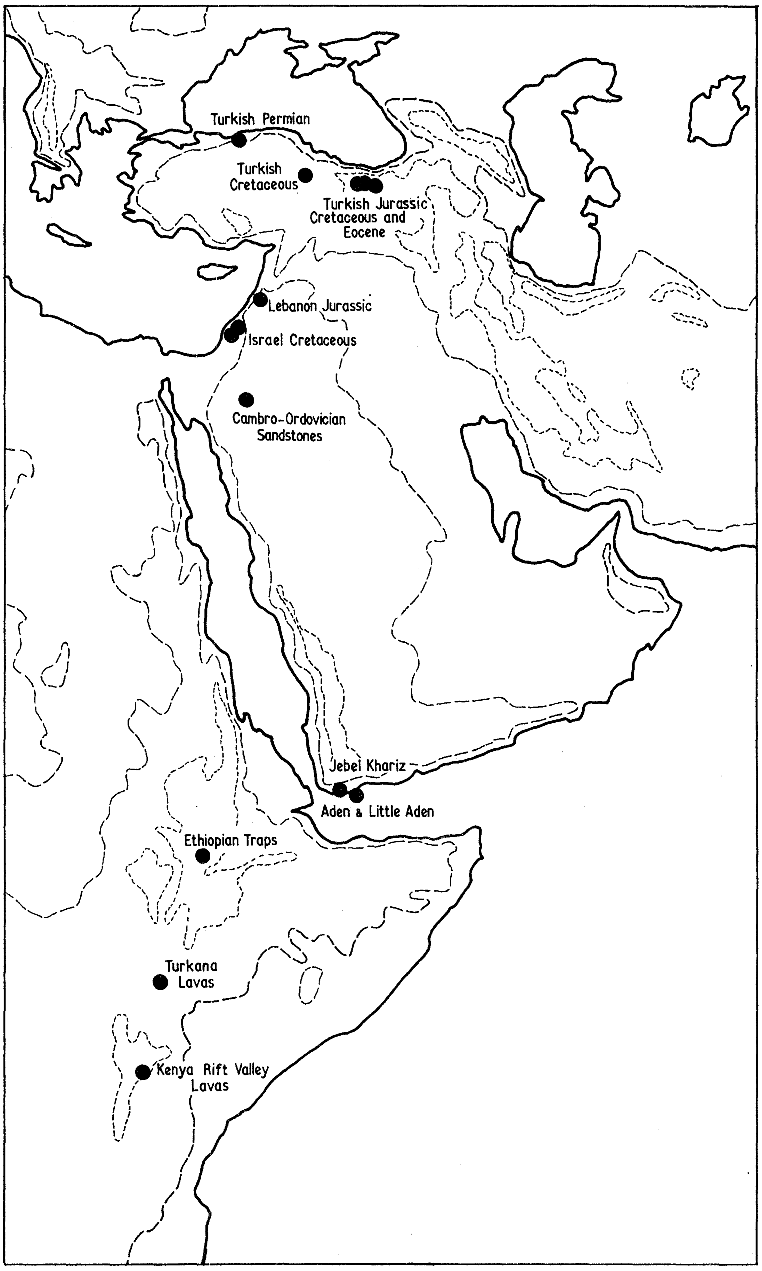

FIGURE 3. Palaeomagnetic sampling sites relative to the origin of the Red Sea and Gulf of Aden.

The results from the Eastern rift valley of Kenya are particularly important as parts of the Late Cenozoic lava succession in this area erupted contemporaneously with those of the Aden Volcanics. The African data shows a 'normal' scatter, i.e. consistent with our simplest model of secular variation, with mean directions which are not significantly different from that of an axial geocentric dipole field. Slightly older rocks from this area and other parts of Africa show a gradual movement of the average pole position with time in exactly the opposite direction to the divergence of the Aden poles (figure 4). The observations therefore seem to confirm the tectonic interpretation of the South Arabian data but much more detailed sampling must be undertaken in Arabia before all aspects relating to secular variation can be excluded from a tectonic interpretation.

