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Southern Arabia and northern Somalia: comparative geology

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[Two charts in accompanying wallet]

Detailed geological compilation maps for the two sides of the Gulf of Aden from various published and unpublished sources were originally prepared on 1:500 000 scale and later reduced to 1:1 000 000 scale (figures 3 and 4, in accompanying wallet). These were reconstructed to postulated pre-separation positions along the 100- and 500-fathom (183 and 914 m) bathymetric contours to give acceptably close fits for most of the area west of Alula–Ras Fartaq, leaving water gaps of 25–40 and 50–80 km respectively between the two shores.

The 500-fathom fit shows several striking similarities and apparent continuity of geological features between the two sides, but detailed correlation reveals a number of offsets and mismatches. The 100-fathom fit gives a considerably improved overall correlation with continuity of structural and facies belts across the intervening water, though detailed comparisons do not bring out many correlations that give direct and positive geological support for separation and these are mainly structural rather than stratigraphic. This paucity in positive correlation may be partly accounted for by the width of the remaining water gap and by the differing geomorphology and degree of erosion between the eastern portion of the two sides. Although the reconstructions reveal appreciable circumstantial support for separation and no major geological evidence against it, an overlap results in the extreme west of the map area (appreciably greater for the 100-fathom fit) where Basement and Mesozoic rocks on either side are superimposed on one another; a considerably greater overlap occurs outside the map area to the west between similar rocks of Yemen and the Danakil alps of Ethiopia. If Arabia moved as a single block in a northeast direction and with counter clockwise rotation away from the Somali (and Nubian) block, reconstructing it to its preseparation position requires the satisfactory resolution of this overlap before it can be acceptable; a separate northeast movement of the Socotra shelf is moreover required to accommodate a fit with the reconstructed Dhufar–Kuria portion of the Arabian block.

Introduction

The present comparative study of the detailed geology on the two sides of the Gulf of Aden was started in 1966 and has subsequently been updated and revised. It arose as a result of renewed interest in the region as marine geophysical work was extended into the Gulf of Aden from the Red Sea and the Indian Ocean. This had established the continuation in the Gulf of Aden of the Indian Ocean mid-oceanic ridge, and the presence of oceanic crust under much of the floor of the Gulf (Laughton 1966, 1967; Mathews 1967; Mathews, William & Laughton 1967; Girdler 1967).

Laughton (1966) made use of simplified general geology from maps of the adjacent land areas in the matching of geological features on the two sides and as support for their continuity across a reconstructed Gulf of Aden before its postulated crustal opening and separation in the Miocene. Some of these data were questioned by the writer as to their validity in furnishing positive geological proof of separation, since they could either be shown to be unreliable matches when examined in detail or else to be open to more than one interpretation (cf. Azzaroli 1968). It was accordingly agreed that a thorough detailed compilation of all geological data onto large scale maps for the two sides of the Gulf was necessary. Following this, reconstruction to postulated pre-separation positions and comparative study and correlation of the details of the geology as far as is feasible, would either furnish acceptable positive support for separation or perhaps provide geological evidence against it.

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The writer undertook this task because of personal familiarity with the geology of considerable portions of the region, the object being to provide the most up-to-date accurate synthesis of geological facts which, in addition to their direct bearing on the immediate problem, can perhaps also be of assistance in allied investigations in the area.

The compilation results are shown on figures 3 and 4 and are summarized in figure 2. The scale used in the final presentation of figures 3 and 4 is reduced from the original 1:500 000 scale compilation and is approximately in conformity with that used for the latest bathymetric plotting charts for the region at a scale of 1:1 000 000 at 33° N latitude. Owing, however, to the different projections between the two base maps, exact conformity has not been possible. Bathymetric contours for 100 fathoms (approximately 200 m) and 500 fathoms (very roughly taken to represent 1000 m) are given so that reconstructions for the edge of the continental shelf and a convenient depth on the continental slope (as used by Laughton 1966 in his reconstruction) may be tried. These two reconstructions are summarized in figure 2 where suggested correlations, mismatches and resulting superimposed overlap are also shown.

In both reconstructions, quite acceptable bathymetric fits were obtained for much of the area west of the Alula–Ras Fartqa region with remaining water gaps between the shores of 25–40 km and 50-80 km for 100 and 500 fathoms fits respectively.

Map compilation sources

The original scale of compilation from which figures 3 and 4 (see accompanying wallet) have been drawn was on 1:500 000 scale. Since the compilation work saw its slow beginning in 1966, a considerable amount of new data (including unpublished maps or work in the press) became available to the writer through the courtesy of colleagues (see acknowledgements), while some additional detail to sketchy portions of earlier maps by the writer were brought up to standard where this was possible, by additional new photogeological interpretation.

Figure 1 shows the Gulf of Aden region as covered by the mapping depicted on figures 3 and 4. It has been divided into several numbered main areas some of which have in turn been subdivided by letters; these indicate the sources from which the original 1:500 000 scale sheets were compiled and from which figures 3 and 4 have been drawn, and which are listed and discussed below:

1 (*a*) *Socotra.* From original unpublished 1:150 000 scale map by Z. R. Beydoun & H. R. Bichan using ground reconnaissance mapping and air photos. A simplified version of the original map forms an enclosure to a recent geological paper on Socotra (Beydoun & Bichan 1970).

(*b*) *Abd-al-Kuri, Darsa and Semha.* From Dainelli (1943) with additional note on Abd-al-Kuri from air photos.

2 *Northeast Somalia.* From Carta geologica della Somalia e dell'Ogaden, 1:500 000 scale, Guardafui sheet 1957, prepared by Azzaroli & Merla from results by A.G.I.P. (1938–9), Mineraria Somalia (1953–4), and the National Research Council of Italy (1956).

3 (*a*) *Northern Somalia.* From former Somaliland Protectorate Geological Survey maps on 1:125 000 scale accompanying survey reports 1 to 4 by J. E. Mason, A. J. Warden, J. A. Hunt & J. E. G. W. Greenwood.

(*b*) *Northern Somalia.* From former Somaliland Protectorate Geological Survey unpublished maps on 1:125 000 scale.

(*c*) *Northern Somalia.* From Somaliland Oil Exploration Company geological map on 1:1 000 000 scale accompanying the report *A Geological reconnaissance of the sedimentary deposits of the Protectorate of British Somaliland,* 1954, based on ground and photogeological mapping.

(*d*) *Northern Somalia.* From unpublished compilation map of the basement complex on 1:750 000 scale by A. J. Warden and Somaliland Oil Exploration Company 1:1 000 000 map (see (*c*) above) for the sedimentary deposits.

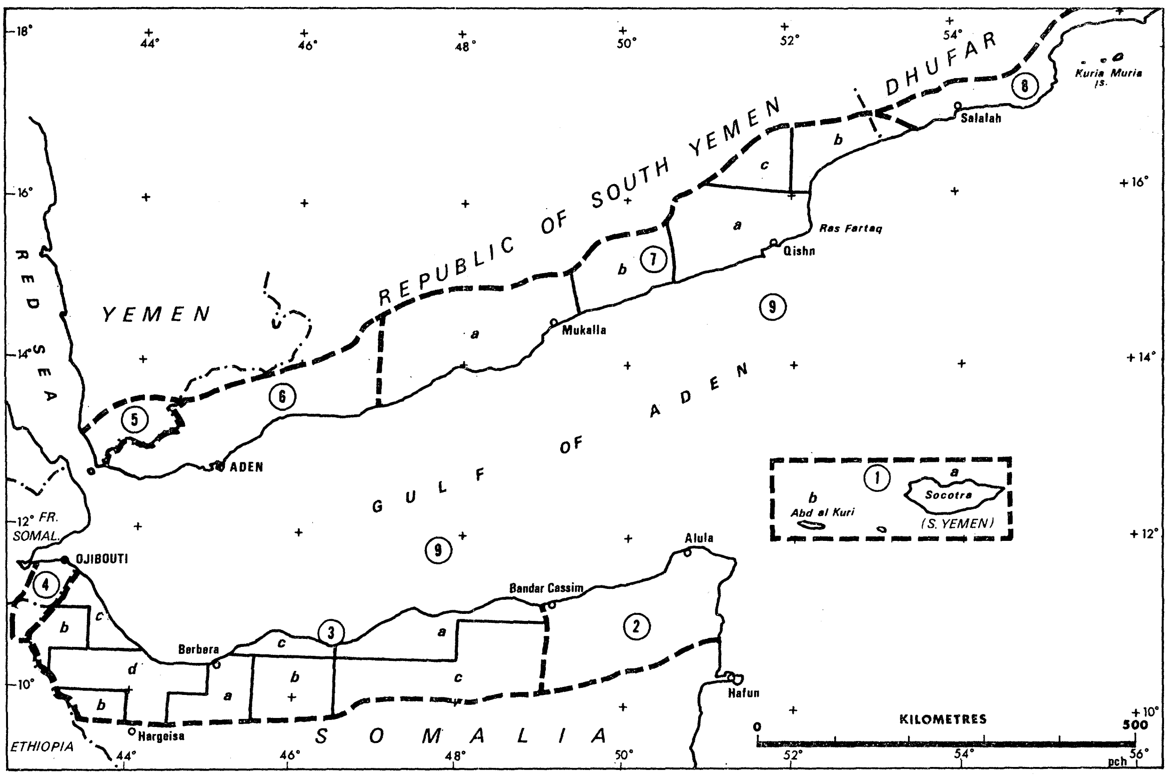


FIGURE 1. Index map of geological compilation sources for figures 3 and 4.

4 *Part of Ethiopia and Territory of Afars and Isas* (*French Somaliland*). From geological map of the Horn of Africa on 1:2 000 000 scale by Mohr (1963).

5 *Part of Yemen.* From Geologic map of the Arabian Peninsula on 1:2 000 000 U.S.G.S./ Aramco (1963) based on work by Geukens (1960).

6 *South Yemen.* From Photogeological map of the Western Aden Protectorate (incorporating data from reconnaissance ground traverses) on 1:250 000 scale by Greenwood (1967), based on 1:80 000 scale air photos and 1:100 000 scale topographic base maps.

7 (*a*) *South Yemen.* From geological maps on 1:500 000 scale accompanying *The stratigraphy and structure of the Eastern Aden Protectorate* by Beydoun (1964), based on 1:100 000 unpublished geological sheets.

(*b*) *South Yemen.* From recent unpublished photogeological work by Z. R. Beydoun plotted onto 1:100 000 topographical base sheets.

(*c*) *South Yemen.* From 1:1 000 000 geological map of the Eastern Aden Protectorate (Beydoun 1964), based on unpublished reconnaissance field traverses by R. Wetzel & D. M. Morton (1948–49).

8 *Dhufar*. From Geologic map of the Arabian Peninsula on 1:2 000 000 scale by U.S.G.S./ Aramco (1963) with some additional unpublished reconnaissance data by R. Wetzel & D. M. Morton and Z. R. Beydoun.

9 *Gulf of Aden bathymetry*. Based on bathymetric plotting charts by A. S. Laughton on 1:1 000 000 scale with revisions up to 1967.

Summary of the geology

(*a*) *Geology of the southern* (*African*) *side of the Gulf of Aden*

There is now an appreciable number of publications dealing with details of the geology of various parts of the southern side of the Gulf of Aden, among which are a number of reports of the former Geological Survey of British Somaliland (see list of references). Good general accounts may be found in Macfadyen (1933), Dainelli (1943), Mackay *et al.* (see Somaliland Oil Exploration Co. 1954), Hunt, Dreyfuss, Dainelli & Tavani (1956), Greenwood (1961), Greenwood & Bleackley (1967), and Beydoun & Bichan (1970). The present synthesis is based mainly on these latter general accounts.

(i) *Basement complex*

Rocks of the basement complex are exposed along the northern Somali coast and on the islands of the Socotra archipelago. They can be broadly divided into three main groups of an older Precambrian igneous and metamorphic series, a younger Precambrian metasedimentary series, and a late Precambrian to Lower Palaeozoic post-tectonic igneous group.

1. *Older basement*. This consists of an earlier phase of granite and gneiss followed by the thick main group of metamorphic sedimentary, volcanic and mafic igneous rocks; a phase of granite invasion with emplacement and formation of synorogenic granites and metasomatic granites followed with the late stages of regional metamorphism and orogeny. Mafic intermediate intrusions including diorite and gabbro appear to have post-dated the main synorogenic granites as late kinematic emplacements but were in turn deformed by later intrusions of granite leading to marginal hybridization on the mainland.

Exposures of this older series extensively occur from the Ethiopian border to the Mait area (longitude 47° 15′ E approx.), at Ras Hantara (longitude 49° 30′ E approx.—migmatite granite) and on Abd-al-Kuri, Semha and Dersa, and in western and eastern Socotra.

Faulting, fracture and grain trends in this older series include NW–SE, WNW–ESE over the main part, with NE–SW and NNE–SSW predominating in the Mait area.

2. *Younger basement metasediments—Inda Ad series and equivalent*. On the mainland this consists of a thick series of weakly metamorphosed (dynamically metamorphosed to the green schist facies) greywackes, sandstones, siltstones, mudstones and limestones with some conglomerates, outcropping between long. 47° 15′ and about 49° 05′ E in a narrow E–W belt. In the east the series is intruded by granite bosses and cut by quartz and pegmatite veins. A probably basal conglomerate between the main series and the older basement, and the absence of polymetamorphic effects suggest a younger age relative to the older basement and most observers are agreed that it is younger, probably of late or very late Precambrian age. It has a pronounced N–S grain with folding on a N–S axis which in the east swings to NNW.

In Socotra a series of bedded mudstones and tuffs (Hadibu series) in places weakly metamorphosed to the green schist facies and folded on NE–SW and then NW–SE axial plane warps, is taken as equivalent to the Inda Ad. This was probably folded, cleaved and lightly metamorphosed by the late kinematic movements that affected the older basement and deformed the gabbros and other intermediate intrusions.

