Geophysical evidence on the nature of magmas and intrusions associated with rift valleys.

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1. Introduction

Recently, there has been a revived interest in the study of rift valleys. This follows largely from a suggestion by Rothé (1954) that the East African Rift System might be in continuity with the mid-Atlantic Rift via the Gulf of Aden and mid-Indian Ocean Ridge. He noticed that the rift valleys seem to be associated with a narrow, continuous belt of shallow earthquakes and hence he proposed their continuity. In 1956, Ewing and Heezen, suggested that the rift system may be continuous on a world-wide scale. Oceanic surveys have tended to confirm these suggestions and it is now recognised that the world rift system follows closely the median lines of the oceans but occasionally intersects the continents in such places as the Gulfs of Aden and California. Because these regions provide connecting links between continental and oceanic rift valleys they are of special interest.

There is a marked contrast between the gravity anomalies over the East African Rift Valleys and those over the Red Sea and Gulf of Aden. Girdler (1958) suggested from a study of the gravity anomalies over the Red Sea that the deep, axial trough is underlain by an intrusive fracture zone filled with basic, igneous rocks. Subsequent geophysical investigations such as magnetic and seismic work (Drake, Girdler and Landisman, 1959) hase confirmed this suggestion and thrown more light on the nature and size of the intrusions. Further, the results show a similarity to those found by Ewing & Ewing (1959) for the mid-Atlantic Rift Valley and it seems possible that there is a close relationship between the world-wide tensional fracture zone and the nature of the rocks intruded.

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2. Evidence from gravity anomalies

The pioneering work of Bullard (1936) in Africa showed that the Bouguer gravity anomalies over the East African Rift Valleys are negative. This is in contrast to the large, positive Bouguer anomalies found over the axial, deep trough of the Red Sea (Figure 1). More recent and detailed gravity surveys over the East African Rift Valleys show that their origin is due to extension of the crust and

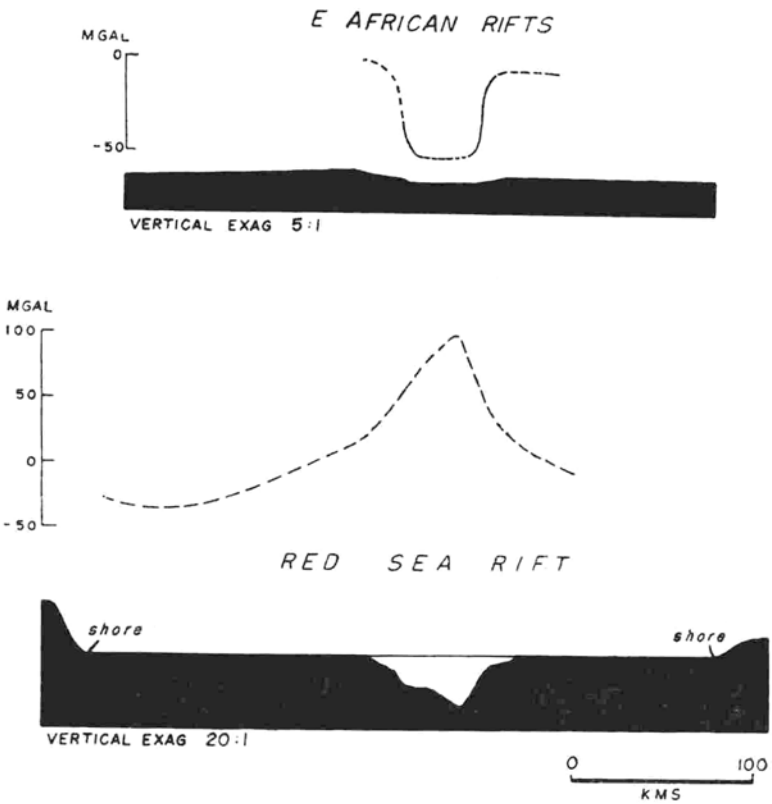

Fig. 1 - Bouguer gravity anomalies for the East African Rift Valleys and Red Sea.

a summary of this work has been given by Girdler (in press). The large, positive anomalies over the Red Sea indicate the presence of heavy material beneath the deep trough and it has been suggested (Girdler, 1958) that the tensional forces in the crust in this region were larger than those in East Africa and large enough to cause a separation of the continental crust and a resulting fracture zone to be partly filled with igneous material with density of the order of 3.0 g/cm^3. The suggested mechanism for the formation of the East African Rift Valleys and Red Sea depending on degree of extension is shown in Figure 2.