Table 1. Palaeomagnetic data relating to the origin of the Gulf of Aden and Red Sea

| | locality | | no. of sites | $k$ | $\alpha_{95}$ | palaeomagnetic pole position | | reference |
|---|---|---|---|---|---|---|---|---|
| | °N | °E | | | | °N | °E | |
| Arabia | | | | | | | | |
| Jordan (Cambro-Ordovician) | 29.7 | 36.6 | — | 20 | 0.7 | 37 | −37 | Burek (1969, personal communication) |
| Aden (5 Ma) | 12.8 | 44.9 | 11 | 81 | 2.7 | 83 | −50 | Irving & Tarling (1961) |
| Jebel Khariz (10 Ma) | 12.7 | 44.1 | 17 | 25 | 0.4 | 81 | −63 | Tarling *et al.* (1967) |
| Africa | | | | | | | | |
| Rift Valley lavas (0 to 2.5 Ma) | 1(S) | 36.0 | 60 | — | 0.3 | 88 | +144 | Reilly (1970) |
| Rift Valley lavas (2.5 to 7 Ma) | 1(S) | 36.0 | 60 | — | 0.3 | 88 | +153.5 | |
| Rift Valley lavas (7 to 14 Ma) | 1(S) | 36.0 | 43 | — | 3.5 | 85 | +140 | |
| Turkana lavas (Miocene) | 3.0 | 35.0 | 62 | — | 2.5 | 85 | +163.5 | Raja (1968) |
| Ethiopian traps (Eocene–Oligocene) | 10.0 | 38.0 | 20 | — | 4.5 | 81 | +168 | Brock *et al.* (1970) |
| other data | | | | | | | | |
| Lebanon (Aptian) | 34.0 | 36.0 | 5 | — | 5.5 | 38 | −78 | Van Dongen *et al.* (1967) |
| Lebanon (U. Jurassic) | 34.0 | 36.0 | 6 | — | 3.0 | 1(S) | −60 | |
| Israel (U. Cretaceous) | — | — | — | — | — | 42 | −96 | Nur & Helsley (1967) |
| Israel (L. Cretaceous) | — | — | — | — | — | 60 | −106 | |
| Turkey (Eocene) | 39.2 | 39.5 | 4 | 33 | 16.0 | 65 | −66 | Van der Voo (1968) |
| Turkey (U. Cretaceous-Eocene) | 40.7 | 39.5 | 6 | 90 | 7.0 | 69 | −99 | |
| Turkey (Cretacous) | 40.6 | 37.0 | 2 | 8 | — | 51 | −64 | |
| Turkey (Cretaceous) | 40.7 | 39.5 | 6 | 35 | 11.0 | 61 | −82 | |
| Turkey (Jurassic) | 40.5 | 40.5 | 1 | — | — | 39 | −95 | |
| Turkey (Permian?) | 41.8 | 32.4 | 3 | — | 18.0 | 11 | −78 | Gregor & Zijderveld (1964) |

3.2. The tectonic unity of the Afro-Arabian block during the Phanerozoic is illustrated by the palaeomagnetic study of some red sandstones of Cambro-Ordovician age from the Arabian platform in southern Jordan (P. Burek 1969, personal communication). After experimental chemical demagnetization, Burek obtained pole positions which are consistent with those of the same age from Africa, confirming that Arabia has behaved as a tectonic entity with Africa at least until the formation of the Gulf of Aden. Results from Turkey are also significant in suggesting that Turkey, in the late Palaeozoic and Mesozoic has also been a tectonic entity with Africa (Gregor & Zijderveld 1964; Van der Voo 1968). These Turkish results must be regarded as preliminary observations as they are based on only a few sites and use moderate strength alternating magnetic field demagnetization—a technique which is open to criticism in rocks containing hematite. However, there is a marked consistency in these Turkish observations which is also found in observations in the Lebanon and Israel (Nur & Helsley 1967; Van Dongen, Van der Voo & Haven 1967). The opening of the Gulf of Aden and Red Sea must, therefore, be viewed against not only the evolution of the Zagros Mountains, but also in the relation between Arabia, Turkey and southeastern Europe.

