PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

A Reconnaissance Survey of the Murray Ridge

P. F. Barker

Phil. Trans. R. Soc. Lond. A 1966 **259**, 187-197
doi: 10.1098/rsta.1966.0006

A reconnaissance survey of the Murray Ridge

By P. F. Barker

Department of Geophysics, University of Birmingham

Bathymetric and magnetic measurements at a 10-mile line spacing across the mouth of the Gulf of Oman have made a substantial contribution to knowledge of the area. A northeast–southwest alinement of bathymetric features, the presence of many fault scarps and the occurrence of elongated weakly magnetized seamounts similar to others farther south suggest that the Murray Ridge is continuous with the Owen fracture zone and support the idea that both are loci of strike-slip movement.

Introduction

At various times between October 1961 and March 1963, H.M.S. *Dalrymple* and the Geophysics Department of Imperial College compiled a reconnaissance magnetic and bathymetric survey of the area of the Murray Ridge, which extends southwestward from the continental slope near Karachi. The profiles, together with those obtained on other tracks of H.M.S. *Dalrymple* in the Indian Ocean, are being published elsewhere (Admiralty 1966).

Early British (Farquharson 1936; Wiseman & Sewell 1937) and German exploration with the then new continuous echo sounders was prompted by the existence of a single shoal wire sounding in the middle of the area. Subsequently, further similar isolated lines of soundings were obtained, mainly by British ships and by *Vityaz* (Zatonskii 1964).

A track chart of the present survey is shown in figure 1. Previous work, of uneven areal distribution and low density, has been used in the production of the bathymetric contour map (figure 2) only in areas of gentle sea-floor topography, where uncertainties in position cause errors small compared with the contour interval.

In 1960 H.M.S. *Dalrymple* collected a number of bottom samples from the area. Dr J. D. H. Wiseman of the British Museum, where they are stored, has permitted petrological examination of the only sample containing hard rock fragments. These are described below in the context of the properties of the body from which they were dredged.

Regional geology

Elucidation of the geology of the surrounding continents, involving in many cases the proposed oceanic extension of continental features, has proceeded parallel with the marine investigations. Lees (1928) and Morton (1959) have described the Upper Cretaceous ophiolitic geanticline of the Oman Mountains and the foreland environment of the area to the southwest. Similar assemblages of serpentinized ultrabasics, spilitic lavas, and radiolarian chert have been described from the Lower Cretaceous of Iran by de Boekh, Lees & Richardson (1929), Lees (1953) and others. The authors of the Hunting Survey Corporation's Report on the geology of part of West Pakistan (1960) describe a geanticlinal 'axial belt' there, extending northwards from Karachi along the boundary of Peninsular

India, and containing the same rock types, of Cretaceous age. The geanticlines were all formed before the main orogenic movements in each area, contain the oldest rocks and have guided subsequent deposition and folding. Uplift occurred at the end of the Miocene in Oman, in the Pliocene in Iran and is still occurring on the Makran coast of Pakistan, having started farther to the north in the Pleistocene.

The surface geology, taken from Morton (1959) the *Carte Geologique de L'Afrique* (U.N.E.S.C.O. 1964), and the Hunting Survey Corp. Report (1960) is shown in figure 1 with the ship's track. The Hunting Survey Corp. Report (1960) follows Argand (1922) in assuming that the geanticlinal structures of West Pakistan and Oman are continuous through the Murray Ridge, the continental rocks of the area now occupied by ocean having been down-faulted in Miocene times. Lees (1928) prefers a southwesterly continuation of the