3. *Younger (post-tectonic) granites*. Granites of a clearly intrusive type are known from a number of areas on the mainland (e.g. Las Bar intruding Inda Ad) and have been shown by isotopic age work to be most probably of early Palaeozoic age. In Socotra, post-kinematic activity is more spectacularly demonstrated in a large complex centred on the Haggier mountains. Recent studies by Bichan (Beydoun & Bichan 1970) indicate an early extrusive phase with outpourings of volcanics and the contemporaneous formation of flow banded gabbros in a subvolcanic chamber. These were later intruded and largely surrounded by granites in two stages. Petrographic and field data suggest that these belong to the same phase as the mainland post-tectonic granites. Strong NNE and NE fractures often occupied by dykes, give the grain direction of the main granite body.

No attempt has been made to differentiate between the different granites of the basement complex in figures 3 and 4 (see accompanying wallet) nor has there been differentiation between the volcanics of Socotra and slightly older volcanic series in southern Arabia.

(ii) *Jurassic*

Jurassic deposits consisting of a basal sandstone formation resting on the basement peneplain and overlain by a succession of limestones generally with some marl and shale intervals outcrop in a number of areas in northern Somalia. The biggest area is in the extreme west, north of latitude 10° N and west of longitude 43° 45′ E, with a smaller area south of Berbera in the Bihendula region, an area of small scattered outcrops south and southeast of Karin (to longitude 46° 07′ E) an E–W belt in the Las Khoreh region between longitude 47° 30′ and 49° 05 ′E, and two restricted outcrops in the Ras Hantara area. The Jurassic is completely absent from almost the entire southern escarpment area, the belt between longitude 46° 07′ and about longitude 47° 30′ E, and from the Socotra archipelago, where Cretaceous sediments rest directly on the basement (figure 3).

Most observers are now agreed that the basal sandstone formation (Adigrat Sandstone) which occurs in nearly all areas though with varying thickness, is of Lower to Middle Jurassic age; it generally grades up into the overlying limestones which have been well dated on the basis of abundant macrofauna as ranging in age from Callovian in the lower part to Portlandian or Tithonian at the top.

In the westernmost part, the Upper Jurassic succession (here taken as including Callovian) is not described in any detail in the literature but from personal examination (Beydoun 1964) it can be conveniently divided into a lower limestone formation with some rubbly intervals, a middle mainly shale-marl formation with some limestone, and an upper fine limestone formation with occasional argillaceous partings and in some areas with a capping thin succession of upper shales and marls at times preserved. Cretaceous beds overly locally with a thin conglomerate.

The Bihendula region has received most attention and, as a result, has served as the type area for the Jurassic in northern Somalia; in fact, the succession there is not typical in its detail of that for all northern Somalia. The Adigrat formation embodies basalt flows near the base which are only known from a portion of the adjacent Karin basin but from nowhere else. The overlying Upper Jurassic has been divided into five forma ions (Macfadyen 1933; Mackay *et al.*

(Somaliland Oil Exploration Co. 1954); Hunt *et al.* 1956) which from base to top, are: the Bihen limestone, the shales and lensing marly and argillaceous limestones of the Gahodleh shale formation, the fine argillaceous Wanderer limestone formation, the shales and mudstones with concretionary limestones of the Daghani shale formation, and the capping fine-grained porcellanous Gawan limestone formation often with shale partings. Azzaroli (1968) referred to the middle three formations in the Bihendula region as being pelagic and noted the presence of intraformational limestone breccias in the upper part of the Wanderer limestone and the lower part of the Gawan taking these as evidence supporting the presence of a tectonic scarp to the south so that open sea connection from Bihendula was eastwards. Beydoun (1964) suggested that the Bihen, Gahodleh and Wanderer formations are represented by the lower limestone formation of the western part, while the Daghani may be equivalent to the middle (shale), and the Gawan to the upper (limestone).

In the Karin–Asseh (downfaulted) basin the lower part of the Upper Jurassic succession is present mainly in the southwest, the nature of the small scattered and often faulted outcrops over the rest of the area generally not exposing down to these lower levels. Mackay *et al.* (Somaliland Oil Exploration Co. 1954) correlated the lower units with those of the Bihendula area but detailed differences were not uncommon. The upper units examined in a faulted block appear similar to the Daghani and Gawan.

Where the Jurassic reappears between the Cretaceous and basement complex in the area east of longitude 47° 30′ E, it is appreciably sandy in a number of levels, the sandstone horizons increasing in thickness at the expense of the limestone westwards. Mackay *et al.* (Somaliland O.E. Co. 1954) consider that the Daghani and Gawan equivalents are generally absent due to erosion. Near longitude 49° E, a section was measured whose age is considered Callovian–Oxfordian which contains appreciable lateral sandstone facies development, while further to the west, an older age (Bathonian–Callovian) has been recorded for a succession of sandy and marly limestone and sandy marl (Somaliland O.E. Co., enclosure 3). Further considerable variations in both thickness and facies have been recorded by others (Greenwood 1960; Mason & Warden 1956).

In the Ras Hantara area where the easternmost exposures occur, the Upper Jurassic (here Callovian–Portlandian, Azzaroli & Merla 1957) over the Adigrat, consists entirely of limestones.

The above résumé of the broad variations in lithology and facies of the exposed Jurassic of northern Somalia coupled with the complete absence of Jurassic from the length of the southern escarpment (possibly only originally very thinly or never deposited owing to early persistance of positive E–W scarp?) and from east of the Karin–Asseh basin (probably due to removal after elevation of a positive feature before the Cretaceous transgression?) indicate a fairly complex palaeographic picture during this period, with shallow areas, local positive (? intermittent) uplift, varied open sea connexions, and late or end Jurassic uplift accompanied by differential erosion to various levels. This makes an acceptably reliable reconstruction of conditions obtaining at the time very difficult to make with the present state of local knowledge.

(iii) *Cretaceous*

Cretaceous sediments outcrop extensively over much of northern Somalia and are present on Socotra and other islands in the archipelago (figure 3).

The outstanding feature concerning Cretaceous period deposits of northern Somalia is that they are predominantly calcareous in the east and predominantly arenaceous in the west. The transition from the former to the latter occurs between longitude 49° and 47° 20′ E and the ratio of limestone to sandstone over this zone changes from 10:1 in the east to 1:10 in the west (Somaliland O.E.Co. 1954). An acceptably accurate boundary between the two provinces can be taken at longitude 48° 30′ E.

The Cretaceous succession overlies the Jurassic with no evident unconformity east of longitude 49° E and only very slight unconformity at longitude 49°, though to the west, this unconformity varies appreciably according to the degree of pre-Cretaceous erosion.

In the northeast of Somalia the succession is entirely calcareous (Azzaroli 1968) and the age range is Barremian to Upper Senonian (Maestrichtian); at longitude 50° E, two calcarenite horizons make their appearance as first indications of detrital conditions and by longitude 49° E two shallow marine sandstone horizons have become quite persistent within the succession of limestones and marls. Westwards of longitude 48° 30′ E the succession has become predominantly arenaceous but three quite well-developed limestone horizons persist westwards and maintain a fairly consistent position within the sequence. The lowest of these is probably of Barremian age and occurs a short distance above the base of the Cretaceous having thinned to a few metres only, from an appreciably thicker more continuous limestone succession (about 100 m at longitude 47° 50′ E where it overlies with a thin sandy base, Jurassic limestone). By longitude 47° 10′ E, the lowest limestone almost directly overlies the basement complex (Jurassic having disappeared here) near the road about 10 km southeast of Mait, but 20 km due west, the second (or middle) limestone which is stratigraphically about 100 m above is in turn lying directly on the basement complex, the lower limestone and intervening sands having disappeared (W. D. V. Jones, personal communication 1968) (see locations on figure 3 and figure 2*a*, *b*). A little farther to the southwest towards Heis, the second limestone which has further thinned, is back in its previous place higher up in the sequence, but the lower limestone does not appear to return; a little farther west, the remaining now very thin limestones tongue out south of Onkhor–Karin (see enclosure 3, Somaliland O.E. Co. 1954).

From the Karin–Asseh region westwards in the area north of the plateau, the Cretaceous succession reaches maximum thickness and consists of cross-bedded quartz sandstones with silty, gritty and pebbly levels (Nubian facies), and it also includes special local thick developments of clays and silts which were previously thought to be of different age (e.g. Shabell beds, Dubato clays, etc.—see Hunt *et al.* 1956).

Along the edge of the southern (western) plateau from approximately the Ethiopian border eastwards to longitude 46° 30′ E, the Cretaceous succession, while still in the same (Nubian) facies as that north of the plateau, is considerably thinner and directly overlies the basement complex, although thick Jurassic is present only a short distance to the north. This indicates the persistence of an E–W positive feature either during the Jurassic and into the Cretaceous or from late Jurassic with considerable erosion, persisting well into the Cretaceous.

In Socotra (and Abd-al-Kuri) the Cretaceous succession is predominantly calcareous though basal sands and grits and sandy levels alternating with limestones and marls are present over most of Socotra except in the north; the age range here, however, is Barremian to Cenomanian and possible Turonian. No Senonian (Upper Cretaceous) is anywhere to be found but despite this big time gap, the overlying Tertiary limestones appear to follow without evident unconformity.

(iv) *Tertiary*

Tertiary sediments are predominant in the plateau areas of northern Somalia and Socotra and also extensively occur in the downfaulted Karin–Asseh basin with younger representatives exposed along the littoral of the Gulf of Aden and in the Darror valley (figure 3).

Four main divisions have been adopted for purposes of the present study, three differentiating Palaeocene–Eocene formations and one for the Oligocene–Miocene to Pliocene with differentiation of the Oligocene (*s.str*) where this is known.

1. *Auradu series* (includes the Auradu limestone and Allahkajid beds of the region west of longitude 49° E but not differentiated in the field in the area to the east). The Auradu series consists of a thick cliff forming hard massive succession of limestones with dolomites, and thin bedded limestones with rubbly marly bands in the upper part. Where the two subdivisions of the series are differentiated, they are frequently seen locally to partly replace each other laterally so that where one is thicker the other is thinner and vice versa (Somaliland O.E. Co. 1954). The age range is Palaeocene–Lower Eocene which is well established east of longitude 49° E (Azzaroli & Merla 1957; Beydoun & Bichan 1970) though the lower age bracket has not been strongly established to the west, mainly because no significant new foraminiferal work has been done since original determinations in 1931. On regional considerations, much of the series has to undoubtedly include Palaeocene.

2. *The Gypsum–Anhydrite or Taleh series.* This conformably overlies the Auradu series often with a transitional contact and it has also been observed to thin and lens out laterally. It consists of a succession of massive to banded gypsum and anhydrite, irregularly bedded with chalky gypseous limestones which often contain fauna; the age range is Lower to Middle Eocene, and the series is developed within limestones of Lower to Middle Eocene age. The westernmost occurrence is about 20 km southeast of Berbera; on the plateau, Mackay *et al.* (Somaliland O.E. Co. 1954) record that it does not occur west of longitude 45° E; it is extensive in the Asseh basin and on the northern (eastern) plateau to the north of the Darror graben, lensing out in the Ras Hantara region though locally reappearing eastwards; it is absent in the Socotra archipelago.

3. *The Karkar series.* This overlies the Gypsum–Anhydrite/Taleh series (where present) conformably and generally gradationally, outcropping extensively on the northern plateau, and west to longitude 46° 15′ E in the Asseh basin. Where the intervening evaporites have lensed out, it rests on the Auradu series without evident disconformity. The Karkar series consists in the west of chalky limestones with shales in the lower part, and rubbly silty bands and has an age range of Lutetian–Auversian (Middle Eocene) on the basis of a good foraminiferal assemblage. East of longitude 49° E a much thicker succession of marly and nodular limestones with shales (Karkar) changes to a detrital limestone facies in the extreme northeast (Gumaio series) and extends upwards in age from Lutetian–Auversian to Upper Eocene (Priabonian); it is conformably overlain in the easternmost part (Ras Binnah area) by the Oligocene where this is developed (Azzaroli 1958). This part of northern Somalia east of longitude 49° E was thus more or less continuously submerged from the Palaeocene to the late Oligocene.

No equivalent Middle or Upper Eocene beds to the Karkar are found in the Socotra archipelago; in the west, however, a succession of estuarine sandstones and shales and some limestones with intervals of marine sandy shales and limestones recorded by Macfadyen (1933) from SW of Berbera (Lower Daban beds) contains Middle Eocene fauna and passes down conformably into the Gypsum–Anhydrite series; this appears to be a special near-shore facies of the

Karkar probably very near to its western shoreline. The Middle Daban beds (sandstones with some shales and limestones) from the same area may be partly Upper Eocene since Macfadyen records that there is no discontinuity with the Lower Daban, but Mackay *et al.* (Somaliland O.E. Co. 1954) give these Middle Daban beds an Oligo–Miocene age.

4. *Oligo–Miocene to Pliocene* (*s.l.*). Deposits of this age occur in the littoral strip of northern Somalia bordering the Gulf of Aden (occasionally extending inland in low-lying regions), as far west as the Bulhar area; they also occur along the Indian Ocean strip with extensive invasion of the Darror valley west of Hafun (see figure 3). No attempt has been made to separate these deposits into units of different ages beyond differentiating the proven marine Oligocene (*s. str*); this latter is restricted to the Ras Binnah area north of Hafun where a succession of marine organic and detrital marly limestones of Lower to Middle and Upper Oligocene age (Hafun series) is present (Azzaroli 1958), and to structural depressions in western Socotra where chalky marly limestones of ?Lower, Middle and Upper Oligocene to Lower Miocene age are preserved (Beydoun & Bichan 1970). Sandy conglomeratic Oligocene with rare limestones containing fauna occurs south of Bandar Cassim, but otherwise most of the remaining varied deposits of conglomerates, gypseous and sandy marls and sandstones and reef limestones, of heterogeneous origin and facies (estuarine, continental and marine) belong mainly (with some exceptions) to the Miocene and extend up to the Pliocene.

(v) *Post-basement extrusive rocks*

1. *Trap series.* A series of bedded lavas of varied but mainly basaltic composition is exposed in the extreme west of the area of study within Ethiopia and French Somaliland. These have been mapped by some as Oligocene–Miocene (Dainelli 1943; Mohr 1963), and dated as Oligocene–Pleistocene (Dainelli, in Hunt *et al.* 1956). Dreyfuss, however (in Hunt *et al.* 1956), differentiates in the Ali Sabieh area in French Somaliland where these Traps occur, between ancient basalts of Cretaceous or ?Eocene age, a rhyolite series of Cretaceous to ?Tertiary age, and more recent basalts. It is thus justifiable to assign a probably Upper Cretaceous to Tertiary (?Palaeocene) age to these flows which appear to belong to the same phase as extruded similar Traps in southern Arabia (see later, p. 282).

