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# The Owen Fracture Zone and the Northern End of the Carlsberg Ridge

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# The Owen fracture zone and the northern end of the Carlsberg Ridge

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Examination of the shape of the earthquake epicentre belt near Socotra led to the suggestion that a major fracture displaces the axis of the mid-ocean ridge in that area (Matthews 1963). Subsequent surveys have confirmed the existence of a fracture zone which extends 1500 miles from the coast near Karachi southwestwards to the middle of the Somali Basin. Linear ridges and troughs in the zone are associated with negative gravity anomalies but not with magnetic anomalies. Where the fracture zone crosses the line of the Carlsberg Ridge a sinuous trough is developed: south of this feature a characteristic pattern of magnetic anomalies is associated with the volcanic structures of the mid-ocean ridge, north of it a line of large non-magnetic seamounts has been found. It is concluded that the structure underlying the Owen fracture zone is a system of parallel transcurrent faults affecting the ocean floor only, at which the axis of the mid-ocean ridge suffers a net right lateral displacement of 170 mi.

## Introduction

In a paper summarizing the geological results of the John Murray Expedition 1933–34 Wiseman & Seymour Sewell (1937) suggested that the seismically active crest of the Carlsberg Ridge might be traced through the Gulf of Aden to join the seismically active rift valley in Ethiopia. Since that time Heezen and many other authors (see, for example, Heezen & Menard 1963) have repeatedly stressed the close resemblance between topographic profiles across the East African rift valleys and sounding profiles across the median valleys of the Mid-Atlantic and Carlsberg Ridges, and Girdler & Peter (1960) have suggested that the deep trough and associated magnetic anomaly which extend eastwards into the Gulf of Tadjura (Ethiopia) represent the landward end of a mid-ocean ridge rift system. Geomorphological studies in East Africa by Pulfrey and others (Saggerson & Baker 1965) indicate that the dominant structure in East Africa is a great swell, fractured along its crest and surmounted by numerous volcanoes. This swell, more than 1 km high and 1000 km wide, is very similar in scale to the Carlsberg Ridge, and the structural analogy is strengthened by the fact that where the swell approaches the Gulf of Aden, in the highlands of Ethiopia, it is covered by more than 1 km thickness of post-Upper Eocene plateau basalts (Mohr 1964; Grasty, Miller & Mohr 1964).

The continuity of the earthquake epicentre belt which marks the crests of the Mid-Atlantic and the Carlsberg Ridges with that following the East African rift valley system was clearly demonstrated by Rothe (1954). Epicentres in the northwest Indian Ocean are shown in figure 1 in which are plotted shocks recorded by the International Seismological Summary and the U.S. Coast and Geodetic Survey up until Christmas 1964. Recomputation of the positions of these epicentres by Sykes & Landisman (1964) has clarified but not appreciably modified the pattern. It will be seen that the epicentre belt runs *north* of Socotra, suggesting that the median structure of the mid-ocean ridge does likewise. However, in 1961, this supposition appeared to be in conflict with the published bathymetric charts of the International Hydrographic Bureau which suggested, following Farquarson (1936), that the Carlsberg Ridge meets the continental margin *south* of Socotra if it does so at all. New data obtained by H.M.S. *Owen* (Admiralty 1963) provided a solution to this conflict of evidence (Matthews 1963). The line of epicentres (figure 1) follows the crest of the Carlsberg Ridge northwards as far as 10° 30′ N, 57° E where it turns sharply to a direction north-northeast, continuing in this direction for about 150 mi.

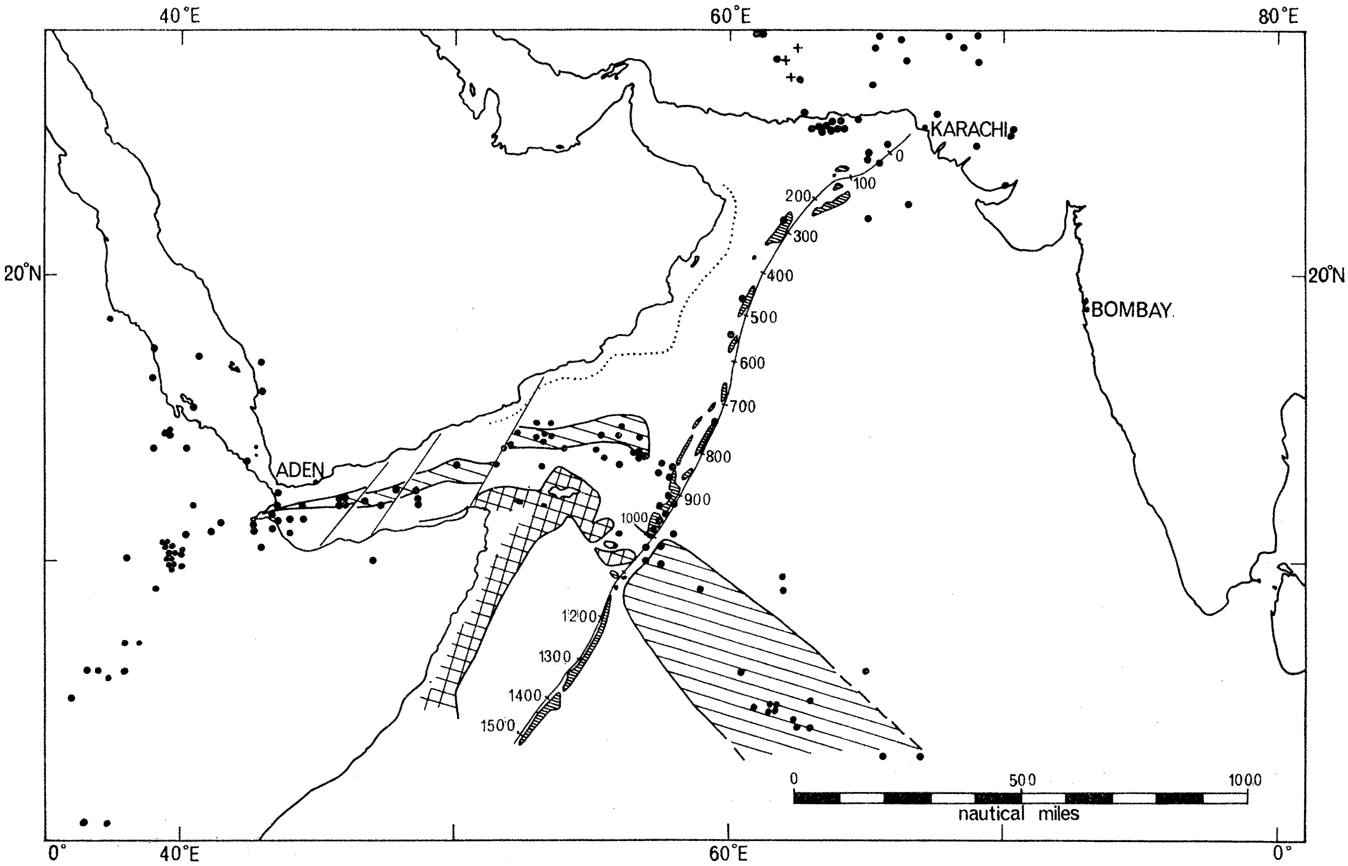


FIGURE 1. Physiographic sketch map showing earthquake epicentres (dots) up to Christmas 1964. Data from I.S.S. and U.S.C.G.S. Preliminary epicentre determinations. All submarine shocks are shallow. Shaded province, magnetic seamounts of the Carlsberg Ridge and their continuation north of the Owen fracture zone. Cross-hatched area, non-magnetic seamounts and continental margin near Socotra. Close shading indicates prominent topographic features along the Owen fracture zone picked out in figure 3.