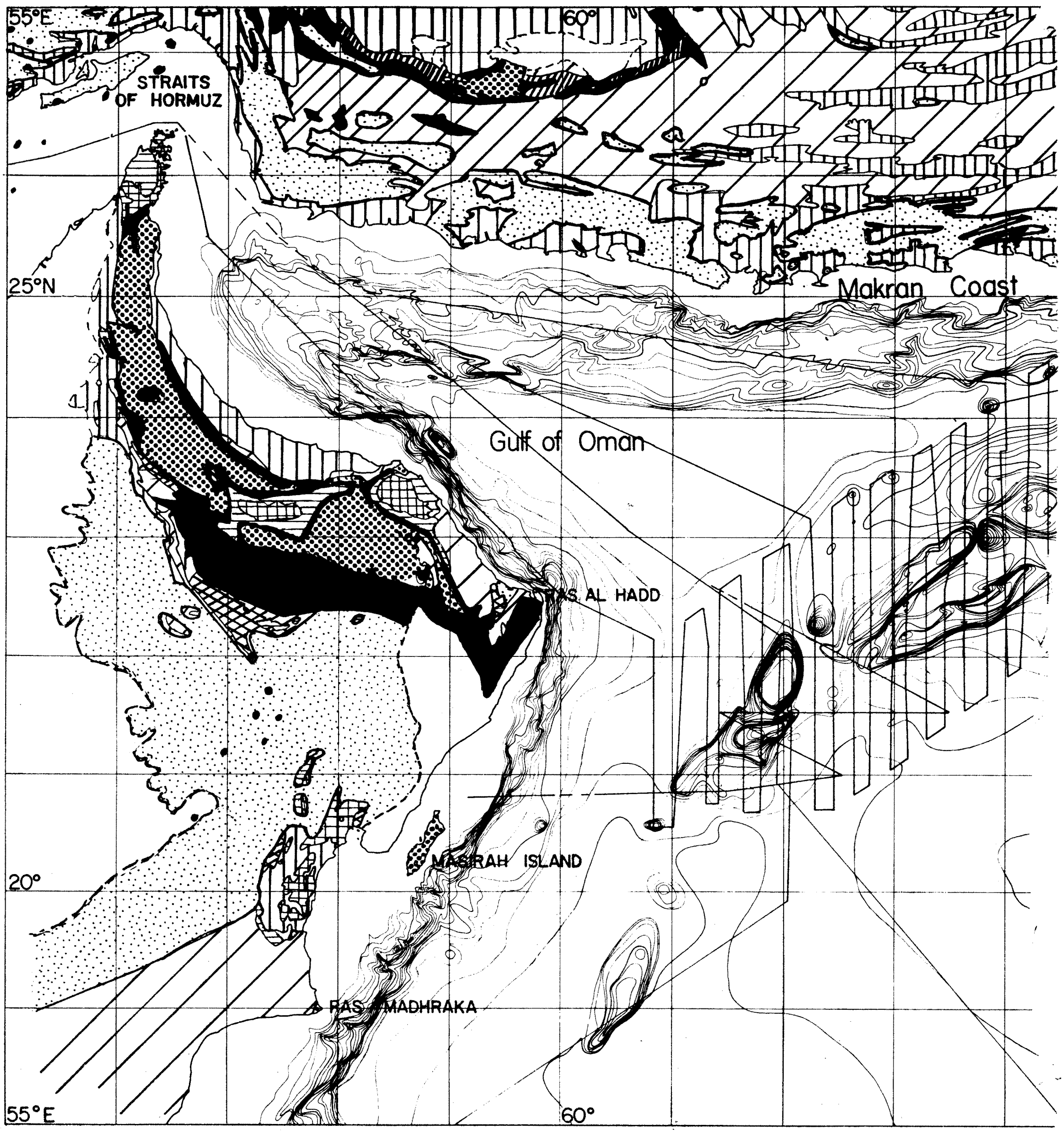

FIGURE 1. Regional geology and sh

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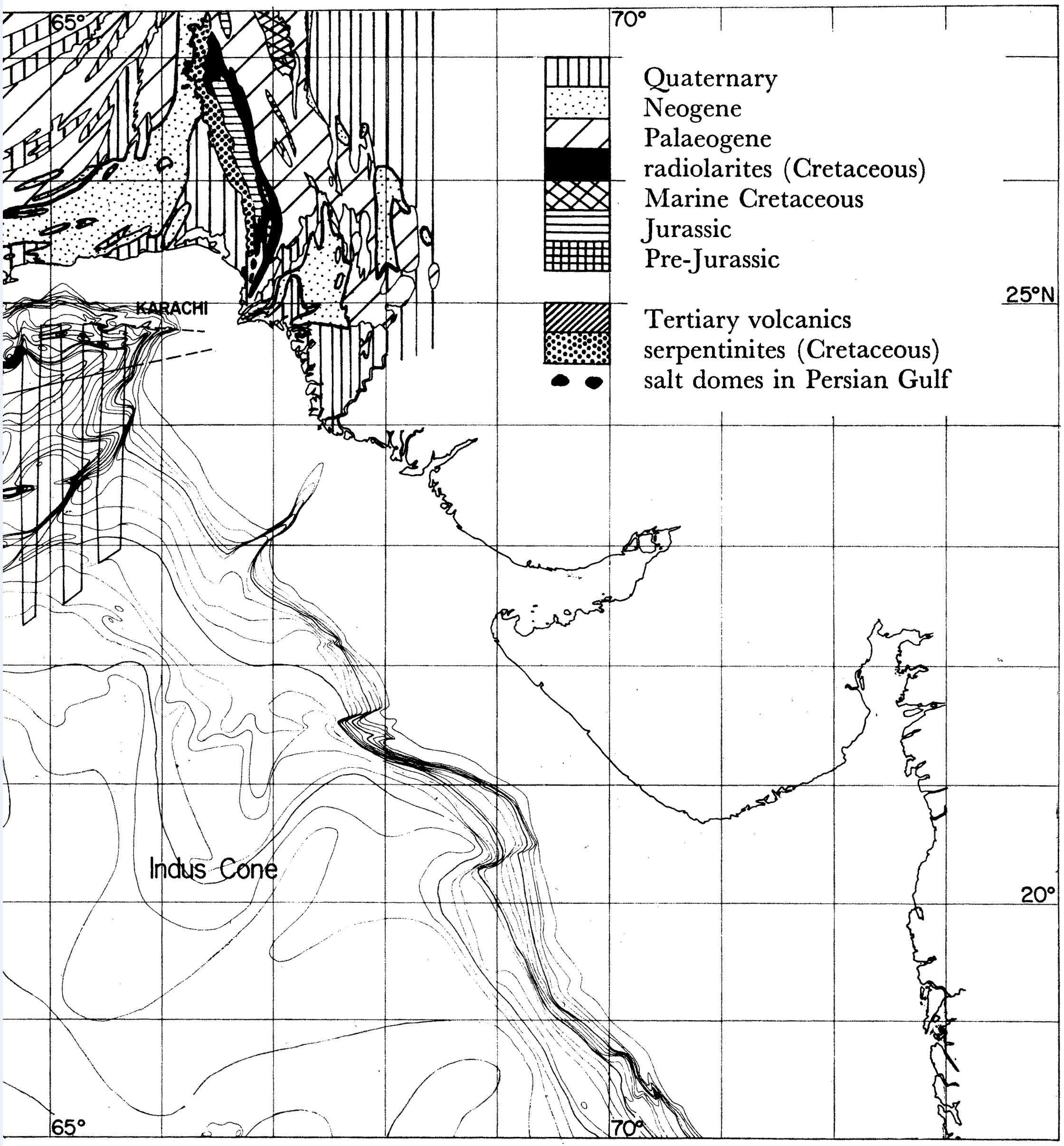
Oman Cretaceous structures through the serpentinites of Masirah Island and Ras Madhraka, but Morton (1959) explains these two exposures by a displacement from the Ras al Hadd area along a right-lateral tear fault parallel to the present coast.

Farquharson (1936) and Wiseman & Sewell (1937) proposed that the Murray Ridge was continuous with the Kirthar Mountains, that is with the Axial Belt, of West Pakistan, and that its southerly extension became a branch of the Carlsberg Ridge.

Matthews p. 172 above demonstrated an intersection of the Carlsberg Ridge and the probable southerly extension of the Murray Ridge. He suggested that the latter was a transcurrent fault, displacing right laterally by 170 mi. the line of epicentres, the median rift and the large negative magnetic anomaly which were being used to follow the crest of the Carlsberg Ridge.



›'s tracks. Contour interval 100 fm.