2. *Aden Volcanic series.* Basalt lavas and pyroclastics of younger age than the Trap series are considered to be of post-Miocene age. They occur in a number of areas in the west and in the northeast (figure 3) and have been assigned a Pliocene–Recent age.

(*b*) *Geology of the northern* (*Arabian*) *side of the Gulf of Aden*

A number of recent publications dealing in some detail with the general geology of southern Arabia has made overall geological knowledge and understanding of that area and the Gulf of Aden region considerably more clear; gaps remaining are mainly in the detail. The present synthesis of the geology of the Arabian side of the Gulf of Aden is primarily based on publications by Geukens (1960, 1966), Beydoun (1964, 1966), Greenwood & Bleackley (1967) and Beydoun & Greenwood (1968).

(i) *Basement complex*

Rocks of the basement complex extensively outcrop from the longitude of Mukalla to the western end of southern Arabia, with smaller occurrences in the east at Ras Sharwayn (near Qishn) and in the Murbat–Kuria Muria regions of Dhufar (figure 4).

The basement complex can similarly be broadly divided here into three main groups as has been done for the African side, with an older Precambrian igneous and metamorphic series, a younger Precambrian metasedimentary series and a later Precambrian to Lower Palaeozoic post-tectonic igneous group.

1. *Older basement.* This consists of an early phase of older gneiss with a main phase of regionally metamorphosed sedimentaries, mafic igneous and volcanic representatives (Aden Metamorphic group), granites and granitized rocks coeval with the main phase of regional metamorphism (syntectonic granites), followed by intertectonic igneous activity with intermediate and mafic intrusions culminated by granites and resultant hybridization. Possibly the last phase of this period was the extrusion of a thick pile of volcanics (Tha' lab group) in the region from the meridian of Mukalla westward to about longitude 48° 15′ E. These are intensely cleaved and are cut by post-tectonic granites and appear overlain by the metasedimentary series. No similar volcanics have so far been recorded from elsewhere in the region; the volcanic episode occurring in Socotra (see p. 271) appears to represent a younger phase. These older basement rocks were only superficially observed in the Dhufar outcrops and Ras Sharwayn. Faulting, fracture and grain in this older basement follows ENE–WSW, NW–SE, and WNW–ESE with only rare N–S occurrences.

2. *Younger basement metasediments—Ghabar group and equivalent.* Rocks belonging to this group are extremely confined in their occurrence and areal extent. The main area is some 50 km WSW of Mukalla at about longitude 48° 42′ E, latitude 14° 17′ N in Wadi Ghabar (Ghabar group) with two subsidiary localities nearby; equivalent metasediments occur again in Dhufar near Ras Sajar (longitude 53° 29′ E latitude 16° 43′ N) and to the west of Salalah (longitude 53° 51′ E latitude 17° 02′ N) (El Hota–Ain Sarit Series). The Ghabar group metasediments consist of N–S striking, tightly folded dynamically metamorphosed conglomerates, sandstones, tuffs, shales and limestones in places reaching the green schist facies while those in Dhufar are similarly folded indurated greywackes, siltstones and shales and mudstones with dolomites, cut by quartz veins. It was originally thought (Beydoun 1964) that the Ghabar group rocks were the lateral equivalent of similar but more highly metamorphosed series occurring some 30 km to the west, although the assumed transition could not be followed in the field, but much more extensive work by Greenwood & Bleackley (1967) showed that in fact these higher metamorphosed beds belonged to the older basement Aden Metamorphic group (see Beydoun & Greenwood 1968).

3. *Younger (post-tectonic) granites.* Granites of a clearly intrusive type similar to those on the southern side of the Gulf are known from a number of localities in the west, in the Mukalla area, Ras Sharwayn and possibly from the Murbat region. Isotope age work on some of these has indicated that they are most probably of Lower Palaeozoic age; they are predominantly calcalkaline and intrude the older rocks. They include a possible tertiary alkaline granite in the region adjacent to Yemen (see Greenwood & Bleackley 1967). No attempt has been made to differentiate between the younger granites and earlier intrusions and granitized bodies of the older basement in drawing up figure 4.

4. *Cambro-Ordovician.* For purposes of this account a limited outcrop area near Murbat in Dhufar exposing a succession of clastics (mainly sandstones, with micaceous shales) of Palaeozoic age overlying the older basement, are included in the basement complex. These comprise the Murbat formation whose age remains debatable but is probably Cambro–Ordovician (see Beydoun & Greenwood 1968). No other post-basement pre-Jurassic sediments are known from exposures anywhere else in the region of study.

(ii) *Jurassic*

Jurassic sediments generally very similar to those present on the Somali side but locally with the additional lateral developments of an Upper Jurassic evaporite facies, overly the basement peneplain and outcrop quite extensively in the western portion from Yemen eastwards to the Mukalla area at longitude 48° 38′ E. In the eastern portion the only definite Jurassic occurs at Ras Sharwayn but very probable Jurassic limestones are present in the deepest exposures of Wadi Masila where they are capped by a thin conglomerate overlain by an interval of undated limestones between them and definite Lower Cretaceous beds. In more recent photogeological work possible Jurassic has been mapped at the base of a fault block below recognizable Cretaceous occurring at the step faulted southern edge of the Hadhramut plateau (longitude 51° 11′ E latitude 15° 11′ N approx.). The area eastwards to Ras Fartak does not expose to the base of the Cretaceous so that it cannot be ascertained if Jurassic underlies the Cretaceous here. Further east in Dhufar, the Jurassic is absent with the exception of a locally preserved succession of basal clastics underlying Cretaceous clastics, which has been identified as Liassic (see Beydoun 1964) (figure 4).

The basal sandstone formation (Kohlan formation) is present almost everywhere and is very similar to the Adigrat of northern Somalia in age and facies; it grades up in a similar way into the overlying Callovian–Tithonian limestones. No lava flows are present, however, within the Kohlan anywhere on the Arabian side like those described for the Bihendula–Karin region equivalent Adigrat.

The overlying Upper Jurassic succession (here taken as including Callovian) has been divided into three formations: the lowest formation is the Shuqra consisting of well-bedded neritic limestones generally with a middle interval of rubbly marls, locally repeated at the top; the middle formation is the Madbi and consists of often shaly or silty marls partly gypseous and with bands and concretions of rubbly marly limestone; the Madbi formation is laterally represented by the Sabatayn formation which consists of evaporites (salt and gypsum, base not seen) with tongues of shales and sandstones, exposed in three salt domes in the area around longitude 48° E and latitude 14° 35′ (see figure 4). Other salt domes outside the map area to the northwest and extending into Yemen indicate the lateral extent of the evaporites which, in the San'a area, can be correlated with non diapiric outcrops (see Beydoun 1964). The uppermost formation is the Naifa which conformably overlies both Madbi and Sabatayn and consists of well-bedded fine grained to porcellanous limestones with common partings of dolomitic shale or rubbly marl; it is often capped locally by a sequence of shaly or rubbly marls with limestones but it seems that this may be a lateral facies change from the well-bedded limestones, one increasing at the expense of the other and vice versa. Locally the Naifa formation extends upwards into Berriasian; in a number of sections north of Bir Ali and the Azzan basin, the lower part contains several levels of intraformational breccia-conglomerate mainly of Jurassic limestone pebbles but also rarely including foreign (basement) elements; these breccia-conglomerates have been cited as support evidence for a barrier which probably separated the evaporitic and neritic open-water facies described above before it was overcome by the Naifa transgression (Beydoun 1964).

The Cretaceous succession generally overlies the Jurassic formations unconformably though not with any obvious angularity; the unconformity can be slight or considerable depending on the extent of post-Jurassic differential erosion; in the area near longitude 48° 38′ E, SW of

Mukalla, locally the Naifa and even Madbi formations may be removed while immediately to the east the entire Jurassic is absent with the Cretaceous resting on the basement (the Mukalla high). A number of such 'highs' are present as is discussed later (pp. 285, 288–9). In the Ras Sharwayn section, the Jurassic–Cretaceous unconformity is almost non-existent being suggested by the presence of a brecciated limestone.

The above description of Upper Jurassic formations is based mainly on extensively studied sections between longitude 47° and 48° 38′ E and in the Shuqra area; variations from these undoubtedly occur (such as the change in the Madbi formation of Ras Sharwayn to predominantly limestone with subordinate marl) but these changes as far as they are known are not sufficiently striking to make correlation difficult. The Upper Jurassic formations (excluding the evaporitic facies) correlate well with their equivalent in the western part of northern Somalia.

(iii) *Cretaceous*

Cretaceous sediments outcrop quite extensively along the whole length of the southern Arabian side of the Gulf of Aden region with probable occurrence on the largest of the Kuria Muria islands (see figure 4).

As with the southern side of the Gulf, the outstanding feature concerning Cretaceous period deposits of southern Arabia is that they are predominantly calcareous in the east and predominantly arenaceous in the west. The transition from the one to the other occurs between the Wadi Masila area (longitude 51° E approx.) and the Mukalla area (longitude 49° E approx.). Unfortunately outcrops between Wadi Masila and about longitude 49° 30′ E have not been examined on the ground, but photogeological work over this area indicates that from about longitude 50° E westwards, the succession is predominantly arenaceous, while a distant observation from the coast of an inland exposure (base not seen) at about latitude 50° 25′ E indicated that the upper part at any rate was still arenaceous. The transition area is therefore probably between longitude 50° 30′ and 50° 45′ E since, in the Wadi Masila section a little farther east, the succession belongs to the calcareous province.

Where the Jurassic succession is present, it is overlain by the Cretaceous with only very slight unconformity in the east but more pronounced though variable unconformity in the west according to the degree of pre-Cretaceous erosion; this in some areas places the Cretaceous directly over the basement peneplain (see figures 2 and 4).

At Ras Fartaq the base of the Cretaceous succession is not exposed but the visible part is entirely calcareous except for an Upper Cretaceous sandstone unit which extends westwards into the arenaceous province; there a lower sandstone formation of Middle Cretaceous age also occurs in the Wadi Masila section (the Middle Cretaceous is absent due to a hiatus in the Ras Sharwayn section between the two). The age range of the Cretaceous formations is Barremian to Upper Senonian (Maestrichtian).

Limestones intervals from the calcareous province extend far westwards into the arenaceous province in the same manner as they do on the Somali side. By Mukalla (longitude 49° 10′ E approx.) three such limestone levels are evident in the otherwise predominantly clastic succession of sandstones with siltstone and mudstone—shale and conglomerate levels; these three limestone levels are quite distinct and well-developed averaging several metres in thickness and maintaining a fairly consistent position within the succession as they are followed west. They are generally fossiliferous and they have been quite satisfactorily dated and named. The lowest is a reduced representative of the Qishn formation of Barremian–Aptian age while the middle is termed the Rays member (of the Harshiyat formation) of Albian age, and the uppermost is the Sufla member (of the top of the Harshiyat) of Cenomanian age (Beydoun 1964; Beydoun & Greenwood 1968).

About 50 km WSW of Mukalla at Jabal Shabb (longitude 48° 30′ E latitude 14° 30′ N) the lowest limestone (Qishn) is thin and rests almost directly on the basement (the Jurassic being absent here). At Jabal Shaqab, 15 km SW, the first limestone and overlying clastics have disappeared and the second limestone (Rays) which can normally be up to 100 m above the Qishn, rests with a thin basal sand directly on the basement. (See locations on figure 4 and figure 2.) A little farther west, the Rays moves up again and the Qishn reappears in the basal part, but by longitude 48° E all three levels have tongued out and the Cretaceous facies here is like that of western Somalia. There is little doubt that these limestones correlate with those described for the Heis–Mait area of northern Somalia (p. 273).

In Dhufar details of the Cretaceous succession are imperfectly known but a general overall similarity to the eastern calcareous province persists despite the occurrence of locally considerable hiatuses. It appears that progressively younger Cretaceous units rest unconformably on pre-Cretaceous rocks from west to east (basement complex units or locally a small Lias outcrop). At Ras Nus, opposite the Kuria Muria islands, only a thin Upper Cretaceous is all that occurs between basement and Tertiary limestones. Sandstones, however, are again apparently abundant in the lower part of the Dhufar succession (as well as the upper) so that a transition towards a nearer shore environment has taken place, probably dominated by a Murbat–Kuria Muria positive area.

(iv) *Tertiary*

Older Tertiary sediments are predominant in the plateaux areas of the southern Arabian side of the Gulf of Aden, while also extensively occurring in the downfaulted Azzan basin in the west; younger representatives occur along the littoral of the Gulf of Aden and in the Wadi Jiza' basin and the Salalah plain (figure 4).

As in the case of the Tertiary sediments on the southern side of the Gulf of Aden, four main divisions have been adopted for the purpose of the present study, in the same way as for the Somali side.

1. *Umm er Radhuma formation* (*s.l.*). This includes the separately differentiated Jeza' formation of the west which, however, is not distinguished in the east. The formation consists of thick cliff-forming hard massive limestones with dolomites, thinner bedded in the upper part and with interbedded shales and rubbly marls (Jeza' formation) mainly developed west of longitude 52° 30′ E. The age range is Palaeocene–Lower Eocene on the basis of an abundant foraminiferal assemblage. Morphology is distinctive as it is for the equivalent Auradu Series of Somalia, and the formation is very widely developed outside the map area in Arabia with little change. The westernmost exposures in southern Arabia are near Ahwar at about longitude 47° E.