before abruptly resuming its northwestward trend. A few scattered shocks continue the north-northeasterly trend towards the Murray Ridge off the mouth of the Gulf of Oman. Sounding profiles revealed an escarpment alined with the north-northeasterly trending part of the epicentre belt, and this feature was interpreted as a fault scarp associated with a right-lateral tear fault displacing the axis of the Carlsberg Ridge by 170 mi. A more detailed survey designed to examine the feature was carried out by H.M.S. *Owen* early in 1963 when Mr B. C. Browne was Senior Scientist on board. The results of this work are presented in this paper. Figure 2 shows tracks made by British ships in the area under discussion during the International Indian Ocean Expedition. Underway observations made along these tracks have been presented in the following reports: Admiralty (1963, 1965*a*, *b*), Department of Geophysics, Cambridge Internal Report (1964). These contain the data on which this paper is based.

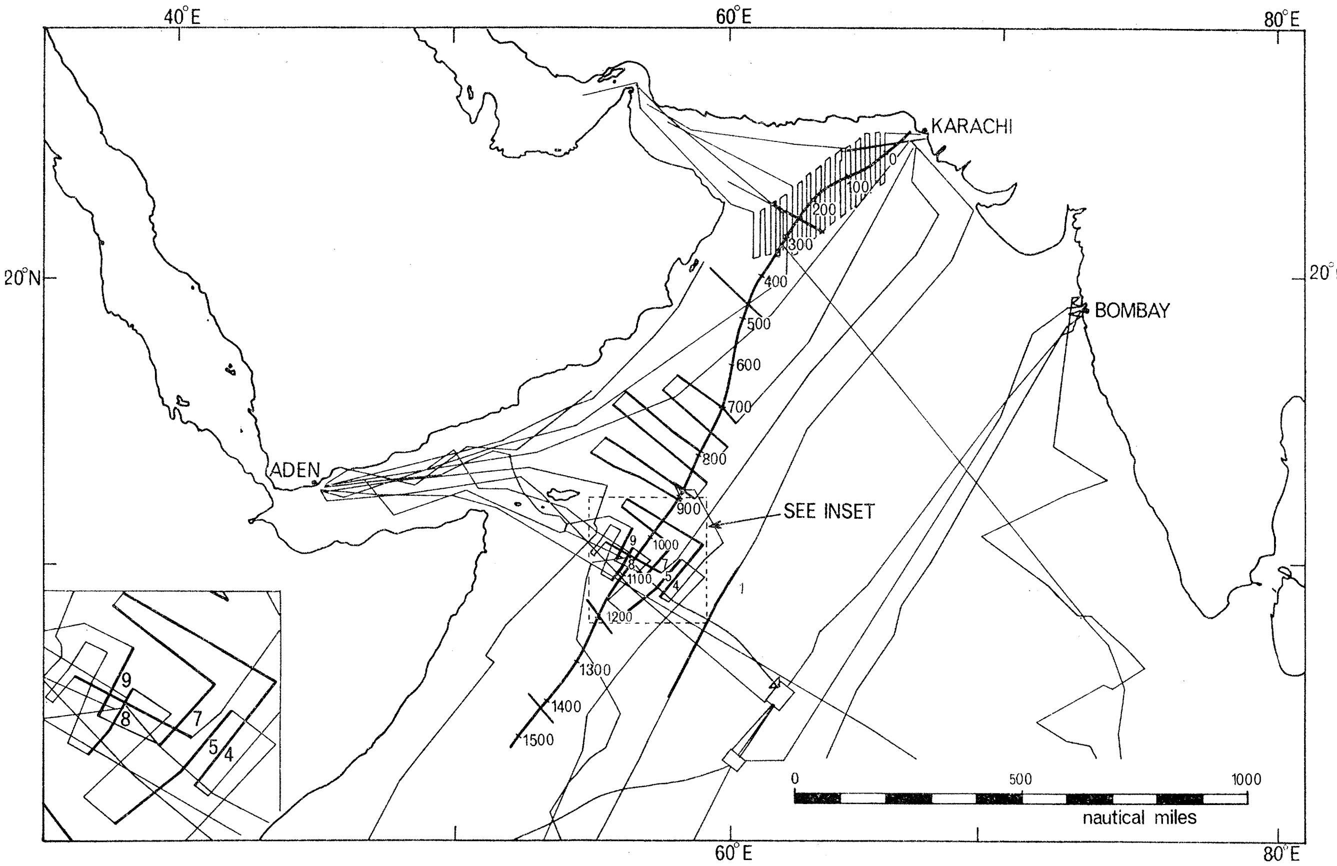


FIGURE 2. Tracks of British ships during the International Indian Ocean Expedition are shown by faint lines. Bolder sections of track indicate the positions of profiles shown in figures 4 to 7. The heavy line marks the Owen fracture zone (see figure 3). The figures along it give distances in hundreds of nautical miles from an arbitrary point near Karachi.