The igneous intrusions associated with the East African rifts are of a small scale compared with those under the axial trough of the Red Sea and are likely to be associated with the marginal rift faults.

3. Evidence from magnetic anomalies

The deep, axial trough of the Red Sea is associated with large magnetic anomalies (Drake, Girdler & Landisman, 1959 and T. D.

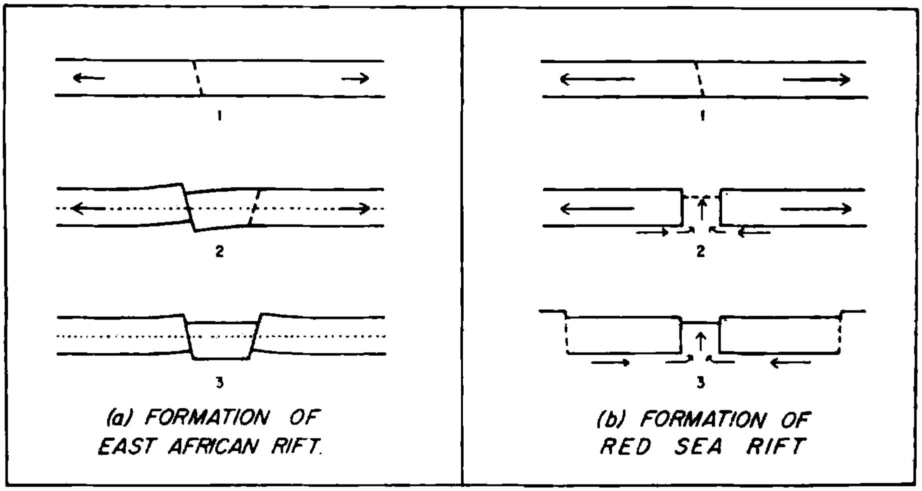

Fig. 2 - Formation of the East African and Red Sea rifts depending on differing degrees of extension in the crust. The centre of the Red Sea is underlain by an axial fracture zone partly filled with igneous material.

Allan, personal communication). An example of the total intensity magnetic anomalies is shown in Figure 3 and it is seen that there are a series of large, sharp anomalies over the axial trough which reach amplitudes of up to 1200 gamma. Using electronic computing techniques, the main features of the anomalies may be reproduced by assuming a series of longitudinal bodies beneath the centre of the

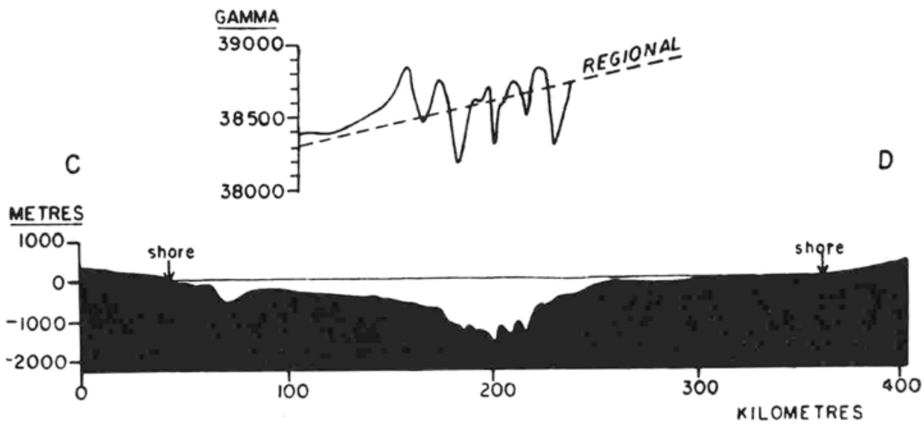

Fig. 3 - Total intensity magnetic anomalies across the Red Sea near latitude 18° N.