2. *Rus formation* (gypsum-anhydrite series). This formation conformably and often gradationally overlies the Umm er Radhuma and, like its counterpart in northern Somalia, it has been observed to thin and lens out laterally. It consists of massive to banded gypsum and anhydrite with irregular beds of chalky gypseous limestone often seen to laterally increase at the expense of the evaporite or to lens out. Where the Rus is absent through lensing out into Lower or Middle Eocene formations, the Umm er Radhuma is directly overlain by the succeeding

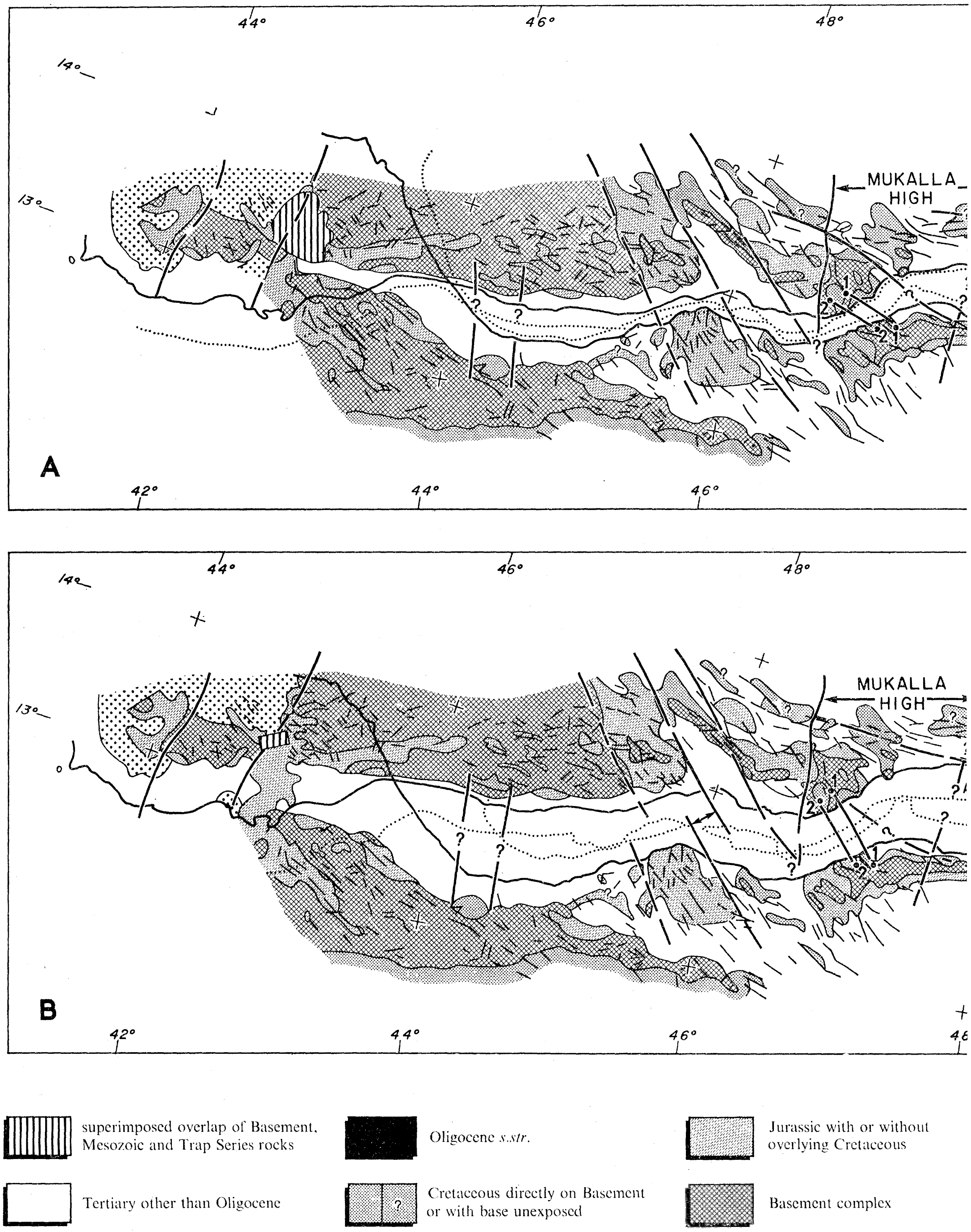
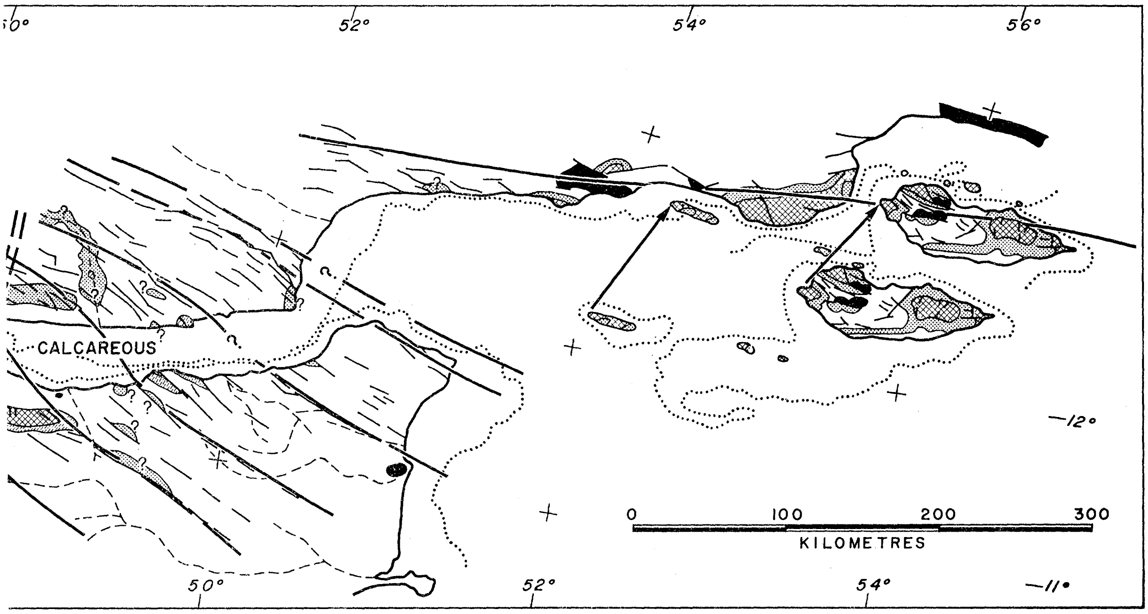
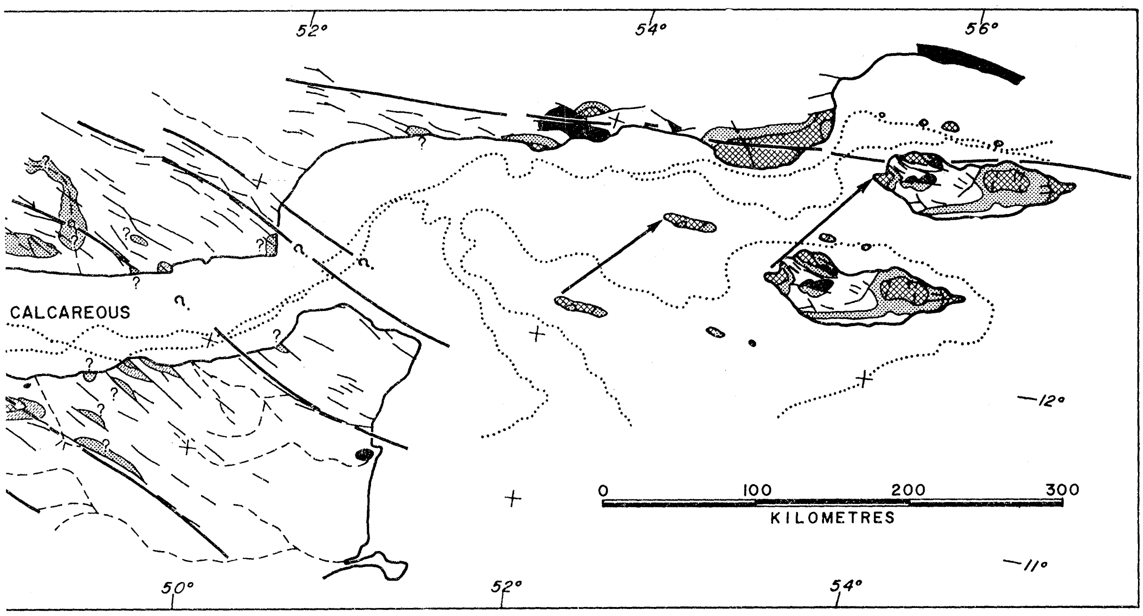


FIGURE 2. The Gulf of Aden reconstructed to presep





Upper Cretaceous Miocene Trap Series — main faults and Basement grain — isobaths: map A, 100 fathoms; map B, 500 fathoms

correlated locations of Cretaceous limestone tongues — suggested correlation lines — drainage

with simplified geology and suggested correlations.

Habshiya formation, making resultant separation of these two on aerial photos very difficult in some areas. The age is taken as Lower to ?Middle Eocene, the formation being developed between limestone units of those ages. Its westernmost extent in the coastal areas is in the Azzan basin (longitude 47° 30′ E. approx.) but it is extensively present on the eastern plateau and in the Jiza' basin from longitude 50° 30′ E eastwards. It lenses out in the Ras Fartaq area and again on the plateau between longitude 52° 50′ and 53° 30′ E.

3. *Habishya formation and equivalent.* This generally overlies the Rus formation gradationally and consists of limestones with marl and shale intervals; in Dhufar facies laterally changes to a lower predominantly shale part and a thicker upper limestone part (Andhur and Qara formations). Where the Rus has lensed out, the formation rests apparently conformably on the Umm er Radhuma. The age is Middle Eocene (Lutetian) on good microfaunal evidence. The formation is mainly confined to the region east of longitude 51° E and primarily to the plateaux but a small isolated outcrop area in a partly sandy facies has been observed in the region 75 km west of Mukalla and 40 km north of Bir Ali; here shales and rubbly limestones are overlain by sandy limestones suggesting nearness to the shoreline. This formation correlates closely with the Karkar of Somalia west of longitude 49° E.

4. *Oligo–Miocene to Pliocene* (*s.l.*). Deposits of this age range are confined to the littoral of the Gulf of Aden with incursions into the Wadi Jiza' basin. No attempt has been made to separate the different deposits into their respective ages beyond differentiating proven marine Oligocene (*s.str.*); this latter appears restricted to the Salalah area of Dhufar and to SW Oman (extreme east of figure 4). The Oligocene of the Salalah area (Taqa formation) consists of a chalky reefoid limestone facies whose upper part may range into Lower Miocene (Beydoun & Greenwood 1968). Other than this formation and the SW Oman occurrences, all other deposits to the west are part of the heterogeneous Shihr group which includes estuarine, continental and marine representatives mainly of Miocene age extending up into the Pliocene, and including conglomerates, sandstones, reef limestones, evaporites, marls and shales.

(v) *Post-basement extrusive rocks*

1. *Aden Trap series.* A thick series of dominantly basaltic lavas with andesites, trachytes and rhyolites, and interbedded pyroclastics occurs extensively in the westernmost part of the area. They have been given an age range of Upper Cretaceous–Tertiary on the basis of field relationship and regional consideration with occurrences in Yemen described by Geukens (1960, 1966) (see Greenwood & Bleackley 1967). There seems little doubt that the extrusion of lavas began in the Upper Cretaceous or end Cretacous to early Palaeocene reaching culmination later in the Tertiary (Oligocene to Miocene?) with intervening periods of quiescence when inter-Trap sediments were deposited. There appears to be no reason why the western occurrences on the African side of the Gulf are not of the same origin and age.

2. *Aden Volcanic series.* This consists essentially of basaltic lavas and pyroclastics though in Aden the series exhibits mixed rocks which can be divided into an older and younger group. The age is post-Miocene and is generally accepted as Pliocene-Recent. The Aden Volcanic series occurs quite extensively in the western part of southern Arabia and more patchily in the east, where the Wadi Masila area forms its limit in that direction (figure 4).

Comparative geology

The recent geophysical work carried out in the Gulf of Aden has established the continuation of the Indian Ocean mid-oceanic ridge-rift along the central part of the Gulf of Aden and shown beyond any serious question of doubt that the greater part of the floor of the gulf is formed of (new) oceanic crust. It must be concluded therefore that the floor of the Gulf of Aden has been formed by seafloor spreading from the median ridge with resultant separation of the bordering Arabian and Somali segments. Most workers are agreed that separation started in the Miocene (probably Middle or Upper?), but there is no unanimity as to whether this occurred regularly or intermittently and how rate, degree, and direction may have varied. Moreover, any assessment of rate and extent of movement between the two sides of the Gulf of Aden is directly related to and has to take into account the amount of movement and opening in the Red Sea and the relative movement of the African (Nubian) block west of the Red Sea and Ethiopian rift system. It cannot be satisfactorily resolved without accounting for the sum total of movement of the three relative to one another, though opinion on this is also varied (see Laughton 1967; Girdler 1967; Mohr 1968; Gass & Gibson 1969, etc.).

Reconstructing the two sides of the Gulf of Aden to postulated preseparation positions by bathymetric fits along the edges of the two continental shelves and examining how details of the geology on large-scale maps match across the remaining much narrowed Gulf, is one way of confirming geologically the extent of separation; it is also a good way of establishing geologically the degree of overlap of preseparation rocks of the two sides on one another in the critical meeting area of the three rift systems at the western end of the Gulf of Aden. Acceptably satisfactory resolution of this superimposed overlap will then have to be found before separation problems can be said to have been resolved.

Reconstructing the Arabian side to its preseparation position by the African side of the Gulf gives, on balance, a favourable general continuity of structural and facies trends across the narrowed remaining water gap. While reconstruction does not bring out any geological evidence opposed to the separation, thus eliminating one main objection against it, neither does it reveal many positively straightforward matching correlations; the 100-fathom (200 m) bathymetric fit, however, has nearly all of these compared to the 500-fathom (910 m) fit. Moreover, both fits require a further northeast movement of the Socotra shelf to accommodate a fit with the Dhufar–Kuria Muria region, while the 100-fathom fit shows an area of superimposed overlap of older rocks in the extreme west which, however, is barely present on the 500-fathom fit. Clearly, although the reconstructions resolve the main problems against separation, they create other though relatively minor problems of their own which require resolution. These correlation problems are discussed in the following pages and the results of the reconstructions are summarized in figures 2*a* and *b*.