## BATHYMETRY

Soundings taken by H.M. Ships *Owen* and *Dalrymple*, by R.R.S. *Discovery* and by other ships of the International Expedition have been collected on a scale of 1:1 000 000 by the Admiralty Hydrographic Department, and bathymetric contour charts have been prepared from these data by Dr A. S. Laughton at the National Institute of Oceanography. I am indebted to him for permission to reproduce a simplified version of some of these charts (figure 3). The soundings presently available suggest that an almost continuous line of features, escarpments, elongated ridges, and troughs, extends from the continental shelf near Karachi (West Pakistan) southwestwards for about 1500 mi. The whole system has been named the 'Owen fracture zone'. The northeastern part has been surveyed in some detail by H.M.S. *Dalrymple* (Barker, p. 187 below). From the southern limit of this survey at about mile 350 (figure 3) southwestwards to the appararent end of the ridge near mile 1500 (3° 30′ N, 52° 20′ E) fifty-two lines of soundings cross the feature,

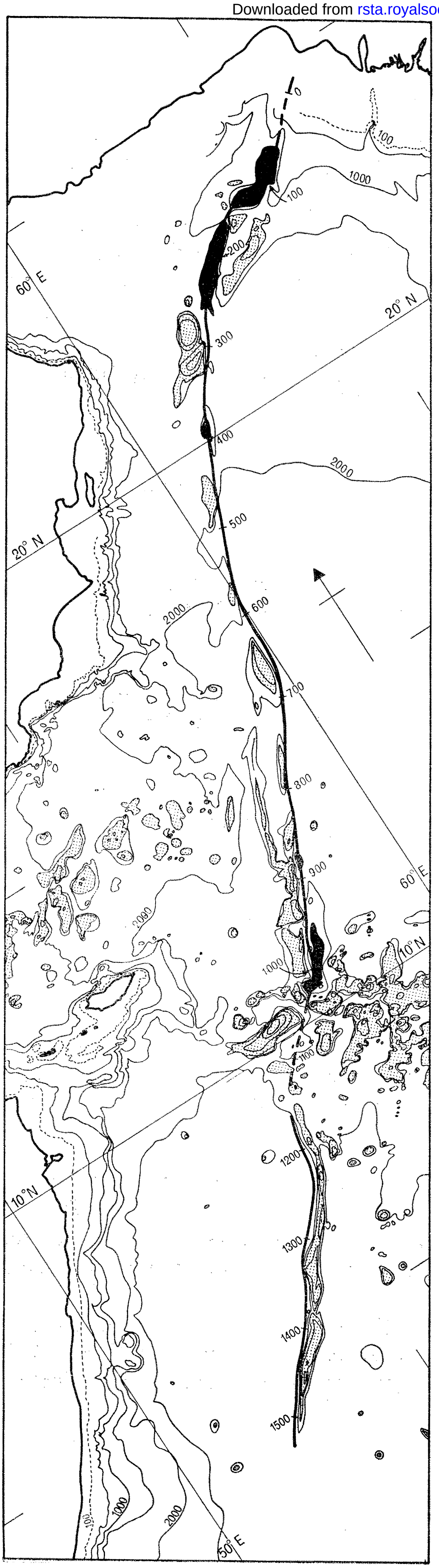


FIGURE 3. Bathymetry of the Owen fracture zone. Contours at 500 fm intervals plus 100 fm. contour (*dashed*). Simplified from A. S. Laughton's 1 : 1 000 000 contour charts by omission of intermediate contours. Stipple indicates hills rising more than 500 fm. above their surroundings, solid black shows troughs more than 200 fm deeper than adjacent abyssal plain. Bold line shows assumed position of the fracture zone. Numbers along it give distances from an arbitrary position near Karachi.



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distributed along 1150 n.mi. of its length. The crossings are not uniformly distributed; fifteen occur near the northern end of the Carlsberg Ridge between mi. 1000 and mi. 1100 (figure 3), and the longest gap between crossings is 90 mi. (near mi. 500). It seems unlikely that no gaps occur in this long line of topographic features but none have yet been found; all the crossings available at the time of writing show some significant topographic feature, and a zigzag track followed by R.V. *Chain* in 1964 (Bunce, Bowin & Chase,

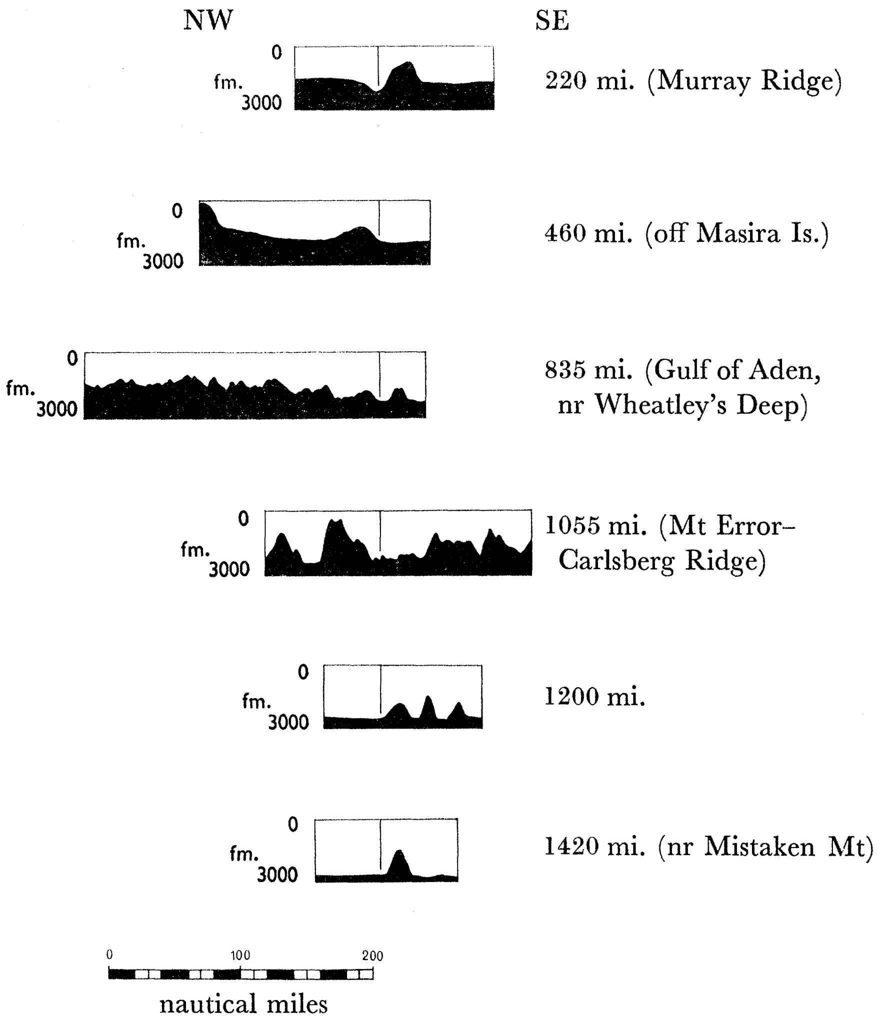


FIGURE 4. Bathymetric profiles across the Owen fracture zone. Numbers give distance of crossing measured in nautical miles along the fracture zone from an arbitrary point near Karachi and serve to locate the profiles on figures 2 and 3.

p. 218 below) effectively confirmed the continuity of the system (here developed as a single narrow ridge) between mi. 1330 and the end. Further sounding profiles across the fracture zone east of the Carlsberg Ridge, between mi. 850 and the *Dalrymple* survey at mi. 350, may be expected to demonstrate that some of the features drawn as discontinuous ridges in figure 3 are actually continuous.