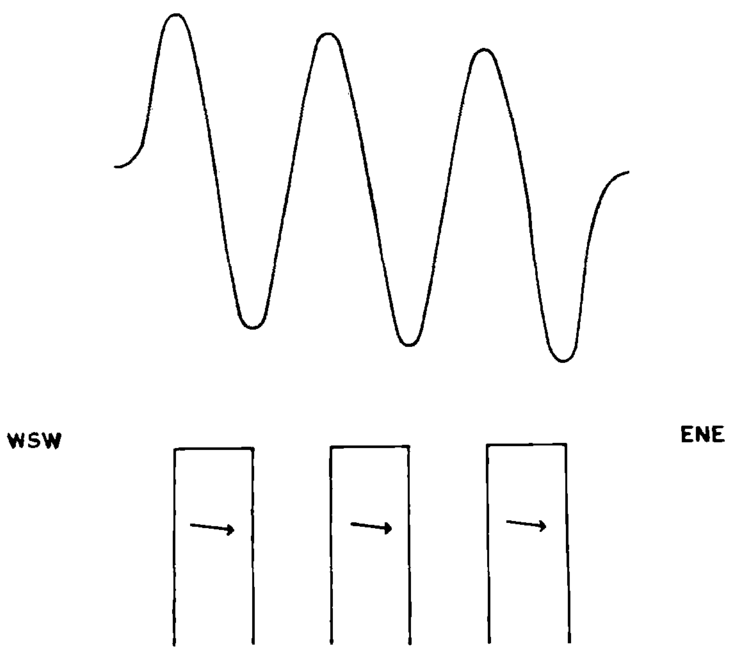

Fig. 4 - Computed total intensity magnetic anomalies for a series of axial dykes parallel to the Red Sea trend (N.N.W.) assuming direction of magnetization parallel to that of the Earth's present magnetic field.

Red Sea with a north north westerly strike (i. e. parallel to the Red Sea trend). A typical computed curve assuming total magnetization parallel to the present field for the region is shown in Figure 4. The bodies can have maximum widths of 8 to 10 kms and total intensities of magnetization of the order of 2×10^{-3} e.m.u./cm^3 are necessary to explain the amplitudes of the anomalies.

Over the Red Sea shelves the magnetic anomalies are small and the large anomalies over the centre provide a criterion for mapping the extent of the fracture zone. It is found that the fracture zone starts near the centre of the Sea at about 24° N. and gradually widens towards the south to reach widths of more than 60 km at latitude 16° N. The margins of this fracture zone are found to closely parallel the Red Sea shores. Hence, the areal distribution and amplitude of the magnetic anomalies confirm the interpretation that the deep, axial trough of the Red Sea is a tensional crack with a series of fissures filled with igneous material. Similar results have been obtained for the centre of the Gulf of Aden and a similar fracture zone filled with igneous material may be mapped (Figure 5).

So far, little magnetic survey work has been done over the rifts of the African continent but a vertical intensity survey by Gouin (1960) across the Ethiopian rift valley showed comparatively small anomalies. In contrast to the Red Sea, the largest anomalies are found near the margins of the rift and are likely to be due to volcanic material and small dykes associated with the rift faulting.

4. Seismic evidence

Some seismic refraction profiles have been obtained in the Red Sea (Drake, Girdler & Landisman, 1959) and these show that the structure beneath the axial, deep trough is completely different from that beneath the marginal shelves.