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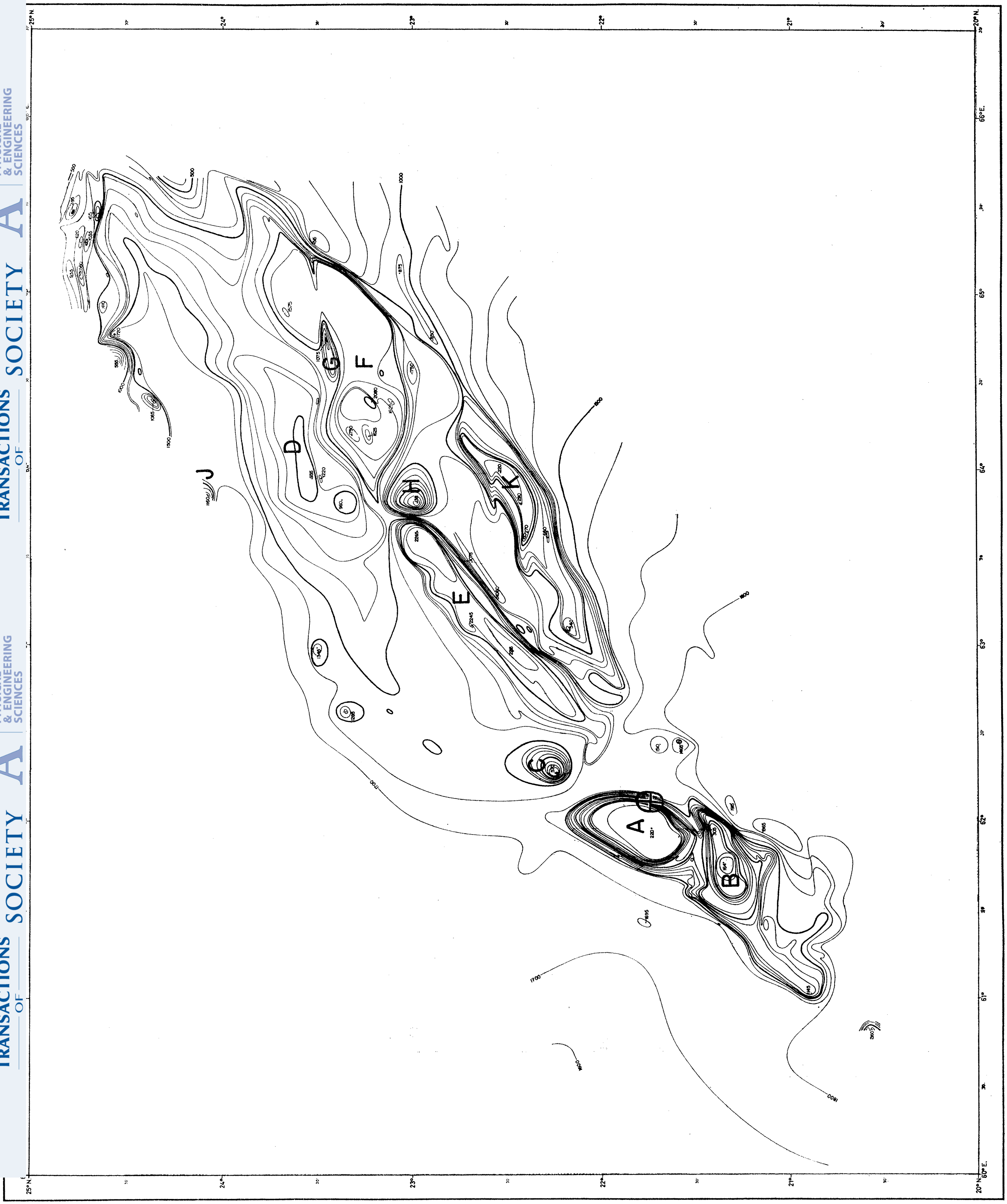

FIGURE 2. Bathymetric contour map. Contour interval 100 fm. Bolder contours at 500 fm. intervals.

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Description of maps

The present reconnaissance survey has produced an even coverage of the area at a 10 mi. line spacing, facilitating a description of the main areas of interest and making it unlikely that any major feature has been missed. The line spacing is inadequate for the description of smaller features and shallow source magnetic anomalies and the bathymetric and magnetic anomaly contour maps (figures 2 and 3) are therefore of limited reliability.

The presentation of the magnetic results is limited further by an uncertainty in the removal of the regional magnetic field. In the magnetic latitude of the survey area the northerly edge of an inductively magnetized semi-infinite rectangular slab of east–west strike produces a dominant negative anomaly. An area such as this, where a magnetic oceanic crust to the south has a roughly east–west boundary with a very much less magnetic continental crust, might therefore be expected to contain one or more of these unbalanced lows, whatever the shape of the actual boundary or set of boundaries. A least-square fit of a low-order polynomial to the observed data was used to estimate the regional field. Such a fit distributes equal positive and negative anomaly volumes about the fitted surface, which will be the case only if all the magnetic anomaly sources are contained within the area of the survey. In practice the fitted regional field will be low compared with the field when all sources have been removed and, depending on the distribution of magnetic material, may be tilted. This uncertainty in the removal of a regional field will affect quantitative interpretation of the magnetic anomalies.

The maps (figures 2 and 3) will be described together; discrete bathymetric features have been lettered for ease of reference.

The major magnetic anomalies can be associated with the observed bathymetry with one important exception, a magnetic low running along the northwest edge of the survey area. This is typical of the anomaly over the north edge of a more magnetic slab and thus attributable to a fault, either strike-slip or with a downthrown northerly side.

The area of disturbed topography in figure 2, alined northeast–southwest, is bounded in the northwest by the abyssal plain of the Gulf of Oman at a depth of 1830 fm., and in the southeast by the very gentle ($\frac{1}{3}°$) slope of the northern edge of the Indus cone.