The southern limit of the system, in the Somali Basin, cannot be defined at present: a line of soundings which crosses the line of the fracture zone near 2° 40′ N, 51° 40′ E (about 70 mi. beyond the last crossing of the ridge near mi. 1500) showed no distinctive



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topographic feature. Sub-bottom reflexion profiles obtained by R.V. *Chain* and *Vema* suggest that the northern part of the Somali Basin, as far south as about 4° N, is floored by flat-lying evenly thin-bedded sediments which may be turbidites ponded between the continental slope, the ridge developed along the fracture zone and an unknown barrier

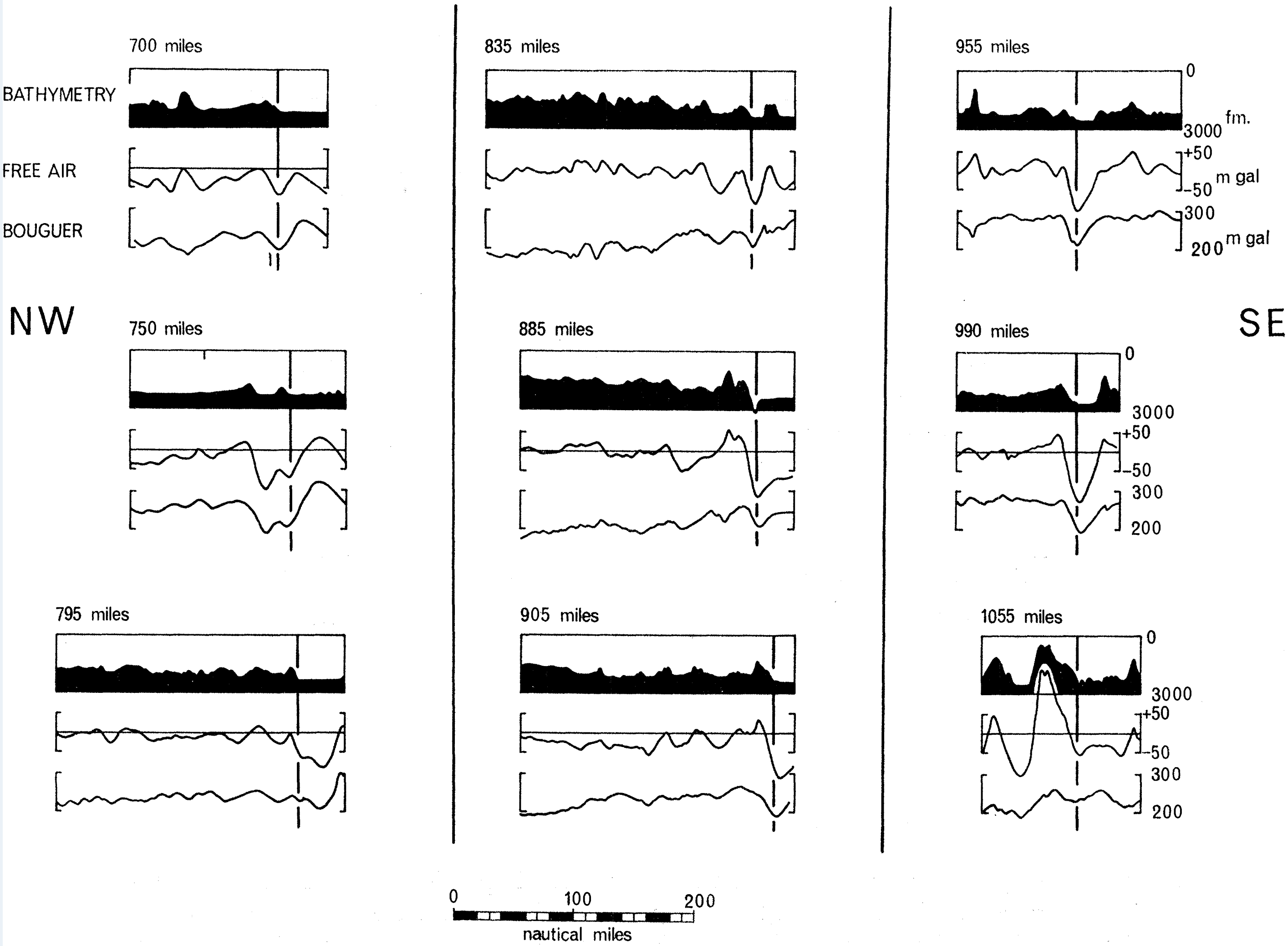


FIGURE 5. Topography and gravity profiles perpendicular to the Owen fracture zone. 'Two-dimensional' Bouguer anomalies were computed for a rock density of 2·67 g/cm³. Numbers give distance of crossing measured in nautical miles along the fracture zone from an arbitrary point near Karachi (see figures 2 and 3).

extending westwards towards the African coast from a point near the southern end of the ridge. Reflexion profiles taken south and east of the ridge, on the other side of the barrier, show no ponded sediments. In this area the main reflector is rough, like the surface of buried abyssal hills (E. T. Bunce & J. B. Hersey, verbal communication).

Selected bathymetric profiles across the fracture zone are shown in figure 4. Additional profiles are shown in figures 5 and 6. The profiles in figure 4 were chosen to illustrate the variety of elongated topographic features developed along the system: a single symmetrical ridge near the southern end, a pair of subparallel ridges, or an asymmetric ridge and trough farther north. A similar diversity of topographic forms has been described by Menard (1964, p. 43) from the well-known fracture zones in the eastern Pacific.

It will be seen from figures 1 and 3 that a chain of large seamounts prolongs the line of the Carlsberg Ridge north of the fracture zone as far as Socotra. A slightly sinuous trough of deep water cuts right across the ridge along the line of the fracture zone, separating this