For the trough a layer with velocity 7.1 km/s was found at the shallow depth of 4 kms. This is considered to correspond to the high density, axial, intrusive material and is overlain by a layer with velocity 4 km/s and thickness 2 km which could correspond to a mixture of lava flows and sediment. There is a further overlying thin layer of low velocity sediments with velocity 2.5 km/s. Material of sub-« Moho » velocity (8.1 km/s) was not found.

For the shelves, material of velocity 5.8 km/.s. was found at a depth of 2.7 km. This is a velocity suitable for metamorphic, shield rocks and most likely corresponds to the downfaulted continental margins of the African-Arabian plateau. It is overlain by a series of sedimentary layers.

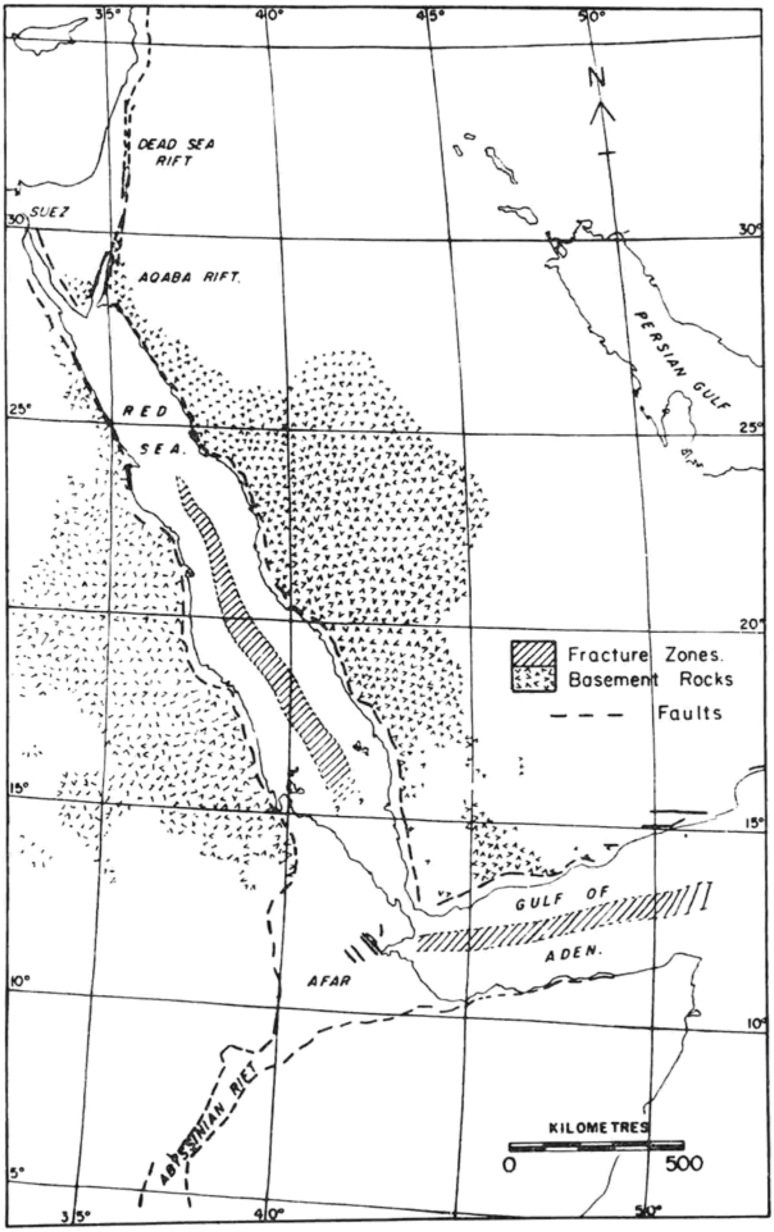

Fig. 5 - Map of the Red Sea area showing the region of very large magnetic anomalies which is interpreted as an axial fracture zone with a series of fissures filled with intrusive rocks.

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The seismic results therefore support the interpretation from the gravity and magnetic anomalies that the deep, axial trough is underlain by a fracture zone filled with basic, igneous rocks and is of entirely different structure from the wide, shallow water shelves.