In the southwest of the disturbed area a large elongated body rises from about 1700 to 1000 fm., above which it divides. The northerly guyot, feature A, has smooth sides and top, measures 30 mi. by 15 mi. at the 400 fm. contour and has a least measured depth to top of 220 fm. In contrast, the southerly feature B has a rough top and sides, with benches at depths of from 800 to 1300 fm. and a least measured depth to top of 164 fm. A computer program developed by Kunaratnam (1963) has been used to obtain a fit to the observed magnetic profiles on the assumption of uniform magnetization of the observed bathymetry of A and B. The fit was good for three westerly tracks in deep water, but not for three easterly tracks in shallower water. The good fits were improved slightly by extending the bases of A and B to 2000 and 2500 fm. From the computer fits the southwestern part of the A–B massif is uniformly magnetized with an apparent susceptibility of about 10^{-2} e.m.u./cm^3 and the magnetic contrast extends beneath the present seabed. Along the easterly profiles, magnetic contrasts of shallow origin prevent the calculation of a valid susceptibility value, but the magnetic anomalies could be attributed to material of

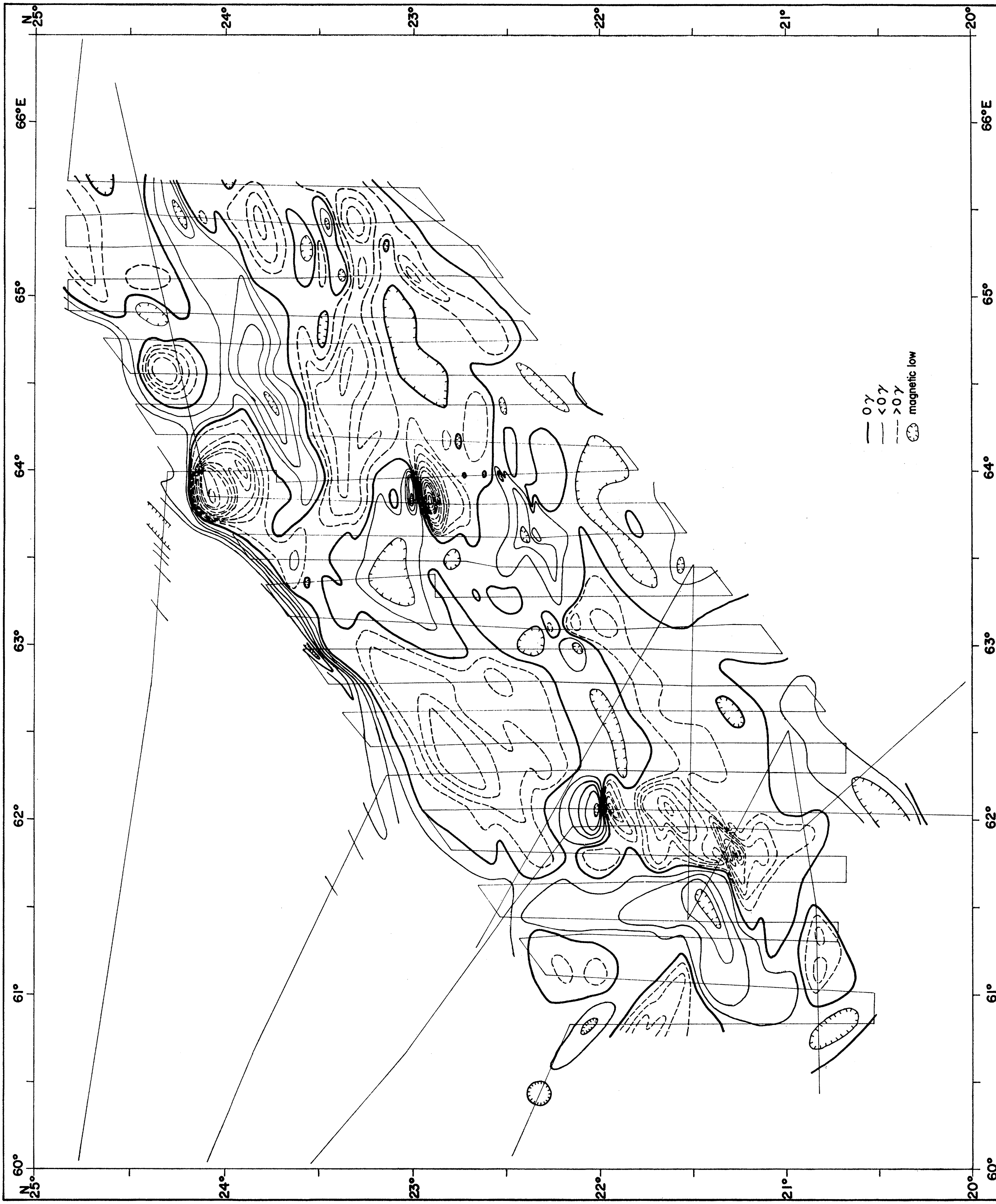

FIGURE 3. Magnetic anomaly contour map. Contour interval 50 γ. Faint lines show ship's tracks.

a similar apparent susceptibility, unevenly distributed at shallow depth and again homogeneous below 1000 fm.