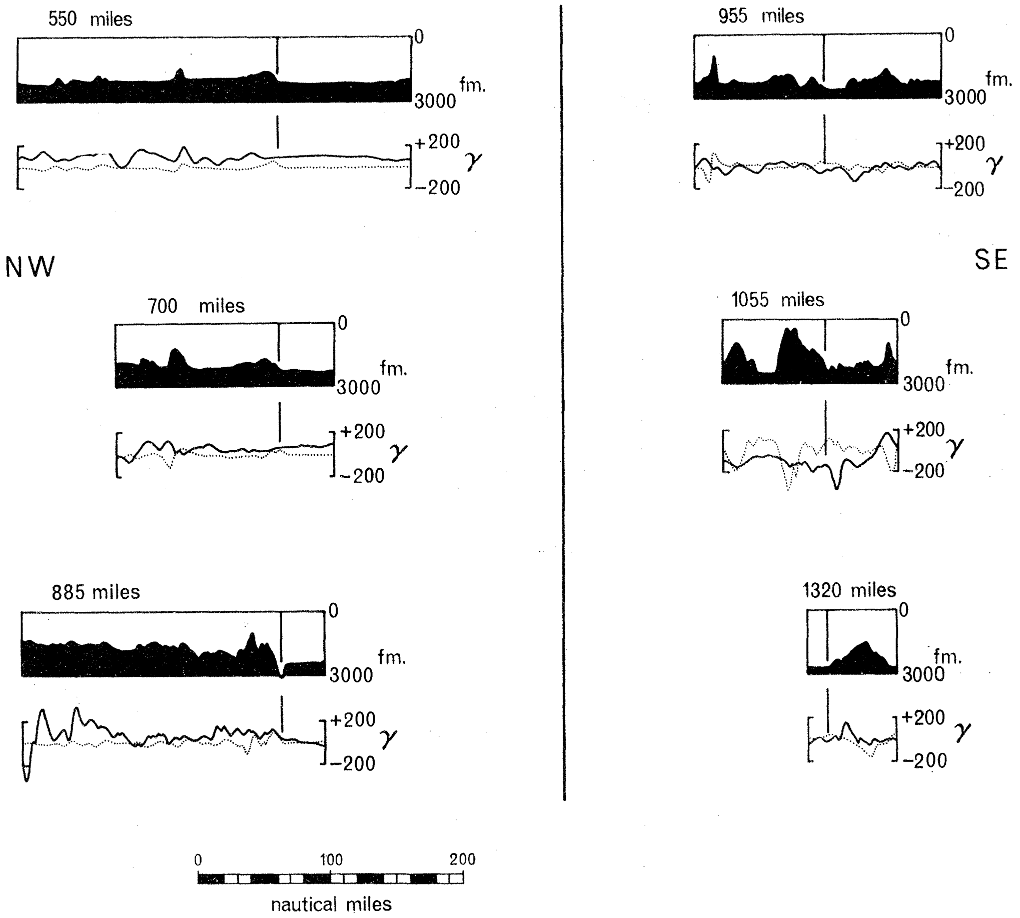


Figure 6. Topography and magnetic total intensity anomaly profiles perpendicular to the Owen fracture zone. Solid line observed anomaly. Dotted line, calculated anomaly assuming two-dimensional model (see text). Numbers give distance of crossing measured in nautical miles from an arbitrary point near Karachi (see figures 2 and 3).

chain of seamounts from the Carlsberg Ridge to the south. Evidence from magnetic profiles, discussed later in this paper, shows that the large rounded seamounts of the chain north of the fracture zone are different in geological character from rough peaks of the Carlsberg Ridge.

A single line has been drawn on the basis of the bathymetric data (figure 3) to represent the mean position of the fracture zone. Clearly this should not be thought of as a single fault feature, but it is useful to lay down an arbitrary line on the map for reference purposes.

## Gravity observations

Continuous gravity profiles were obtained with an Askania sea-gravimeter aboard H.M.S. *Owen* (Admiralty 1963, 1965*a*). Results obtained along tracks which cross the Owen fracture zone almost perpendicularly are shown in figure 5. It is clear that a substantial negative free air anomaly occurs in the vicinity of the fracture zone. Bouguer anomaly profiles have been calculated on the assumption that the topography is infinitely extended perpendicularly to the track, an assumption which appears to be adequate in this case. The density of sea water was taken as 1·03 g/cm$^3$. Densities of 2·4, 2·67, and 2·8 were tried for the topography but the effect on the profiles of these alterations was negligible. Since the magnetic results considered in the next section suggest that basic igneous rocks do not form a large part of the rocks exposed in the fracture zone this range of densities covers the main possibilities. Bouguer anomalies calculated for a rock density of 2·67 g/cm$^3$ are shown in the figure. There is no change in the general level of the anomaly (and no characteristic change in water depth) at the fracture zone, which indicates that the density distribution in the crustal and subcrustal rocks is not grossly different on opposite sides of the feature. All the profiles except the one at mi. 885 show a negative Bouguer anomaly of about 40 mgal ($\pm$15 mgal) at the fracture zone. This might be interpreted in terms of sediment-filled troughs developed along the fracture zone. Assuming a density contrast of about 0·7 g/cm$^3$ ($\pm$0·3 g/cm$^3$) between the hard rocks and the soft sedimentary infilling, the troughs would have depths of about 800 fm. ($1\frac{1}{2}$ km). Several flat-floored troughs of a few hundred fathoms depth do occur along the fracture zone (figure 3) but the deepest and most spectacular trough is the Wheatley Deep, a short elongated trench at 12° 40′ N, 58° 15′ E (mi. 885, figure 3). The trench is about 7 mi. wide and 20 mi. long at the 2500 fm. contour, and on its south side it abuts directly against the very gently undulating India abyssal plain at a depth of 2450 fm. The trough has a V-section, narrowing to a flat floor about half a mile wide at a depth more than 700 fm. below the plain. It is significant that this trench, which is clearly young and contains little sediment, is associated with the smallest of the recorded Bouguer anomalies, about 20 mgal. This suggests that the anomalies observed at other crossings of the fracture zone can be explained in terms of buried topography.

Reference to figure 1 will show that a few epicentres occur in the Arabian Sea along the line of the fracture zone between the mouth of the Gulf of Aden and Karachi. This fact, taken with the bathymetric and gravity data, justifies the conclusion that a still partially active geological structure extends more or less continuously for 1500 mi. southwestwards from near Karachi. Magnetic profiles discussed in the next section indicate that this structure is not an igneous one and suggest that it is probably a fault.

## Magnetic observations

A selection of the thirteen available profiles showing total field magnetic anomalies observed on tracks which cross the fracture zone is presented in figure 6. All the profiles illustrated were taken by H.M.S. *Owen* except the last which was taken by R.V. *Chain* and is reproduced by permission. It is clear from the figure that no characteristic magnetic anomaly occurs at the fracture zone. All the available observed profiles have been projected on to lines which cross the fracture zone at right angles and then compared with 'two-dimensional' anomaly profiles calculated on the assumption that the magnetized topography can be represented by prisms extending to infinity in a direction parallel to the fracture zone. This procedure is justified except in the case of the first and the last profiles shown in the figure which cross the structure very obliquely. For the calculation the prisms were given an intensity of magnetization of $5 \times 10^{-3}$ e.m.u./cm$^3$ in the direction of the dipole field of the earth. The results of this comparison indicate that north of mi. 800, and south of mi. 1300, the elongate topographic features in the fracture zone are weakly magnetized with intensities less than $1 \times 10^{-3}$ e.m.u./cm$^3$. It follows that strongly magnetized basalt lavas do not figure prominently amongst the rocks which make up the elongated ridges associated with the fracture zone.