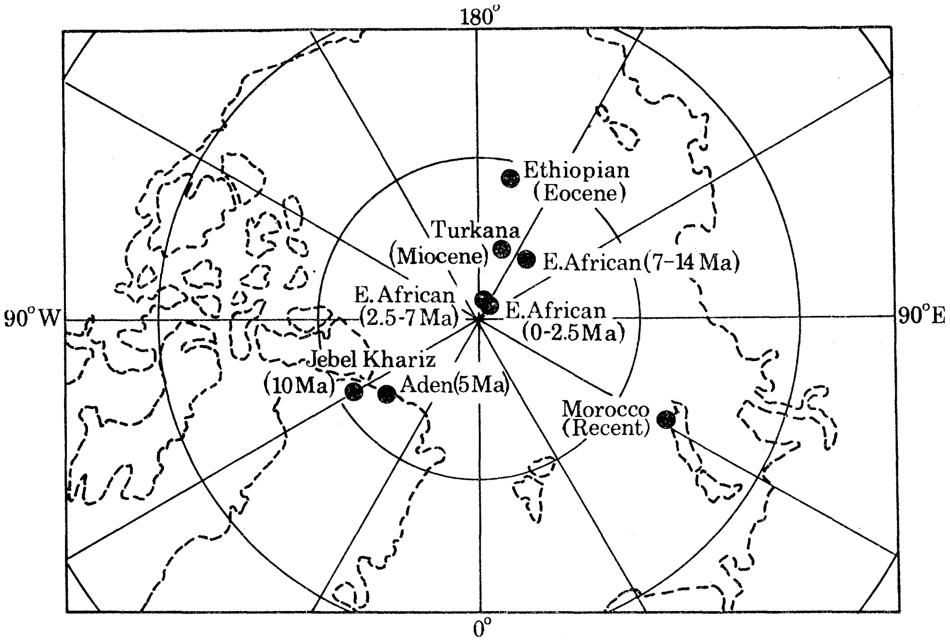

Figure 4. Palaeomagnetic pole positions from Africa and Arabia determined from rocks of Cenozoic age. The pole positions have been determined with varying statistical reliability—see table 1.

3.3. Finally, there is the suggestion (Girdler 1968; Brock 1968) that Africa has been rotating in a generally anticlockwise direction since at least the end of the Palaeozoic until some time in the Late Cenozoic, when its direction of movement was reversed. This suggestion appears to be confirmed to some extent by the new African data which indicates that this rotation ceased by the Oligocene, and it is tempting to assume that this cessation may be associated with the collision of Africa with Eurasia. This collision possibly affecting the sea floor spreading to the south of the continent and straining areas of pre-existing weakness, such as the Red Sea and Gulf of Aden, which then became sites of upwelling convection. However, all continents show some suggestion of a reversal in the direction of movement relative to the average geomagnetic pole during either the late Cretaceous or Tertiary, so such an effect in Africa could result from polar wandering which is independent of the movement of the individual continents.

## 4. Conclusions

The palaeomagnetic data from Africa and Arabia can be seen to be essential in setting the overall tectonic pattern of events against which the late Cenozoic evolution of this critical region must be judged. The consistency of the Pliocene–Pleistocene directions of magnetization in Arabia seems to confirm the tectonic interpretation of the results, despite the necessary adjunct to such an interpretation that secular variation must have been abnormally low for this period, and further implies that the motions which have given rise to this rotation of Arabia have mainly been active during the last 5 Ma. However, if the rotation took place in more than one stage, as seems probable, it may only be the final phase which can be detected palaeomagnetically if the previous phases involved small rotations about far distant axes as opposed to the latest phase which involves a rotation about an axis in the eastern Mediterranean area.

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