On this evidence it is unlikely that the A–B massif is of continental origin. It could be a volcanic complex, with tuff or coral in its upper parts, but this explanation is incomplete. The depth to which the magnetic contrast extends, the straight sides, the inhomogeneity, a partly filled trench on the southeast side and a recent precisely located earthquake epicentre (marked ⊕ in figure 2) suggest that the massif is fault-guided and perhaps fault dissected.

Separated from the A–B massif in the northeast by a depth of 1650 fm. is an asymmetric non-magnetic body of small extent, feature C, which on one traverse rises to 570 fm.

To the northeast again is feature D, a 30 mi. by 180 mi. rise, seemingly running into the continental slope near Karachi and characterized by broad 200 γ anomalies in its western part.

The southeast side of D falls by a series of short unconnected scarps to two trenches, feature E in the southwest and feature F in the northeast. The bottom of trench E was seen as smooth, implicitly sediment-covered, on four traverses and rough on four more. Its greatest measured depth was 2260 fm. Its steep southeast wall, in places 1100 fm. high, is of non-magnetic material, although some magnetic contrast occurs along it at depth. Trench F is divisible into three distinct basins, the middle being the only one with undistorted sediment cover. The southwesterly third is deepest, at 2050 fm., and as no obvious feature separates it from the middle third, which has no obvious sediment source, its rough bottom may have been caused by tectonic movement after the deposition of the sediments. A ridge, feature G, with an associated magnetic anomaly, separates the middle from the rough-bottomed northeasterly third, at the eastern end of which two recent earthquake epicentres are located, lending weight to the idea of recent movement.

Trenches E and F are separated by a seamount H, associated with a well defined magnetic anomaly suggesting an apparent susceptibility of 10^{-2} e.m.u./cm^3, and having a least measured depth to top of 137 fm. Scarps on the north wall of this volcano could again indicate recent movement, although if this movement is regarded as forming trench F entirely, the tempting hypothesis that E and F were continuous before the eruption of H has to be dismissed. A better explanation is that movement in the region of E and F occurred before, during and after the eruption of H.

Another probable seamount, feature J, occurs on the line of the postulated fault along the northwest edge of the area. One bathymetric profile rose to 1160 from 1650 fm. before a 90° alteration of ship's course, and the magnetic profile had turned a peak of 600 γ ($1\,\gamma = 10^{-5}$ G). A further traverse 10 mi. away also showed a 600 γ anomaly, but no topographic expression, and it therefore seems likely that the seamount is mostly buried in sediment and does not rise much above 1160 fm.

The disturbed topography in the extreme northeast of the area is part of the Makran coastal belt, being non-magnetic and probably consisting of contorted sediments.

Feature K

Separated from trench E by a smooth triangular bench of non-magnetic material at 1100 fm. is a rough elongated seamount, feature K, 90 mi. long at the 800 fm. contour and with a least measured depth to top of 220 fm. Magnetic anomalies over the body nowhere exceed 200 γ, and while some are of shallow origin, they cannot usually be correlated with the topography. The body is magnetically inhomogeneous with some magnetic contrast extending beneath its topographic expression. It can possibly be characterized by a 'mean' apparent susceptibility of 2×10^{-3} e.m.u./cm^3, considerably less than that of the usual oceanic basalt and such that in deeper water the magnetic anomalies produced would not seem significant.