For qualitative interpretation all the available magnetic profiles must be considered in their correct geographical relationships to one another and to the underlying sea-floor topography. To facilitate this we have made a model on which the anomaly profiles, cut out of thin polystyrene sheet, have been stuck on to Perspex sheets and placed over the 1:1 000 000 bathymetric contour charts prepared by Dr Laughton. The paragraphs which follow present conclusions drawn from a study of this model.

Three profiles shown in figure 6 merit further discussion: those which cross the fracture zone at 885, 955 and 1055 mi. The first, at 885 mi., runs close to the earthquake epicentre belt north of the fracture zone (cf. figures 1 and 2). The profile crosses the Wheatley Deep. Magnetic anomalies along the northern part of this profile begin abruptly at the fracture zone. At the northwest end of the profile the ship altered course to southwest (as shown in figure 2) and the character of the magnetic record altered, the anomalies becoming narrower suggesting that the causative igneous bodies are elongated northwest–southeast parallel to the epicentre belt. Zigzag tracks made over the Wheatley Deep near the southern end of the profile suggest that there may be a large negative magnetic anomaly situated near 13° N, 58° E just off the line of the illustrated profile, and another large negative anomaly can be seen in figure 6 at the northern end of the profile. In this magnetic latitude the median structure of the mid-ocean ridge is associated with a large negative magnetic anomaly (Vine & Matthews 1963; see also figure 7, this paper). These facts taken together are interpreted to mean that the north-northwesterly trending branch of the epicentre belt indicates the extension of the median structure of the Carlsberg Ridge north of the Owen fracture zone, marked in this region by the characteristic magnetic anomaly but not by characteristic topography. This point, which is crucial to discussion of the Owen fracture zone, requires confirmation at sea; it is hoped that magnetic field measurements will be made during 1965 by R.V. *Meteor* along tracks transverse to this part of the epicentre belt (Professor Dr E. Seibold, personal communication).

If the foregoing hypothesis is correct the second profile, at mi. 955, is significant because it is situated over the southwest flank of the mid-ocean ridge north of the fracture zone, and over the northeast flank of the ridge south of the fracture.

The profile at 1055 mi. runs along the epicentre belt on the southeastern side of the fracture zone. Immediately north of the fracture it crosses a very large seamount, Mount Error, which rises to a depth less than 300 fm. below sea level. This seamount extends more than 60 mi. at the 1500 fm. level in an east–west direction, oblique to the fracture zone.

A detailed survey was made of its crest, and seismic refraction profiles, bottom photographs and dredged rocks were obtained on it. The results (unpublished) show conclusively that Mount Error is quite unlike the volcanic seamounts of the Carlsberg Ridge.

The abrupt change in structure which occurs at the fracture zone in this area (around mi. 1055) is further illustrated by a selection of profiles across the northern end of the Carlsberg Ridge shown in figure 7. These profiles are perpendicular to the Carlsberg Ridge, parallel to the Owen fracture zone. Numbers 1 to 7 show the characteristic median

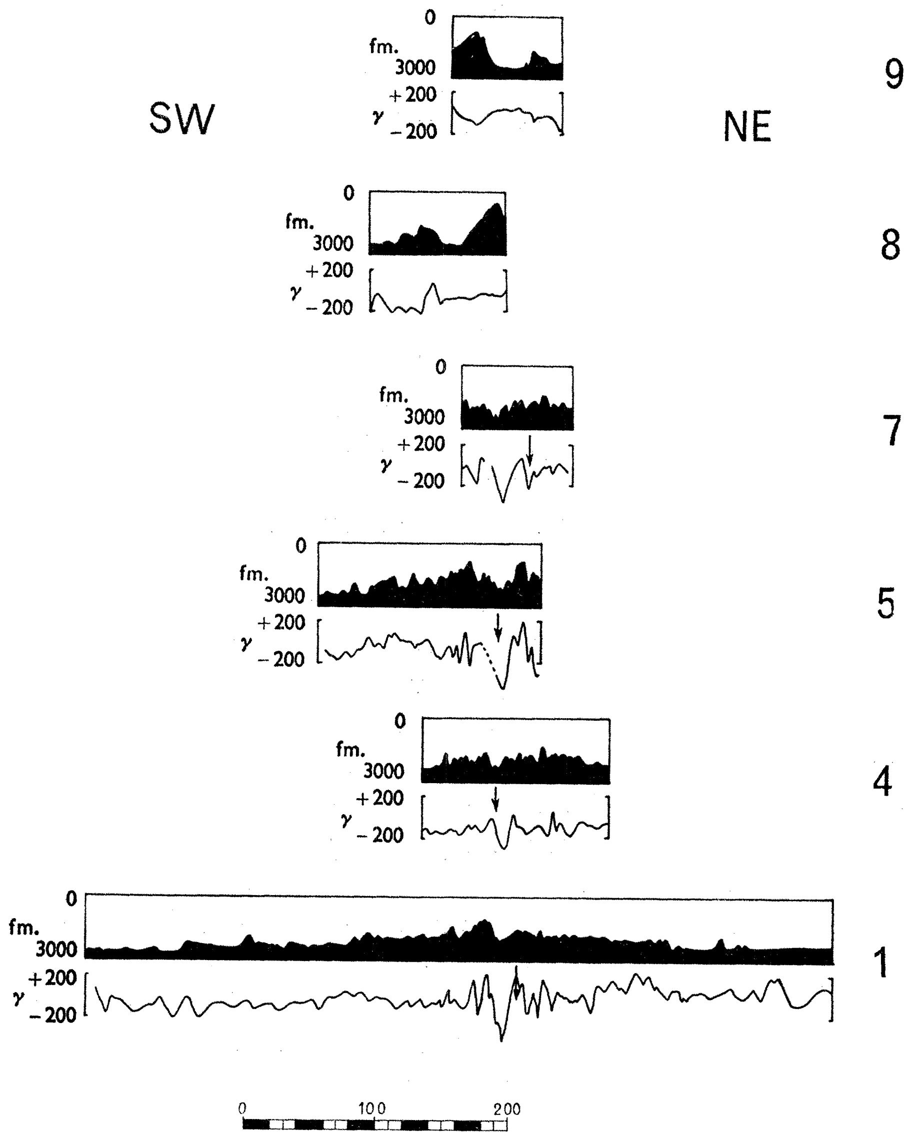


FIGURE 7. Bathymetric and magnetic profiles perpendicular to the Carlsberg Ridge. Profiles 1 to 7 south of the Owen fracture zone, profiles 8 and 9 north of it. The numbers (1, etc.) correspond to those in figure 2.

magnetic anomaly, associated in profiles 1, 4 and 5 with a median valley. In the figure the broad arrow marks the intersection of the profile with a line representing the epicentre belt. (Rather few earthquakes have been recorded along the northern part of the Carlsberg Ridge, so the position of this line is uncertain by more than 30 mi.) Profile 7 is the


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northernmost one available of those which show the median anomaly. It runs parallel to the fracture zone about 30 mi. to the south of it. The two northernmost profiles, numbers 8 and 9, lie to the north of the fracture zone. Both of them cross Mount Error and illustrate the non-magnetic character of this very large seamount.