5. Possible nature of the Red Sea intrusive zone

It is clear from the nature of the magnetic anomalies over the Red Sea (Figures 3 and 4) that the deep, axial trough is underlain by a series of parallel dykes or fissures. These partly fill a wide tensional crack in the continental crust, the extent of which is shown in Figure 5. The evidence given in Sections 2 to 4 suggests that the zone is of tensional origin and the systematic widening of the zone

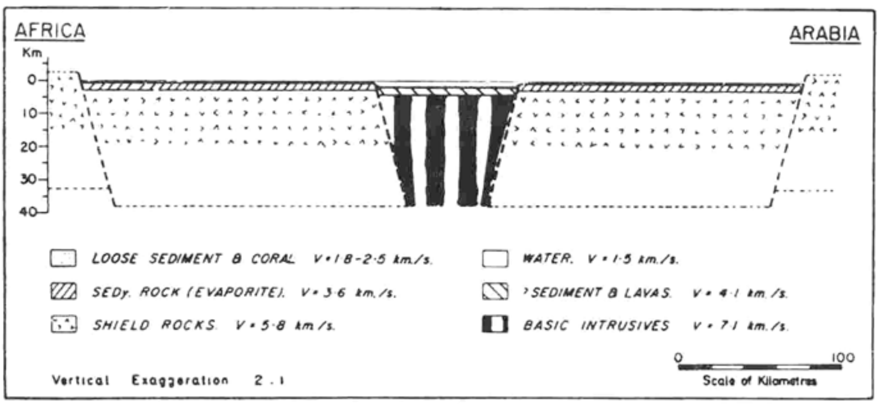

Fig. 6 - Structural section across the Red Sea near latitude 16° N. The section provides the simplest interpretation of the gravity, magnetic and seismic results.

towards the south of the Red Sea and to the east of the Gulf of Aden suggests that this is associated with a rotational movement of Arabia relative to Africa. The gravity, magnetic and seismic results enable a simplified section to be constructed across the Red Sea and such a section for latitude 16° N. is shown in Figure 6. This is a diagrammatic representation of the geophysical data and intended to give a broad picture of the structure; the sedimentary layers may not be of uniform thickness and the faults may be a series of step faults.

The seismic refraction results show that the depth of the main intrusions is approximately 2 km beneath the sea floor. It is of interest to speculate on the nature of this zone. Any postulation as to the type of rocks must satisfy the following constants — density of the order of 3.0 g/cm^3, total magnetic intensity of the order of 2×10^{-3} $e.m.u./cm^3$ and seismic longitudinal wave velocity of 7.1 km/s Both density and magnetic intensity are suitable for some kind of basaltic rock and the seismic velocity of 7.1 km/s is intermediate between the 6.7 km/s for the oceanic « basaltic » layer and the 8.1 km/s for sub-Moho material. The slightly high constants lead to the speculation that the intrusive zone may be « olivine basalt » in composition. The assumption of some kind of basalt is reasonable in the light of geological evidence as basaltic volcanoes exist in the southern part of the Red Sea and basaltic volcanic ash and glass have been dredged from the sea bottom. There seems a strong possibility that the 7.1 km/s layer is « olivine basaltic » and this is overlain by a mixed zone of basaltic lavas and sediments giving a velocity of 4 km/s.

It is of further interest to consider the origin of the « Basaltic » material filling the tensional crack. The volume of material is very large, for example, the cross sectional area of the fracture zone at latitude 16° N. is at least 60×30 km and one immediately suspects that such a large volume of material must come from « Moho » depths. In this case, it is seen that all the constants are too low for sub-« Moho » material (density, 3.3 g/cm^3, seismic P velocity, 8.1 km/s) and there must therefore have been some change either of phase or composition associated with the changing pressure/temperature conditions accompanying the formation of the tensional crack. One such possibility is the eclogite $\rightleftharpoons$ basalt phase change proposed for the « Moho » discontinuity. A tensional zone in the crust would provide a region for the low pressure phase and hence the intruded material would be of basaltic composition rather than eclogite. Steady-state arguments (Bullard & Griggs, 1961 and Wetherill, 1961) and the results of experimental petrology (Yoder & Tilley, 1961) show that the pressure/temperature conditions are suitable for this phase change for the « Moho » under the continents but not for the « Moho » under the oceans. Such a phase change could therefore explain the nature of the material associated with the Red Sea and other continental fracture zones.