The reasons for the comparative paucity of distinct matches in the details of the geology may perhaps be mainly explained by two points:

(*a*) The still relatively considerable gap remaining between the reconstructed shores occupied by water or alluvial deposits where no data on the solid geology is available, and where features from either side may alter or terminate; this is particularly significant for structural features.

(*b*) The striking difference in the geomorphology of long stretches of the matched sectors as a result of broad structural expression. Whereas the greater part of the northern side between longitude 49 and about 52° E is formed by the step-faulting of the flank of the plateau down to the coast with consequent drastic diminution in deep level erosion (see Beydoun 1964, plate 14), the southern side between longitude 47 to about 50° E mainly shows the reverse; much of it forms the northern uplifted edge of the gently southerly dipping plateau, exposing in its steep north face all of the succession down to the basement complex (see Mackay *et al.* (Somaliland O.E. Co. 1954, enclosure 2); Azzaroli 1957). This results in apparent absence of correlation between those otherwise matching sectors which is in fact probably almost entirely misleading.

The 100-fathom fit involves a 430 km movement of the Arabian block at the Ras Fartaq area southwestwards to the Alula area and an 8° clockwise rotation to restore the area to a postulated preseparation position, while that for the 500-fathom fit involves a 400 km movement. Both require a separate and additional movement of the Socotra shelf of from 75 to 90 km in a northeast direction with clockwise rotation varying from 7 to 5° respectively.

(*a*) *Basement complex*

Basement complex rocks provide only very general indirect support for separation in their broad distribution. The older basement occurs in the western part of both sides, while the younger metasediments are located to the east with a further region of older basement to their east which in places includes further metasediments. The distribution of post-tectonic granites is erratic and provides no evidence either way.

Older basement outcrops distribution at their junction with the Azzan/Karin–Asseh basin follow a NW–SE trend which is more or less repeated on the east side of this basin. Grain and fault patterns in this older basement have much in common in trend directions on both sides of the Gulf. On the northern side, however, this broad separation of older basement and younger metasedimentaries is complicated by the appearance of an extensive series of volcanics occurring from the longitude of Mukalla westwards for about 90 km (see figure 4) which are not present on the Somali side. Their absence in Somalia does not in itself furnish proof against separation since volcanicity is by its nature generally of limited areal extent and may have been restricted to the area where it is now exposed.

The westernmost limit of the restricted occurrence of metasediments on the northern side (Ghabar group) is at about longitude 48° 30′ E overlapping with the volcanics; while the westernmost extent of the equivalent Inda Ad of the southern side is at about longitude 47° 10′ E which, for the 100-fathom reconstruction, is equivalent to about 75 km farther east; as both series strike N–S, this makes the Ghabar group exposures of the north side unmatched on the south, unless such a match existed and was later removed by erosion. The main Inda Ad belt of the south extends for over 180 km from west to east and is unmatched to the north because of the lack of exposure below the Cretaceous; there is no reason why it should not be present in the subcrop but only deep drilling will resolve this problem.

The return of older basement at Ras Sharwayn near Qishn in the north and at Ras Hantara to the SSW suggests some old connexion in a probably ?N–S striking feature more or less obliterated by superimposed later NW–SE trending block faulting.

Finally the Dhufar Kuria–Muria basement with that of the Socotra archipelago (after additional NE movement), suggests a continuous E–W belt of older basement with local occurrences of metasediments and post-tectonic granites, over which no Jurassic appears to have been laid or left.

(*b*) *Jurassic succession*

The present distribution of Jurassic rocks does not furnish any data that can be used in support of preseparation reconstructions for the region. At the same time there is no evidence which emerges that can be called impossible to reconcile with separation (see, for example, Azzaroli 1968). One important fact that emerges from examination of all the available data is that neither the Arabian nor the Somali Jurassic formations have been studied regionally in sufficient detail to permit reliably accurate palaeogeographic differentiation of the individual Jurassic stages or to permit the delineation of facies distribution in sufficient detail to provide support for or against separation.

On the Arabian side the Jurassic has not been studied over its entire distribution area from behind Shuqra eastwards to the Azzan basin (figure 4), while over a longer sector between longitude 48° 38′ E and Ras Sharwayn, the Jurassic is either absent (Mukalla 'high') or not exposed. In the best-studied region between longitude 47° and 48° 38′ E the Jurassic shows sufficient variations in the development of an evaporitic facies, the presence of intraformational conglomerate-breccias as well as quite striking thickness changes (see pp. 277–282) to indicate a fairly complex palaeogeography. This indication is more than confirmed by the variation in lithology of the Somali occurrences as already discussed, with presence of neritic, pelagic and detrital facies and intraformational breccias (see pp. 271–2). All these go to show that Jurassic period palaeogeogaphy was influenced by changing neritic areas, open sea spans, localized barred-basins as well as positive areas providing detritus which may have had protracted persistance or only short positive spells.

With the late or terminal Jurassic, the development of more regional E–W uplifts as well as generally N–S highs and lows further complicated the already varied picture. Part of the Somali plateau became positive on an E–W trend as indicated by the absence of Jurassic and thinning of the Cretaceous over this area (Somaliland O.E. Co. 1954; Azzaroli 1968). Recent evidence indicates that similar but probably older uplift had taken place on the Arabian side where the Jurassic is absent or only patchilly thinly preserved along a westward prolongation of the Kuria Muria–Murbat E–W basement axis of the North Hadhramut Arch (Beydoun 1970). Across this regional E–W trend was superimposed at the end of the Jurassic a succession of block-faulted highs and lows which were originally thought to trend N–S but which now appear to vary from NW–SE through NS to possible NE–SW (see figure 2). These were subjected to differential erosion and the Jurassic appears to have been removed from the highs and (generally) preserved in the lows; the effect of this terminal Jurassic erosion is minimal to absent in the SE part of South Yemen (Qishn region) and in NE Somalia. The best known of these highs in southern Arabia (Mukalla high) where Jurassic is absent was correlated by some workers (see, for example, Laughton 1966) with a similar area on the Somali coast, but examination of the data shows in fact that no reconstruction matching of these features is justified (see figure 2). This question is discussed further in § (*e*).

(*c*) *Cretaceous succession*

Cretaceous deposits provide more direct support for separation mainly because of the clear change in a westerly direction from predominantly calcareous to predominantly arenaceous facies, and in the correlation of identifiabele limestone tongues across the water gap. Despite this general continuity of facies, however, correlations in detail are not without their problems.

Taking first the change from calcareous to arenaceous facies, this occurs at longitude 48° 30′ E on the Somali side but can only be estimated to occur between longitude 50° 30′ and 50° 45′ E on the Arabian side for reasons already discussed (see p. 278). If the estimate for the Arabian occurrence is correct, this would give a more or less south to north change line on the reconstructed maps, though this could be even inclined to SSW to NNE. In either case, the suggestion is of the sea transgressing from the east or slightly south of east onto a gently sloping peneplained surface with few undulations.

Correlating next the limestone horizons in the arenaceous province to the west; the Barremian–Aptian Qishn limestone and the Albian Rays member of the Arabian side have their counterparts in the first and second limestones respectively of the Somali side. In the areas where firstly the lower or first (Qishn) limestone then the upper or second (Rays) limestone directly overlies the basement (see pp. 273 and 279), the lines joining the localities on either side give a NW–SE trend (see figures 3 and 4, and figure 2 for locations). This is also the trend of many of the faults and some of the structural features of the region and suggests that manifestations of this trend were operative in the Lower Cretaceous. The consecutive position of the two limestones on the basement indicates a positive area striking NW–SE and persisting probably till end of the Albian. How far this positive area extended in either direction can not be assessed, but it was probably of local nature as suggested by the return of the lower (Qishn) limestone to the west on the Arabian side (Beydoun 1964, plate 13) though not apparently on the Somali side (Somaliland O.E. Co. 1954, enclosure 3).

At Jebel Mukalla only part of the Lower Cretaceous is present but immediately adjacent, the whole Cretaceous succession occurs; at Ras Sharwayn the entire Middle Cretaceous is absent; there are other examples of intra-Cretaceous unconformities. None of these appears to continue to the Somali side but this is undoubtedly because of their small size and local nature so that their non-continuity does not furnish proof against separation. All these examples of intra-Cretaceous breaks indicate local complexities in the otherwise broadly simple palaeogeographic picture of the Cretaceous, brought about by local movements on NW–SE trends and probably persistence or reactivation of some older terminal Jurassic features (N–S and other directions).

These remarks lead on to a point raised by Azzaroli (1968) concerning the presence of persistent sandstones in the Cretaceous of the otherwise calcareous province of the Arabian side, which have no counterpart east of about longitude 49° 30′ E on the Somali side except for calcarenites at longitude 50° E. Following on what has been discussed above, these sandstone occurrences which are of Senonian age are probably the result of emergence in the ?north on the Arabian side with local regression not extending to the Somali side; these sands are also present in the Ras Nus area of Dhufar where they were most probably derived from the Murbat basement. In this area of Dhufar–Kuria Muria/Abd al Kuri–Socotra (allowing for additional NE movement of the latter to accommodate a fit with the Arabian side), observations are insufficient to assist in correlations other than to confirm the extension of positive areas during the Cretaceous, at times persisting to the Upper Cretaceous (Ras Nus) while others were elevated in the Upper Cretaceous (Socotra). This whole area may well have constituted an overall more positive region than elsewhere to the west, and that after the early Cretaceous transgression, the open sea may have been more to the south and west than to the east.

(*d*) *Tertiary successions*

Tertiary sediments distribution does not provide data that can be used in support of separation. This is mainly because of extensive uniformity in facies of the individual formations and the fact that they mainly occupy plateau areas where geomorphological differences between the two sides (with resultant differences in the degree of formation erosion) cancel out any advantages that may have resulted from broad lithostratigraphic distribution.

Two observations concerning the older Tertiary formations may be pertinent. The westernmost outcrops of Auradu series (Palaeocene–Lower Eocene) occur in the Hargaisa–Bulhar area of Somalia while the westernmost outcrop of the equivalent Umm er Radhuma formation occurs near Ahwar in southern Arabia; these suggest a possible western limit around longitude 43° E in Somalia and perhaps longitude 46° 30′ E in southern Arabia. Detrital sandy Middle Eocene sediments (Lower Daban series) outcrop SE of Berbera in Somalia and sandy Middle Eocene limestones (Habshiya formation) outcrop north of Bir Ali in southern Arabia suggesting a shoreline not far to the west, probably from longitude 45° E in the south to longitude 48° E in the north.

The extension into definite Upper Eocene of the Middle Eocene Karkar formation in the area east of longitude 49° E in Somalia and the development of a special detrital (calcarenite) facies in the Cape Guardafui area continuing upwards into Oligocene (Azzaroli 1958, 1968), together with the absence of Upper Eocene from the Arabian side, is considered as merely indicating that most of this part of the region remained submerged in the Upper Eocene; the easternmost part continued submerged into the Oligocene. Elsewhere to the west and in southern Arabia as well as in Socotra, uplift took place during the Upper Eocene with local invasion of the latter in the Oligocene. The Indian Ocean thus covered NE Somalia east of longitude 49° E in the Upper Eocene, with open sea to the southeast, retreating eastwards in the Oligocene in this region but invading into coastal Dhufar and the Socotra–Kuria Muria 'shallows' as indicated by the distribution of marine Oligocene (*s. str.*) in all these areas; the western limit of this Oligocene sea could not have been much beyond the longitude of Ras Fartaq although arenaceous conglomeratic Lower Oligocene occurs near Bandar Cassim and may have marked the early shoreline in the proto-Gulf of Aden which retreated eastwards with time. The occurrence of a clastic-evaporitic succession of (possible) Oligocene age within the Daban series near Berbera (Macfadyen 1933) is of continental facies, or may in fact belong to the Miocene cycle when marine invasion reached far along the Gulf to the west probably as separation was being initiated.

(*e*) *Structure*

Continuity of structural features including fault or fracture belt trends and block-faulted highs or basins with the added presence or absence of Jurassic sediments on some of these as additional guides, provides the best geological support for the separation origin to the Gulf of Aden, although ambiguities in interpretation remain. This continuity of structural features is much more striking with the 100-fathom bathymetric fit reconstruction, although it is quite apparent on the 500-fathom reconstruction, but then so are the offsets in matchings (figure 2).

Classifications of the different fault trends occurring in the region have been given by earlier writers (e.g. Macfadyen 1933; Mackay *et al.* (Somaliland O.E. Co. 1954); von Wissmann, Rathgens & Kossmat 1942; Henson, in Beydoun 1964, and others) and it is not proposed to go again into this question here. However, figure 2 indicates that the majority of fault trends if not all as shown in detail in figures 3 and 4 belong to a preseparation phase of the structural evolution of the region because of the remarkable continuity displayed by the reconstruction. If separation was initiated in the Miocene (probably Middle or Upper Miocene) then the majority of these faults would appear to be pre-Miocene in age (or pre-Middle or Upper Miocene). Azzaroli (1958, 1968) claims that the main phase of faulting in the region is post-Oligocene (Burdigalian ceasing at end of Miocene) on the basis of questionable source for the Lower Oligocene clastics of NE Somalia to occur near Hargaisa; this would thus call for an entirely different drainage system than exists now, modified and controlled by the fault pattern. In fact the clastics could have had as a source several (basement) areas much nearer to their present occurrence such as the Ras Sharwayn area on the north, or Ras Hantara or the Las Khoreh areas, with little modification to the stream patterns. It is suggested that uplifts and fault movements during the Miocene when the plateaux were elevated, followed and augmented existing faults or trends because these provided easy tension release since they were already lines of weakness.

There is a striking swing of fault patterns from NW–SE to W–E and back again to NW–SE in the eastern part of the region (west of the Alula–Ras Fartaq region) as can be seen in figure 2*a*. The 100-fathom bathymetric contour at the NE tip of the Somali coast as well as the parallel trend of the coast finds continuity on trend in the northernmost NW–SE fault belt on the Arabian side. In the 500-fathom reconstruction (figure 2*b*), although the other fault patterns may be apparently correlated across, the NE coast line and 100-fathom contour are visibly offset from the northernmost Arabian fault belt.