In the light of the magnetic data we may conclude that the Carlsberg Ridge is abruptly truncated along the line of the fracture zone near 10° 10′ N, 56° 45′ E; south of the fracture the seamounts are strongly magnetic, north of it they are not. The large rounded seamounts which lie between this point and Socotra, of which Mount Error is the largest and southernmost, must be different in origin from the rugged volcanic peaks of the mid-ocean ridge. Investigation of similarly non-magnetic features in the Atlantic has shown them to be continental in type (Black, Hill, Laughton & Matthews 1964).

## Discussion

The separation between the truncated ends of the mid-ocean ridge near 13° N, 58° E and near 10° N, 57° E is 170 mi. (figure 1) and if the conclusions advanced so far are accepted it is tempting to regard this as evidence that the Owen fracture zone is a simple transcurrent fault system with a right lateral displacement of this amount. This interpretation is almost certainly an oversimplification. It involves two further assumptions: that the two portions of the mid-ocean ridge were continuous before faulting, and that no new oceanic crust has subsequently been formed between them. Either or both of these assumptions may be incorrect.

When discussing possible movements along the fracture zone it is natural to seek for other linear features that might have been displaced, and in view of the striking displacements of the magnetic anomaly pattern by fracture zones off the west coast of North America it is natural to look for magnetic lineations transverse to the fracture zone. Figure 8 shows lineations clearly visible on the magnetic anomaly cut-out model. A number of excellent correlations have been established along a length of about 400 mi. between adjacent tracks over the Karachi abyssal plain (figure 2), but this pattern appears to die out as it approaches the fracture zone and there are not yet enough tracks available to prove or disprove its existence north of the fracture. (It is hoped that studies planned for R.V. *Meteor* will provide the necessary data.) Meanwhile, the disappearance of anomalies near the fault is of interest for its own sake. The profiles available so far suggest that all transverse magnetic anomalies die out within 30 mi. of the fracture zone except near the displaced ends of the mid-ocean ridge. A possible explanation of this phenomenon has been provided by studies of a minor fracture zone which displaces the axis of the Carlsberg Ridge through only 10 mi. near 5° N (Matthews, Vine & Cann 1965). These led to the suggestion that the pattern of magnetic anomalies is expunged in the vicinity of the fault by extensive brecciation and hydrothermal alteration of the oceanic crustal rocks within the fault zone.

At its northern end the fracture zone meets the continent somewhere to the north or northwest of Karachi (figure 8). There is no obvious large displacement of the continental slope there and no tear fault with a comparable throw is known to displace the continental crustal rocks in that region. Unless the Owen fracture zone is somehow connected with an undiscovered fault hidden beneath the alluvium of the Indus plain or, more plausibly, with the recently discovered Onach-Nal dislocation which runs through West Pakistan almost along the meridian 66° E (Hunting Survey Corp. 1960, p. 367) we are forced to conclude

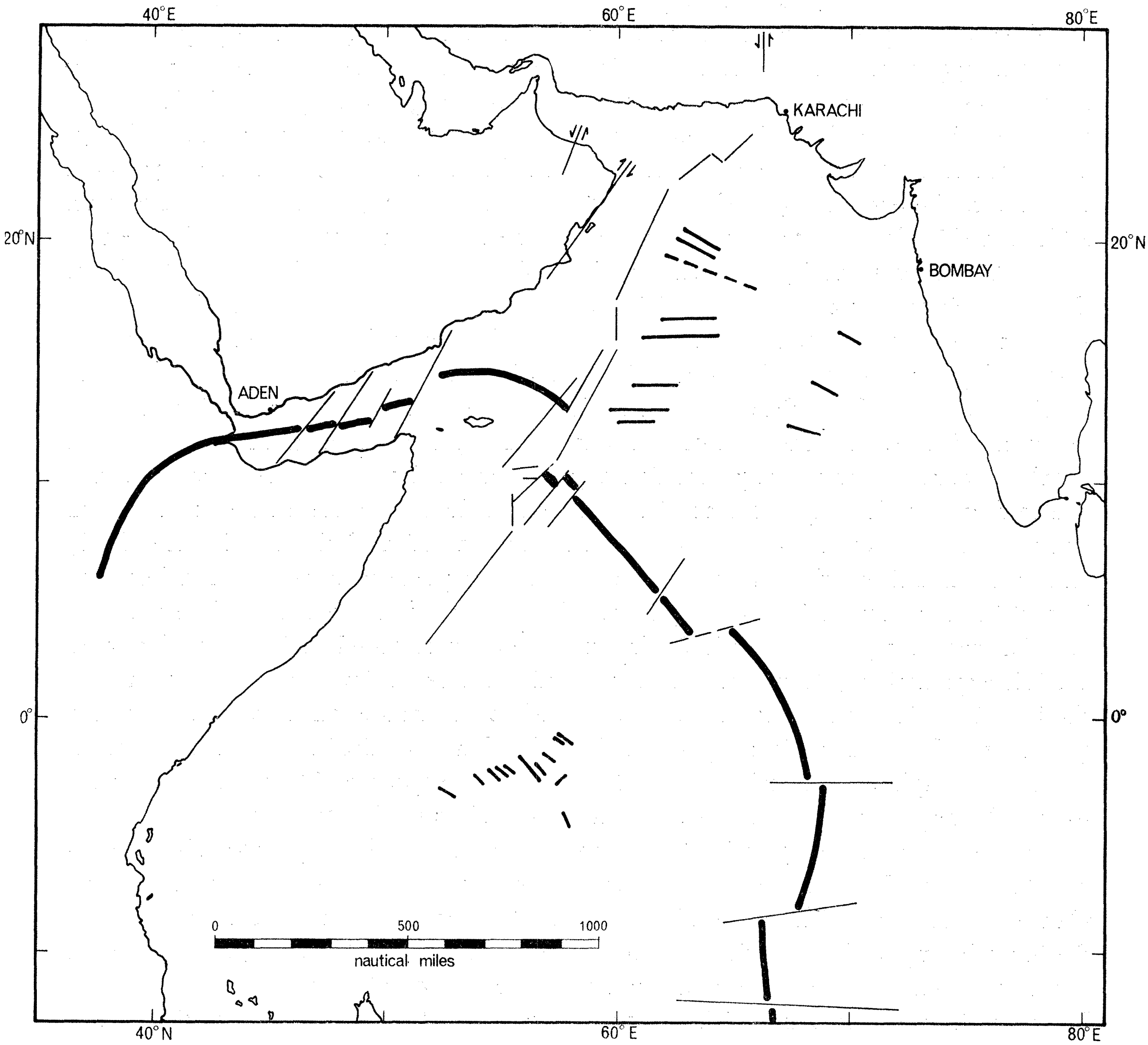


FIGURE 8. Diagrammatic map of linear features in the northwest Indian Ocean. The heavy line marks the axis of the mid-ocean ridge and the associated epicentre belt which is displaced by fracture zones. The short bold lines show lineation established by correlating prominent peaks and troughs on adjacent magnetic anomaly profiles. Postulated transcurrent faults in Arabia from Morton (1959) and in West Pakistan from Hunting Survey Corp. (1960, p. 367).

that it does not displace the continental rocks. This situation is closely analogous to that of the Mendocino fault and the other well known faults of the eastern Pacific which do not connect with major dislocations on land (Menard 1964, p. 44). Fuller (1964) has suggested that the basic rocks of the oceanic crust which are displaced by these faults slope down beneath the continental block so that the great oceanic faults produce only indirect effects in the continental rocks above them.