6. Nature of the oceanic rift valleys

The Gulf of Aden and Red Sea is one region where the world-wide oceanic rift system intersects a continental area. Another such region is the Gulf of California where the structure in the southern part is very similar to the southern part of the Red Sea. For example, the gravity anomalies indicate that the deep water is underlain by heavy rocks and a 7.5 km/s layer has been found at shallow depths.

These two regions are in continuity with the oceanic rift system which in general follows closely the median lines of the oceans. The Gulf of Aden is continued by the Carlsberg Ridge, the mid-Indian Ocean Ridge, the Atlantic-Antarctic Ridge and the mid-Atlantic Ridge. Many studies of the mid-Atlantic Ridge have been made by Ewing and his associates and the geophysical results are remarkably similar to those for the Red Sea. There is a maximum in the Bouguer anomaly curve over the axial rift fracture; there is a very large magnetic anomaly of up to 2000 gammas and the seismic results indicate the presence of basaltic volcanic rock at a depth of 2 km and a basaltic intrusive zone (velocity 7.2 km/s) at a depth of 5.4 km (Ewing & Ewing, 1959).

In addition to the similarity of the geophysical data, there seems to be a similarity in the petrological character of the rocks dredged from the rift zone. Samples from the Carlsberg Ridge have been described by Wiseman and Sewell (1937) and from the Mid-Atlantic Ridge by Shand (1949) and Hess (1954). The rocks are gabbros and basalts with or without olivine and serpentine and also some peridotite xenoliths. It appears that these rock types may be characteristic of the world-wide rift tensional fracture zone.

If the eclogite $\rightleftharpoons$ basalt phase change is used to explain the basaltic (7.1 km/s) rocks associated with the oceanic tensional fracture zone the material must come from a considerable depth beneath the « Moho » as the pressures and temperatures at the oceanic « Moho » are not high enough for eclogite to exist (Yoder, personal discussion). A deeper origin is plausible as the earthquake foci associated with the oceanic rifts reach depths of 60 km indicating that the fracture zone may extend to this depth. The eclogite $\rightleftharpoons$ basalt phase change is a convenient way of explaining the nature of the rocks associated with the world-wide fracture zone as the fracture zone is filled with material with constants appropriate for the low pressure/low temperature phase. However, there is no direct evidence for the phase change and so far eclogites have not been found associated with the world rift system. Peridotites and dunites have often been recorded and the second possibility of some kind of compositional change from peridotite to basalt may be an equally acceptable explanation.

The question remains as to the origin of the tensional forces associated with the world-wide rift system. Hess (1954) supposed that the mid-Atlantic Ridge and rift are due to a rising convection current. More recently, Runcorn (1962) has used the idea of a world-wide mantle convection pattern to explain continental drift and the present position of the continents whilst Girdler (1962) has shown that the same convection pattern explains very well the location of the world-wide rift zone. It is possible that the world rift system locates the position of rising mantle convection currents with associated high heat-flow. The diverging currents cause a tensional fracture zone which becomes partly filled with intrusive « Basaltic » rocks.

7. Acknowledgments

I am greatly indebted to various members of the Department of Geodesy & Geophysics, University of Cambridge and the Lamont Geological Observatory, Columbia University, New York for helpful discussions and especially to Drs T. D. Allan and C. L. Drake. This paper was prepared during my stay at the Department of Geology, Kyoto University, Japan and I extend my sincere thanks to Professor Z. Hatsuda, Professor N. Kawai and Dr S. Kume for their help and hospitality.

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