Continuity of block-faulted highs and basins is on the whole quite evident in the western part of the region. The down-faulted NW–SE trending Azzan basin finds reasonably acceptable matching continuity in the Karin–Asseh basin on the Somali side for the 100-fathom fit, and a reasonably obvious offset for the 500-fathom fit (figure 2). This Azzan–Karin–Asseh basin has a well-developed Jurassic–Cretaceous succession overlying the basement complex.

The immediate eastern border of the basin is formed by a parallel trending high where the Jurassic is absent and the Cretaceous directly overlies the basement; the eastern limit of this high is more evident on the Arabian side than on the Somali side because of return in the former of Jurassic sediments to the east, between it and the Mukalla high, whereas the extension eastwards of the belt with no Jurassic cuts out this limit on the southern side (see figure 2 and also figures 3 and 4). Two more such highs where the Jurassic is absent and the Cretaceous overlies the basement are indicated in figure 2 for the area west of the Azzan–Asseh basin. If the correlation of these occurrences is valid, then they are seen to have different trends to that on the east, one being N–S and the other NNE–SSW. This would appear to confirm what has already been mentioned, namely that terminal Jurassic highs are not necessarily on true N–S trends as was previously thought (Beydoun 1964, etc.).

The Mukalla high (Beydoun 1964) is an area where the Jurassic is absent as a result of terminal Jurassic differential uplift and erosion. (There is no evidence of thinning in the complete Jurassic succession immediately adjacent on the west as the edge of the high is approached—Beydoun 1964.) This feature was assumed to be a N–S high whose observable western limit (longitude 48° 38′ E) coincided with the western limit of a geophysically mapped N–S high north of Wadi Hadhramut some 200 km to the north, and a tentative assumption of continuity across an unknown area was made. The eastern limit of the Mukalla high was then assumed on the basis of this correlation, to coincide with the mapped eastern limit of the geophysical high since there was no other way of delineating it because of the lack of deep exposures above the base of the Cretaceous. In fact this eastern boundary is completely hypothetical and it would appear from recent reassessment of the data, that the tentative assumption of continuity between the Mukalla high and the geophysical one in the north is not justified. The eastern limit of the Mukalla high may perhaps be placed at about longitude 50° E where possible Jurassic rocks recently identified from air photographs outcrop; on the other hand, these possible Jurassic sediments may extend farther west in the sub-crop. If the latter is the case, their western limit may coincide with an extension northward of the eastern limit of the Somali high where Cretaceous overlies basement on the west and Jurassic overlies it on the east. There is no way of confirming any of these suggestions at the present, but even if the last assumption is valid, the western limit of the Somali high is appreciably further to the west (at least 50 km) merging with that forming the eastern limit of the Azzan–Karin–Asseh basin (see above). These points are sufficient to show that the correlation of the Mukalla high southward with a similar feature in Somalia to provide evidence of continuity (Laughton 1966) is not valid or justifiable. Figure 2 summarizes some of these points.

In the Dhufar–Kuria Muria–Socotra shelf sector, Jurassic rocks are again absent and Cretaceous beds overly the basement complex. It cannot be ascertained if this region constitutes several positive areas on the scale of the Mukalla high, or more likely the eastern prolongation of the North Hadhramut Arch where the Jurassic is now known to be mainly absent, or only patchy and thinly preserved (Beydoun 1969). It is probable that both influences have contributed.

(*f*) *Superimposed overlap*

The most serious challenge to reconstructions of the Gulf of Aden is in the superimposed overlap of pre-Miocene rocks (basement complex and Jurassic–Cretaceous sediments and Cretaceous–Tertiary Trap rocks) that result in the westernmost part when this is done. This overlap of rocks that could not have occupied one and the same area prior to separation as their respective ages and virtually undisturbed nature shows, is considerably greater for the 100-fathom reconstruction than it is for the 500-fathom one (figure 2). Part of the South Yemen–Yemen basement complex, Jurassic, Cretaceous and Trap series are superimposed and overlapped onto the Aisha-Ali Sabieh horst (*auct.*) of Somalia where Jurassic and Cretaceous sediments on basement, and Trap rocks occur. The overlap area is at least 2000 km^2 for the 100-fathom reconstruction. Part of this overlap may perhaps be accounted for by differences in the degree of mapping detail, the western part of the southern side being more general, but this leaves much of the overlap unaccounted for. Moreover considerably more superimposition a little farther to the west outside the map area also develops, involving a much larger area where basement and Jurassic/Cretaceous rocks of Yemen overlap on similar rocks outcropping in the Danakil alps of Eritrea. Although a variety of explanations have been offered to account for these areas of unquestioned superimposition, none of them by itself forms an entirely satisfactory explanation that acceptably deals with the problem or the ambiguities that remain. Clearly, more detailed work in this critical area is needed before this problem can be resolved.

(*g*) *Drainage*

Laughton (1966) suggested preseparation continuation of the Wadi Hadhramut–Masila drainage system across NE Somalia to the Indian Ocean either via the Darror valley or alternatively, via the more direct route to the northeast where the drainage now flows both west to

Candala and east to the Ras Binnah area (figure 3). On the face of it, this suggestion provides attractively simple support for separation, but detailed examination indicates that it cannot furnish acceptably valid evidence or support.

Taking first the northern alternative, the head waters for the two drainage systems are located in a gentle watershed of about 600 m elevation. The east-flowing drainage to the Ras Binnah area is very young and insignificant cutting only superficially through Upper Eocene Karkar beds; it could thus never have represented the mouth of the system now flowing to Candala, let alone the mouth of a mighty system like the Hadhramut–Masila (see also Azzaroli & Merla 1957).

The Darror valley route is more complicated to discuss. The Darror drainage system flows from about longitude 48° E on the Somali plateau in the west to enter the Indian Ocean near Hafun in the east at about longitude 51° E. For about the eastern two-thirds of its length, the Darror valley is between 25 and 50 km in width and most of this area is occupied by a series of Miocene (Burdigalian-?Helvetian) lagoonal deposits with brackish and evaporitic phases, consisting of marls, clays, gypsum, sand and lenses of fine conglomerate (Scusciuban beds, Azzaroli 1958). The valley is referred to in the literature as a 'graben' because of bounding faults; in it the Scusciuban beds overly the Karkar formation (Azzaroli 1957, sections, 1958, and confirmed by deep drilling) with no indications of riverine deposits between the two, as may be expected if the Masila had flowed this way before separation. It may thus be concluded that the Darror Valley was a tectonic embayment invaded by the Miocene sea after retreat of the Oligocene, but frequently receiving river transported replenishments from the surrounding land; the Darror drainage system itself would thus be post Helvetian (Middle Miocene).

An interesting feature is the occurrence of a narrow gorge-like funnel (5 km wide) about 25 km south of Bandar Cassim, connecting the Oligocene–Miocene embayment of this area with the Darror valley (figure 3); this funnel would have provided the route traversed by Wadi Masila if it had flowed to the Indian Ocean via the Darror and it is tempting to attribute its formation to river erosion. It is, however, also easy to attribute the formation of this funnel to faulting making of it a tectonic gap utilized by the Miocene sea in a local invasion from the Gulf of Aden littoral, possibly to connect with the Darror–Indian Ocean embayment (see Azzaroli 1958, figure 34), and later utilized by local drainage from the plateau flowing to Bandar Cassim. If this drainage had originally flowed south, some deeper incising would be expected if its direction of flow had been reversed.

Finally, if the Wadi Hadhramut–Masila system had flowed through via Bandar Cassim and the Darror, it would have had to considerably change direction to accommodate the present offset in drainage mouths on either coast (figure 2). It is more probable that the Wadi Masila entered a (proto) Gulf of Aden close to where it now does, and that the Bandar Cassim area was an embayment in this Gulf.

Synopsis of geological history

From the foregoing sections it can be seen that a fair amount of evidence now exists which indicates that the Gulf of Aden area has been a region of intermittant structural weakness since the Jurassic; this is suggested by linear uplifts of the Somali plateau and similar uplift of (part) of the south Arabian plateau in the Jurassic, by relative cross-uplifts on different trends in the terminal Jurassic and various stages of the Cretaceous, and by outpouring of basaltic traps in the western part and the adjacent Ethiopian area from the Upper Cretaceous intermittantly through much of the Tertiary. Henson, (in Beydoun 1964) suggested that the Gulf of Aden was probably a region of chronic instability at the intersection of several major fracture zones including the Red Sea and Ethiopian rifts. Emergence with gentle arching of the southern Arabian and most of the Somali plateau and formation of the Gulf of Aden downwarp (?mega syncline) occurred initially in the Upper Eocene as discussed elsewhere (Beydoun 1964, etc.) and limited ingression into a proto Gulf of Aden occurred in the Oligocene with substantial invasion in the Miocene. The mechanism of compression resulting from transcurrent movement along the regional lineaments or major fracture zones of the area was invoked for the uplift and broad arching. Recent work on processes leading to upper mantle upwelling has, however, been shown by Gass & Gibson (1969) to offer a more acceptable uparching mechanism consistent with the separation origin of the Gulf of Aden (and adjacent areas) and the formation of new oceanic crust, as well as with the downwarping of the flanks which were subsequently modified by faulting. Downwarping often masked by considerable erosion and faulting has also been observed in the Red Sea and Ethiopian rift areas (Whiteman 1968; Gillmann 1968; Mohr 1962).

With the Oligocene–Miocene the flanks of considerable portions of the bordering Gulf of Aden uplifts were being gravitationally broken down by faulting on ENE–WSW and EW trends. If separation was initiated soon after, i.e. in the latter part of the Miocene, further augmentation movements along these trends was mainly due to the rise of the land on either side and it is difficult to separate this from earlier movements.