Evidence about the southwestern end of the Owen fracture zone was presented in the section on bathymetry; the fault appears to die out in the middle of the Somali Basin. An alternative suggestion has been made by Heezen & Tharp (1964) whose physiographic diagram suggests that the northern part of the Owen fracture zone, from the Murray Ridge southwards as far as about mi. 1100, is part of a much larger fault system which includes the eastern boundary fault of Madagascar and the western margin of the Amirante Ridge. The southern part of the Owen fracture zone (the 'Owen Ridge' or 'Chain Ridge', from mi. 1100 to the end) is regarded by these authors as a branch, or as an isolated feature. Although this view is attractive when seen in the light of the tectonics of the western Indian Ocean as a whole, and although the bathymetric evidence for the continuity of the Owen fracture zone summarized in figure 3 is less compelling in the short stretch between mi. 1050 and mi. 1150 than anywhere else along the 1500 mi. length of the feature, I prefer the view advanced in figure 3 where the 'Chain Ridge' is drawn as the continuation of the Owen fracture zone. Bathymetric evidence of a topographic connexion between this area and the Amirante Trench is not yet convincing. There are several possible alternatives in this region which might be clarified by additional survey work.

The fact that the displacement of 170 mi. established near the centre of the Owen fracture zone seems to die away to nothing at either end of the fault in a distance of only some 600 mi. indicates that the structure cannot be a simple tear fault of the kind described in text-books although it is analogous to other oceanic fracture zones. One is led to question the assumptions on which this interpretation is based and to look for other possible explanations. A very plausible mechanism for expansion of the oceanic crust by the injection of swarms of basaltic dykes parallel to the mid-ocean ridges has been suggested by Bodvarsson & Walker (1964) in the light of their studies in Iceland. This type of mechanism implies that lengths may not be conserved on opposite sides of a fracture zone, so that the apparent displacement between the two sides might vary from place to place along it. A comparable suggestion has been made by Menard (1964, p. 150). The assumption that the mid-ocean ridge was continuous prior to dislocation is an arbitrary one, plausible in the light of the current hypothesis that the crest of the mid-ocean ridge marks the line of an upward convection current in the upper mantle. However, this hypothesis can be true only in a general sense: earthquakes occur along both parts of the disrupted Ridge, both north and south of the fracture zone, and unless it can be shown that one or other part has become inactive we must conclude that both are the sites of volcanic activity at the present time. It follows therefore that the underlying convection system, which provides the source of volcanic heat, has either suffered a displacement of 170 mi. together with the crustal rocks at the fracture zone or that the upward convection current is so broad that heat is available over a zone considerably more than 200 mi. wide which does not precisely conform to the midline of the ridge.

Since the simple interpretation in terms of horizontal displacement encounters some difficulties we may examine possible alternatives. The linear non-magnetic features that characterize the Owen fracture zone away from the Carlsberg Ridge might be interpreted along entirely different lines. For much of its length the fracture zone is situated near the foot of the continental rise parallel to the coasts of Arabia and Africa. It is conceivable that the linear features represent a trench and ridge system developed at the continental margin, and that the apparent displacement between the ends of the oceanic Carlsberg Ridge and the Gulf of Aden rift system is fortuitous. This suggestion, though more nearly consistent with the views of A. G. Jones and his colleagues working on land (Hunting Survey Corp. 1960, p. 394), seems at present to be even more difficult to support than the one adopted in this paper. It is certain that the last word has not been said on this topic since the conclusions advanced as a result of geological survey on land are flatly contradictory to those presented here.

It is concluded as a result of the work at sea that the structure underlying the Owen fracture zone is a system of transcurrent faults along which the axis of the mid-ocean ridge system suffers a net right lateral displacement of 170 mi. This displacement may not be constant along the length of the fracture zone because new dyke material may have been added to the oceanic crust.

The age of the fault system is unknown. It is presumably younger than the displaced portion of the mid-ocean ridge. The eruption of flood basalts at the western end of the ridge in Ethiopia began in Upper Eocene time (Grasty *et al.* 1964) and fresh basalts dredged from the Carlsberg Ridge near 5° N and dated by the $^{40}K$:$^{40}Ar$ method appear to be Pliocene in age (Grasty & Miller, personal communication). Laughton, p. 169 above, suggests that the displacement of the mid-ocean ridge occurred during the most recent phase of the development of the Gulf of Aden, in late Tertiary time.

Throughout this paper the fault system has been referred to, for convenience, as a single fracture, but it is clear that the line drawn on the map marks the locus of parallel faults within a shear zone (figure 8). Morton (1959) has postulated the existence of major transcurrent faults having the same trend parallel to the coast of Arabia; the several ridges developed in the northern part of the fracture zone are probably fault bounded, and Mount Error (10$\frac{1}{4}$° N, 56° E) appears to be bounded by faults which diverge from the fracture zone. On the oceanward side of the line at the northern end of the Carlsberg Ridge there is clear evidence of two minor faults parallel to the fracture zone which displace both the median valley and the prominent negative magnetic anomaly associated with it by about 30 n.mi. The troughs associated with these faults can be seen in figure 3 cutting across the ridge and displacing the median valley near 10° N, 57$\frac{1}{2}$° E and near 9$\frac{1}{2}$° N, 58° E. All these faults suggest that very great shearing took place towards the end of Tertiary time in a direction parallel to the Owen fracture zone. This shearing could be related to the northward movement of peninsular India envisaged in the theory of continental drift.

In addition to people mentioned in the text it is a pleasure to thank Dr and Mrs F. J. Vine for computations made on Edsac II. Mrs Vine has carried out a large proportion of the onerous data reduction and drafting involved, directly or indirectly, in the preparation of this paper. I am grateful too for fruitful discussions with colleagues, with Drs A. S. Laughton, B. C. Heezen and R. L. Fisher and with Professor J. T. Wilson.

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