A dredge sample obtained by H.M.S. *Dalrymple* in 1960 from a depth of 300 fm. at the northeast end of feature K yielded 15 angular fragments, of linear dimension from 0·25 to 3 cm. The fragments were mostly of tuff and variolitic or spilitic basalt, with one microdiorite and one red, fine-grained sediment which could be other than tuff. The basalts and tuffs were weathered and altered, and veined with feldspar, carbonates and zeolite to an extent which on land would be consistent with burial beneath a further 1000 ft. of basalt. The specimens showed magnetic susceptibilities varying from 2000 to 3×10^{-6} e.m.u./cm^3 with a mean of 80×10^{-6} e.m.u./cm^3, and remanent intensities of from 6 to 1500×10^{-6} with a mean of 300×10^{-6}. The single high susceptibility was held by the microdiorite, the high remanences by the variolitic basalts. These highest magnetic intensities, if applicable to feature K as a whole, could produce the observed anomalies, but the specimens are all surface-weathered and cannot be considered typical of the whole seamount. Although both contain basalt and tuff, there remains the unexplained order of magnitude difference in the magnetic anomalies associated with feature K and with normal seamounts. The low magnetization and elongated nature of feature K is shared by the seamount near 19° N $60\frac{1}{2}$° E (see figure 1) and others along the line which cuts the Carlsberg Ridge as described by Matthews (1963), and extends southward into the Somali Basin. All are probably fault-guided and fault-dissected and, in addition, their magnetic properties might be caused by prolonged hydrothermal alteration or the presence of basic or ultrabasic intrusive rocks.

Seismicity

The distribution of epicentres of shallow focus earthquakes is shown in figure 4, with the Tectonic Axes. The latter have been taken, in Pakistan, from the Hunting Survey Corp. Report (1960) and sites of similar structure and lithology chosen with reference to the *Carte Geologique de l'Afrique* (U.N.E.S.C.O. 1964) in Iran, and Lees (1928) and Morton (1959) in Oman.

Seismicity is concentrated in a zone parallel to the Recent folding in Iran and Pakistan. The Hunting Survey Corp. Report (1960) relates the structure and seismicity around Quetta to Wadia's explanation of the Hindu Kush seismicity in terms of the protrusion of a buttress of Peninsular India into the mobile belt of the Himalaya (Wadia 1932). J. V. Harrison (in Hudson, McGugan & Morton 1954) compared the structures north of the Straits of Hormuz with those of the Hindu Kush. The distribution of earthquake epicentres in Iran supports his view, and suggests that the Oman geanticlinal structures, and also the floor of the Gulf of Oman are now acting as part of the stable block of Arabia, which is moving towards the Zagros fold-belt of Iran.

The distribution of epicentres also shows that some relative movement of the Tectonic Axes of Pakistan and Peninsular India is taking place. The Murray Ridge–Owen fracture zone is also the well defined locus of a few epicentres.

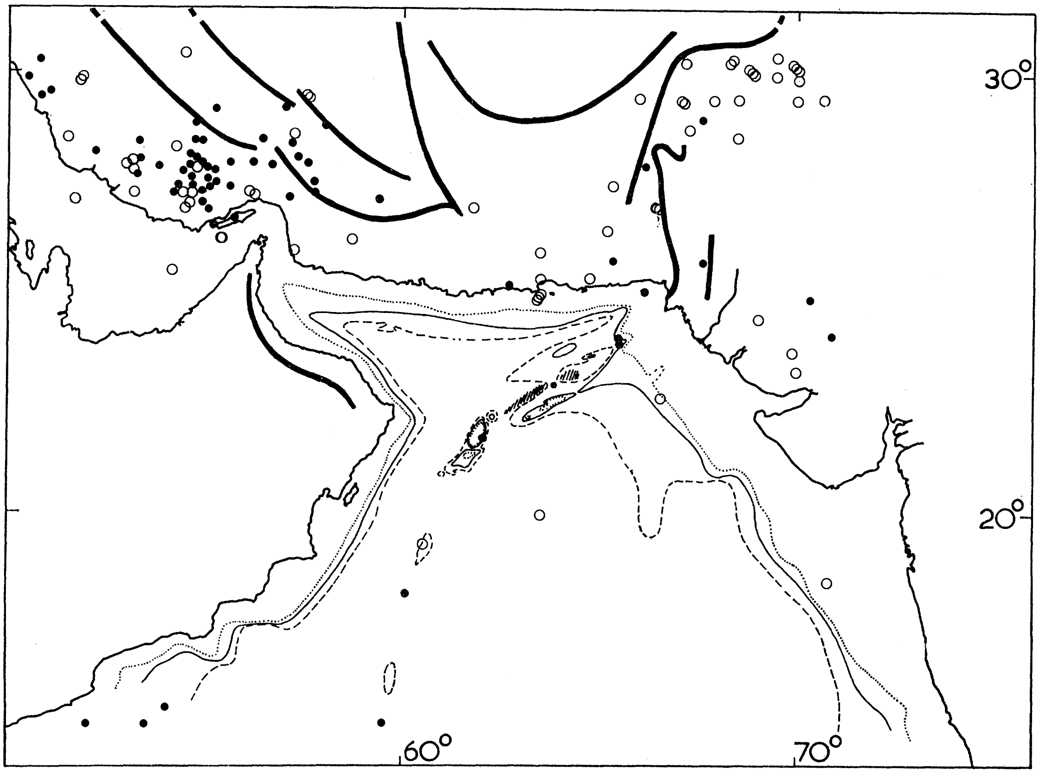

FIGURE 4. Seismicity and structure. Bold lines, tectonic axes; ○, epicentres I.S.S. 1937–56; ●, epicentres U.S.C. and G.S. 1959–63. Submarine contours: . . . , 500 fm; solid line, 1000 fm; – – –, 1500 fm; areas below 2000 fm are shaded.