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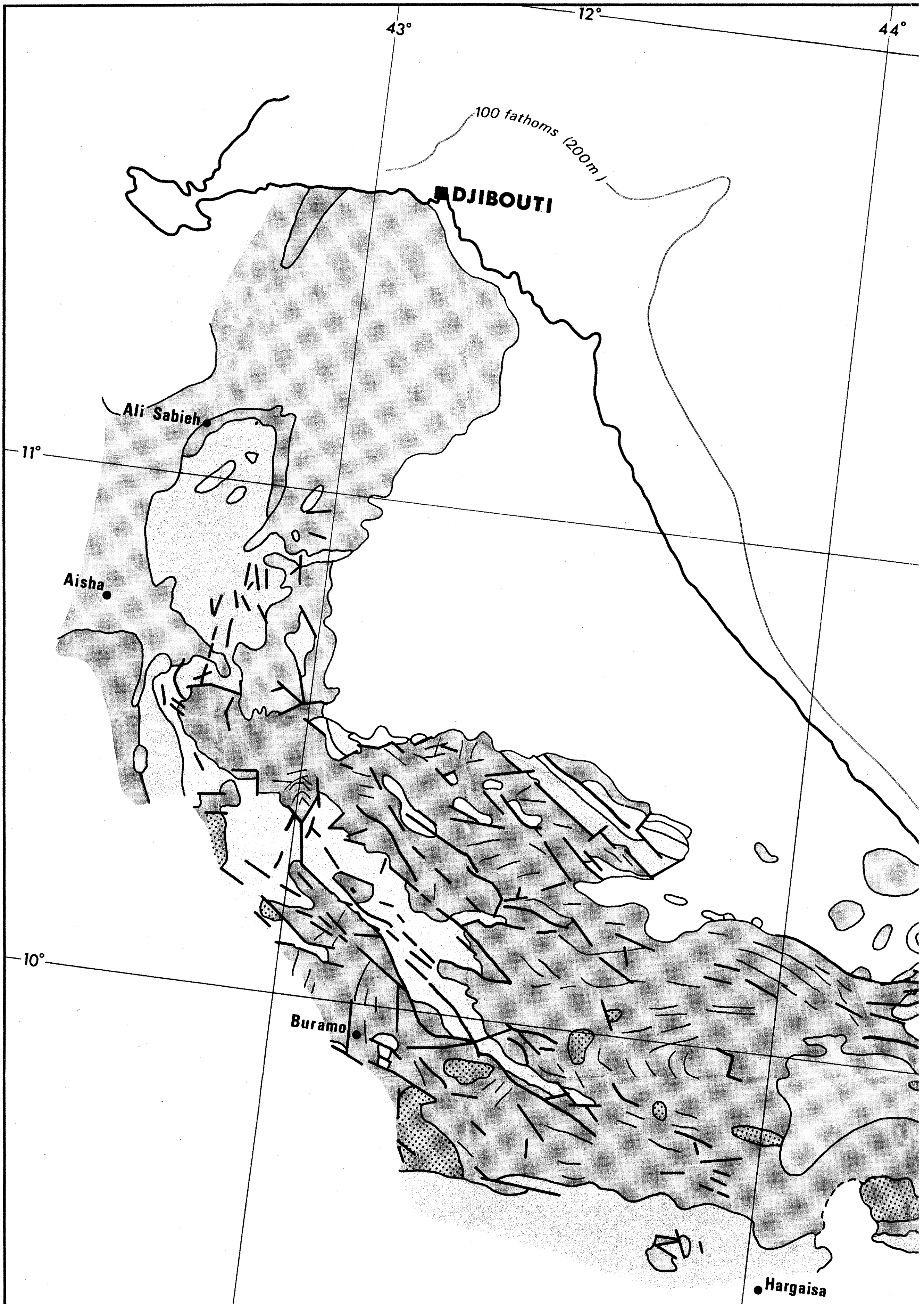
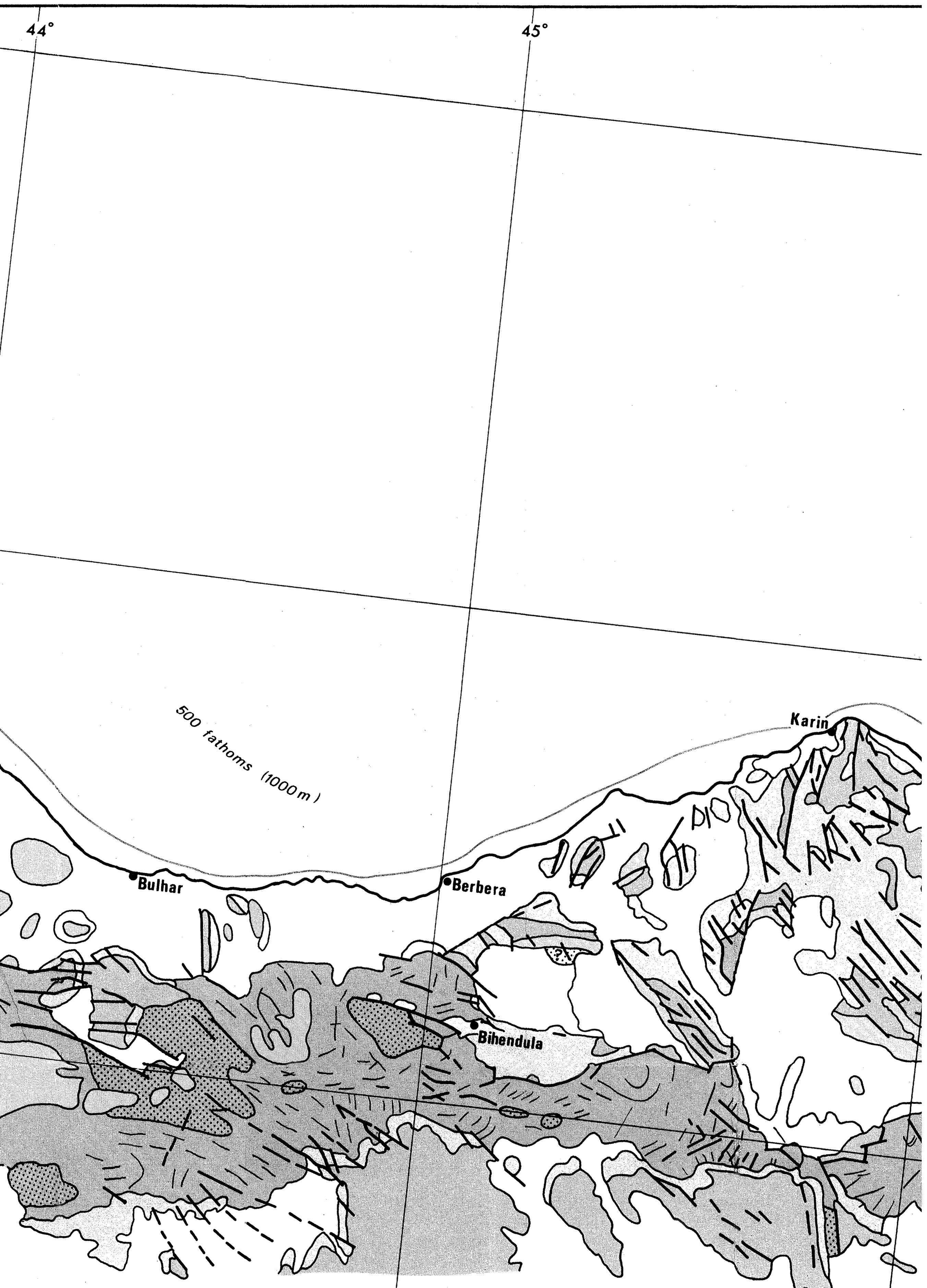
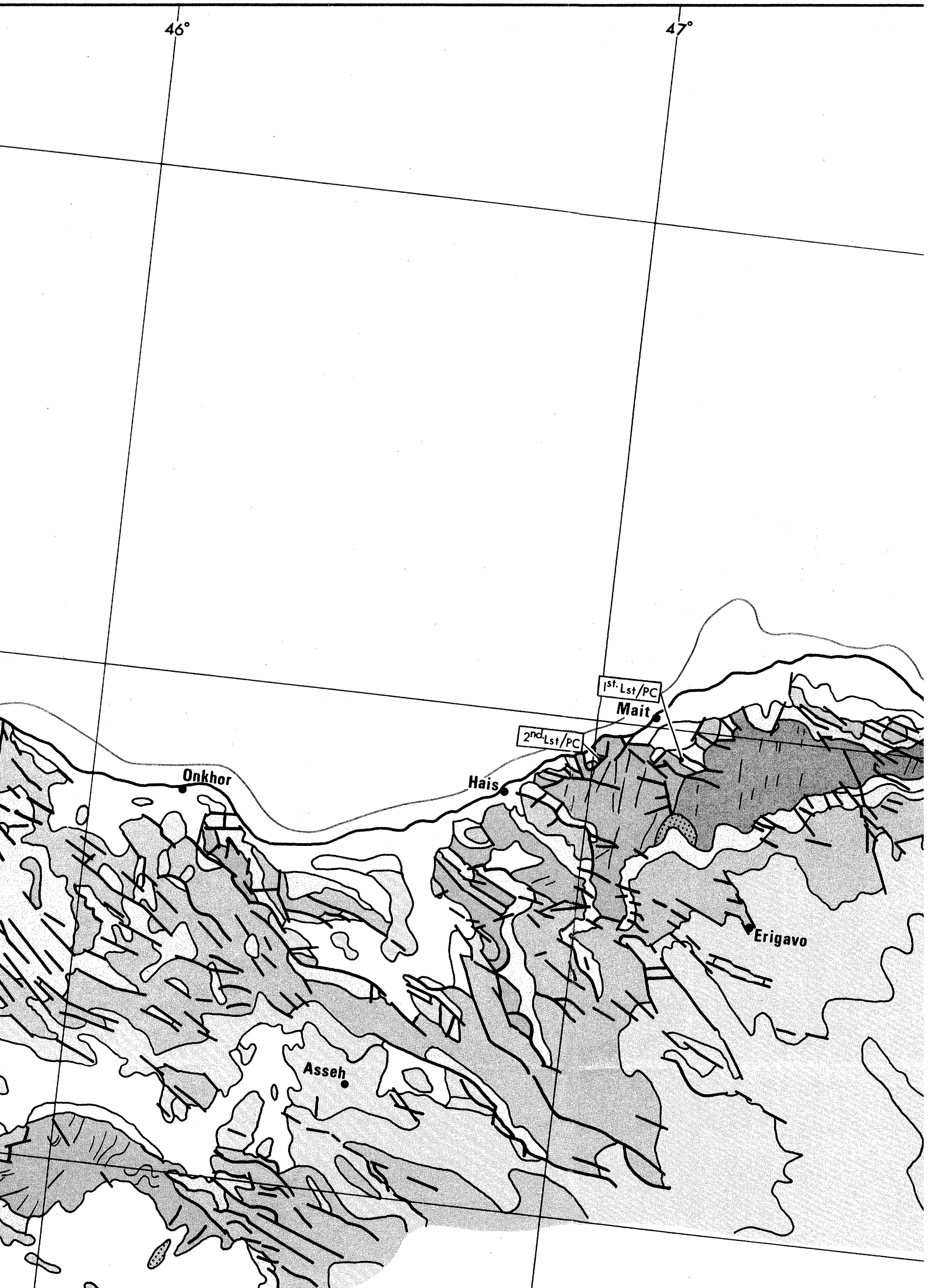


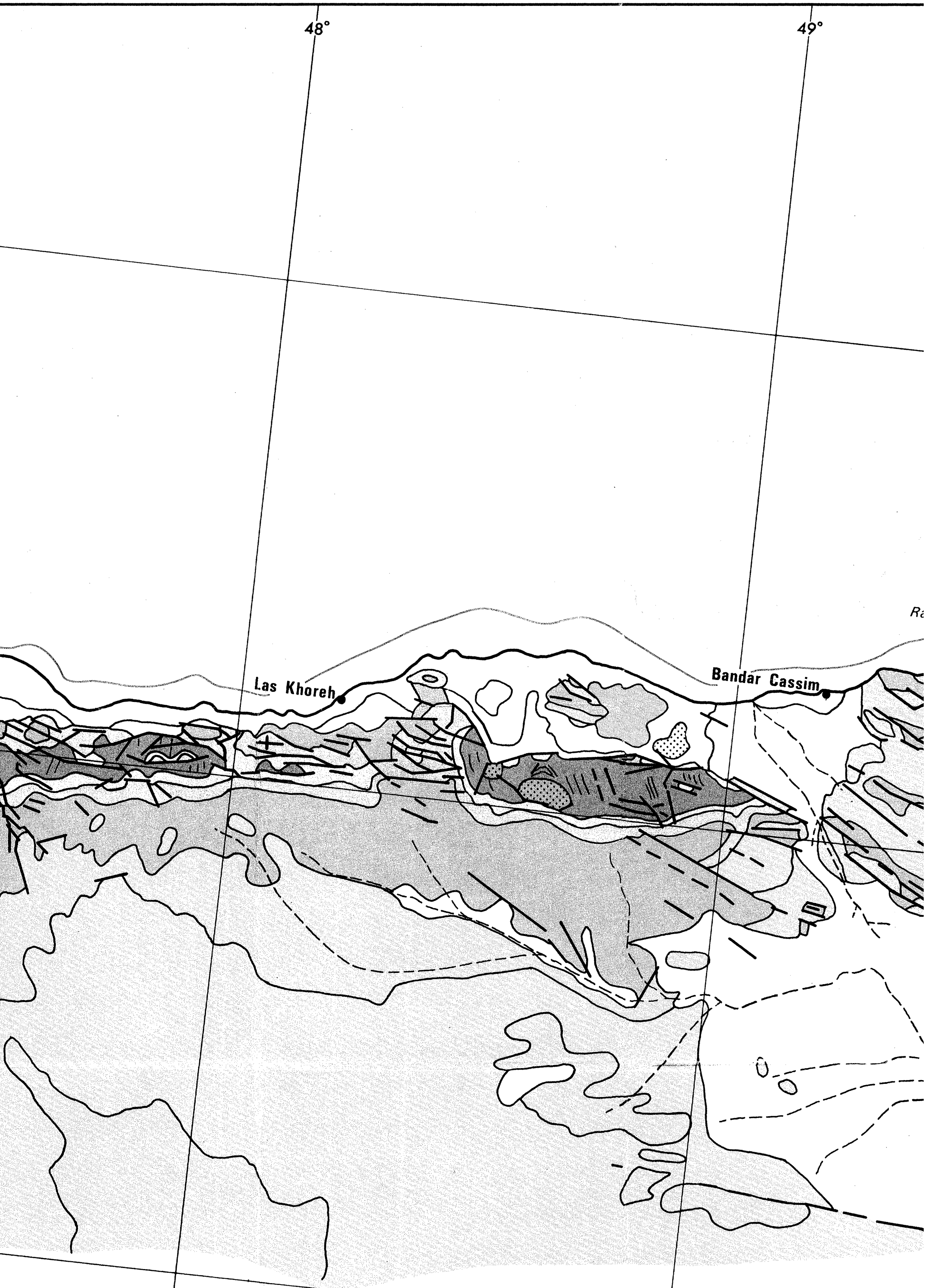
12°
43°
44°
100 fathoms (200m)
DJIBOUTI
Ali Sabieh
11°
Aisha
10°
Buramo
Hargaisa

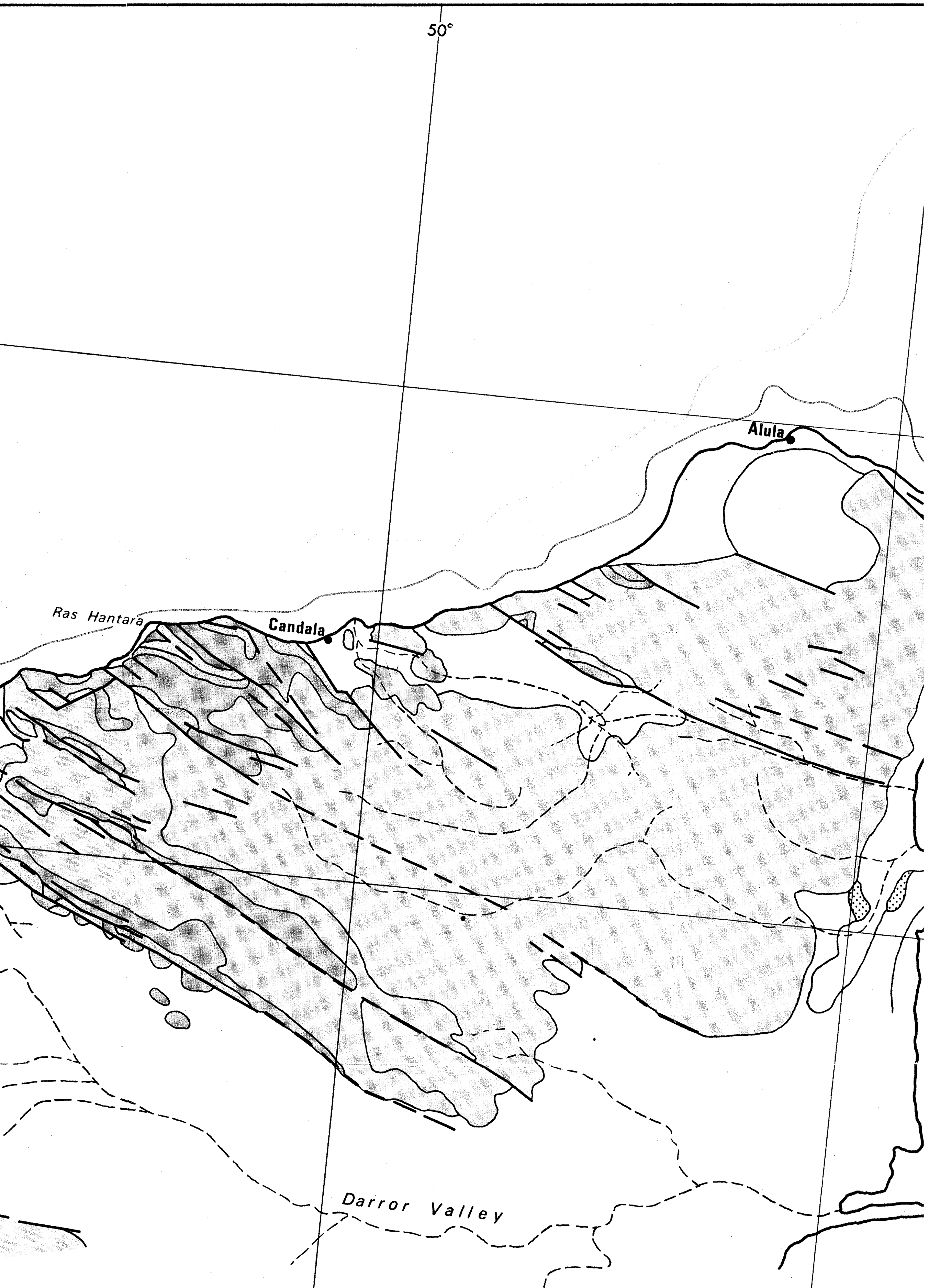


44°
45°
500 fathoms (1000 m)
Karin
Bulhar
Berbera
Bihendula
?