DISCUSSION

No positive evidence of large scale strike-slip movement was found in the survey area. Such evidence might have been found by a more dense survey of a larger area if, as off the West Coast of America (Raff & Mason 1961), the magnetic anomaly pattern was suitable. Although isolated magnetic profiles to the south of the area considered here have contained anomalies with a possible east–west alinement, there is no guarantee that they continue to the proposed fracture zone or will be detectable in the 100 mi. or so of deep water between there and the continental shelves of Africa, Arabia and Pakistan.

However, the dominant characteristic of the area described above is the northeast–southwest alinement of bathymetric and magnetic features. These features are also tectonically connected at present with the Owen fracture zone, where the Carlsberg Ridge is 'displaced'. It may be argued that this connexion is fortuitous, the recent structures having used the older compressive lineation of an Oman–Pakistan geanticline, but the K-type elongated seamounts extend almost from the Equator to Karachi with no diminution in size northward, and the existence of these seamounts between Oman and Pakistan is one of the main arguments used in favour of the geanticlinal connexion.

Rather less tenable is the postulate which comes from the realization that the magnetic character of feature K and the lithology of the dredge samples are similar to those of the serpentinized ultrabasic intrusive rocks and spilitic lavas of the Las Bela geanticline in West Pakistan. This is that the geanticlines may have their preorogenic cores formed along strike-slip faults. The geology of West Pakistan is complicated, but the authors of the Hunting Survey Corp. Report (1960) are confident that the axes are of compressional origin. Two long north–south strike-slip faults, the Nushki–Chaman and the Ornach–Nal faults, exist but are considered anomalous to the main structural pattern. It is interesting that, unlike that of the Carlsberg Ridge, their displacement is left-lateral, pointing to northward movement of India rather than of Arabia. A northward movement and anticlockwise rotation of India is required by the palaeomagnetic evidence from India and Africa, which is mostly from rocks untreated for stability (Blackett, Clegg & Stubbs 1960).

By accepting the Carlsberg Ridge as an active mid-ocean ridge, and the Maldive–Laccadive Ridge as another, active in Cretaceous and Eocene times but now dead, the means can be found for such a northward drift. That the offset of the Carlsberg Ridge is in the opposite sense is not necessarily contrary evidence; 'displacement' means little when new material is being supplied along the line of the Carlsberg Ridge, perhaps at different rates on opposite sides of the Owen fracture zone.

Thirlaway (in the Hunting Survey Corp. Report 1960) reported a negative gravity gradient southwards from the Makran coast, which is still rising. Thus gravity profiles across the Murray Ridge should show if it is part of the coastal geosyncline; it seems inconceivable that the Murray Ridge should be a part of the Oman–Pakistan geosyncline if it is both submerged and in isostatic equilibrium, whereas isostatic equilibrium is not incompatible with large shear movements. Whether we should consider the Owen fracture zone as caused solely by the opening of the Gulf of Aden, or if it is also the line along which India has moved northwards relative to Afro–Arabia is still undecided. The existence of aseismic (Sykes & Landisman 1964) elongated less magnetic bodies in the fracture zone south of the Carlsberg Ridge, and the apparent bend and partial change in character of the Owen–Murray system at about 22° N are subjective pointers towards a phase of movement earlier than the present one.

This reconnaissance has raised many problems, which further investigations using in particular gravity, seismic and sampling methods, and detailed magnetic surveys, might solve.

The author would like to thank the Hydrographer of the Navy, and Cdr. H. R. Hatfield and the crew of H.M.S. *Dalrymple* for the initiation and willing implementation of the project, which was supported by grants from the Department of Scientific and Industrial Research and British Petroleum. Professor J. McG. Bruckshaw read the manuscript and made many helpful suggestions. The Seismological Summary supplied epicentre locations for 1937–56 and the U.S. Coast and Geodetic Survey did likewise for 1959–62 and also re-determined the positions of four epicentres in the Murray Ridge area. The Pakistan Meteorological Service gave station data from Quetta for the reduction of the magnetic records.

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