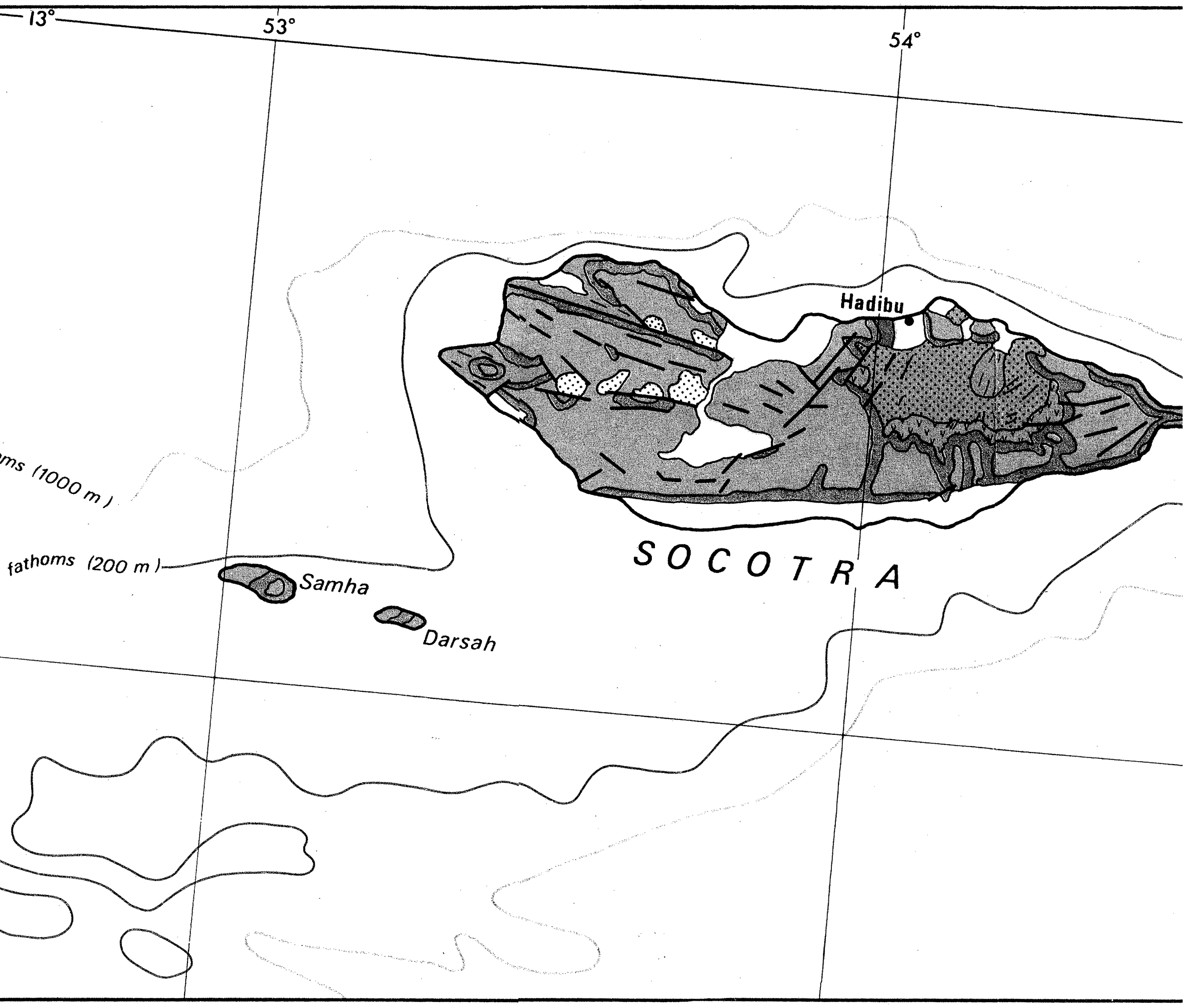


46°
47°
1st. Lst/PC
Mait
2nd. Lst/PC
Onkhor
Hais
Erigavo
Asseh


48°
49°
Las Khoreh
Bandar Cassim


50°
Alula
Ras Hantara
Candala
Darror Valley

13°
51°
52°
500 fathoms (1000
100 fathoms
Abd al Kuri
C. Guardafui
(Ras Aser)
Ras Binnah
100 fathoms
(200 m)
500 fathoms
(1000 m)
Hafun
NORTH
Quaterr
Oligoce
Oligoce
Middle
longitud
Lower-
Gypsum
Palaeoc
Auradu



GEOLOGICAL MAP
RTHERN SOMALIA AND SOCOTRA, GULF

Compiled by Z.R.BEYDOUN (see Figure 1 for sources)

MILES 10 0 20 40 60 80 1

METRES 10000 0 50 100 150 K

Lambert Conical Orthomorphic Projection

Quaternary undifferentiated

Oligocene–Miocene–Pliocene
Oligocene *s.str.* with Lr Miocene

Middle Eocene (to Ur Eocene east of longitude 49° E) Karkar Series

Lower-Middle Eocene
Gypsum-anhydrite and Taleh Series

Palaeocene–Lr Eocene
Auradu Series

Cretaceous undifferentiated

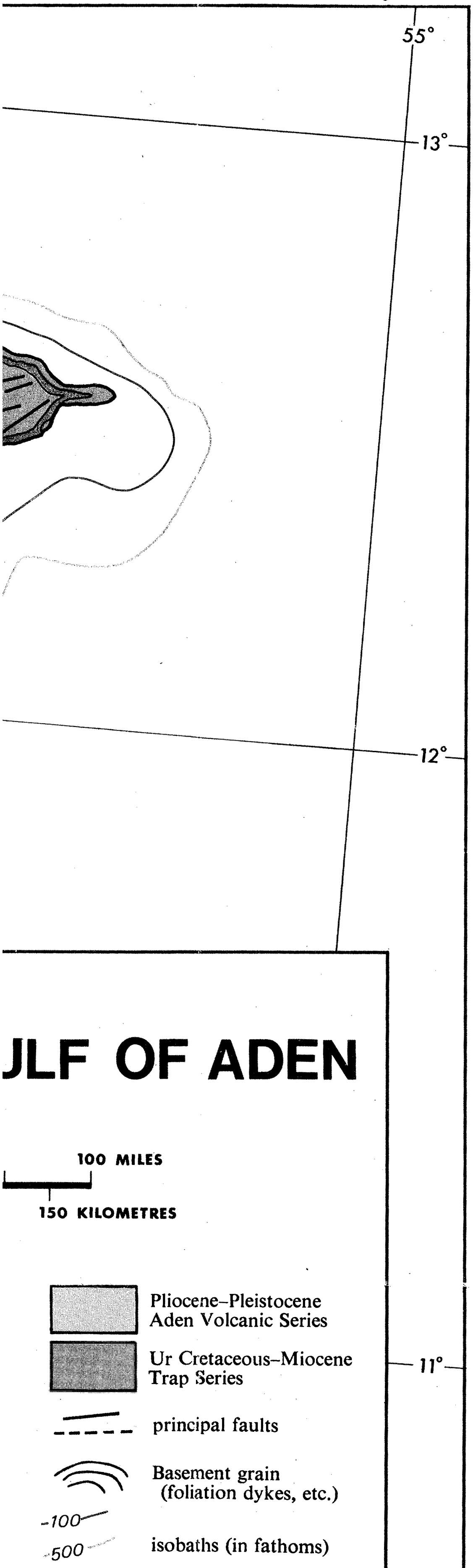
Jurassic undifferentiated

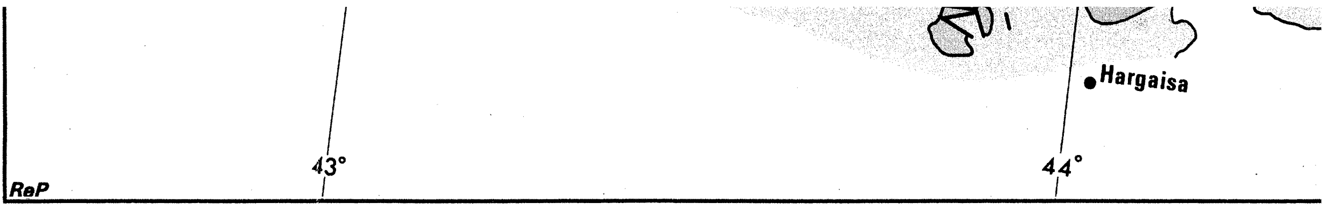
Precambrian metasediments

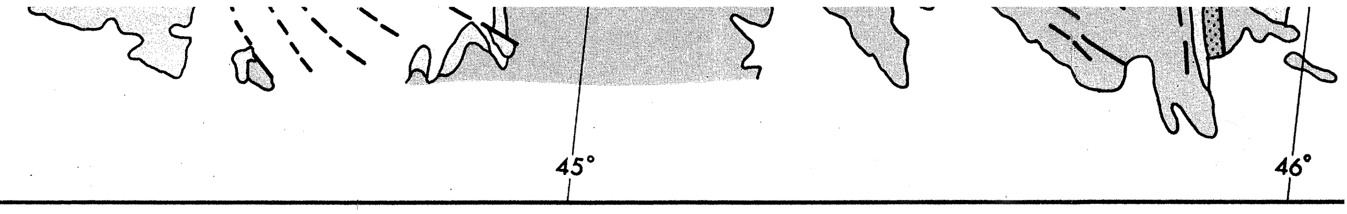
Precambrian and Lr Palaeozoic granites
? Precambrian–Lr Palaeozoic volcanics

Precambrian undifferentiated

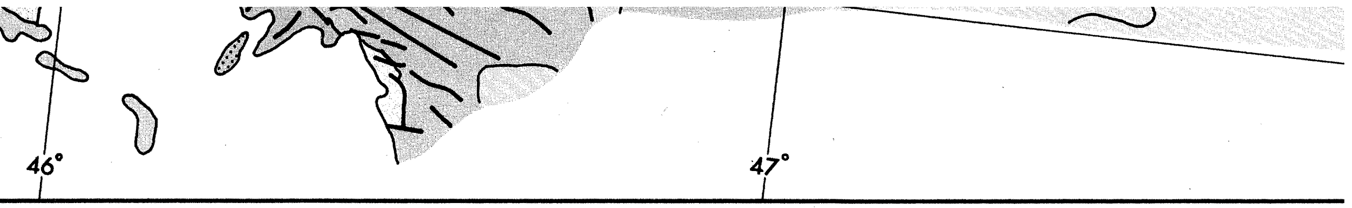
-100
-500

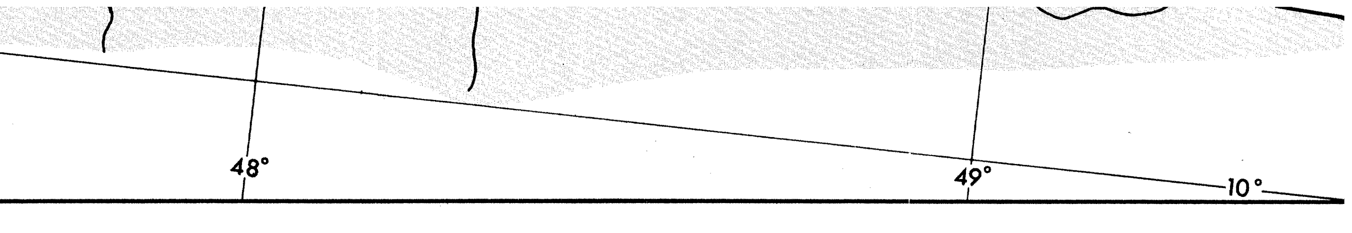

55°
13°
12°
11°
JLF OF ADEN
100 MILES
150 KILOMETRES
Pliocene–Pleistocene Aden Volcanic Series
Ur Cretaceous–Miocene Trap Series
principal faults
Basement grain (foliation dykes, etc.)
100
500
isobaths (in fathoms)


Hargaisa
43°
44°
RaP



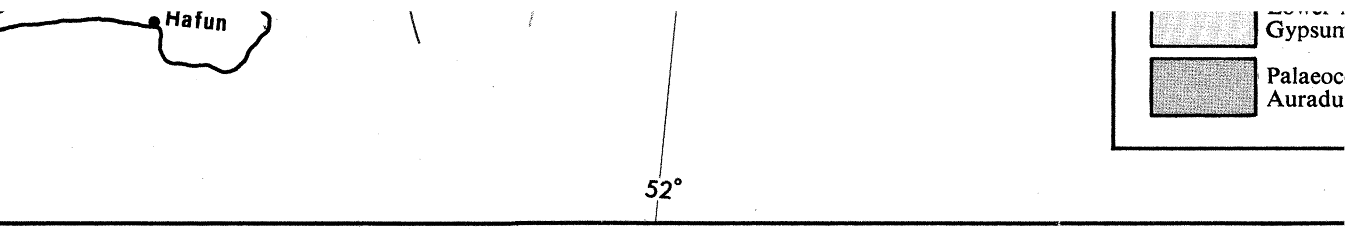
45°
46°


46°
47°



48°
49°
10°

50°
51°


Hafun
Gypsum
Palaeoc
Auradu
52°

Gypsum-anhydrite and Taleh Series

? Precambrian–Lr Palaeozoic volcanics

Palaeocene–Lr Eocene
Auradu Series

Precambrian undifferentiated

-100
-500

53°

54°

(foliation dykes, etc.)

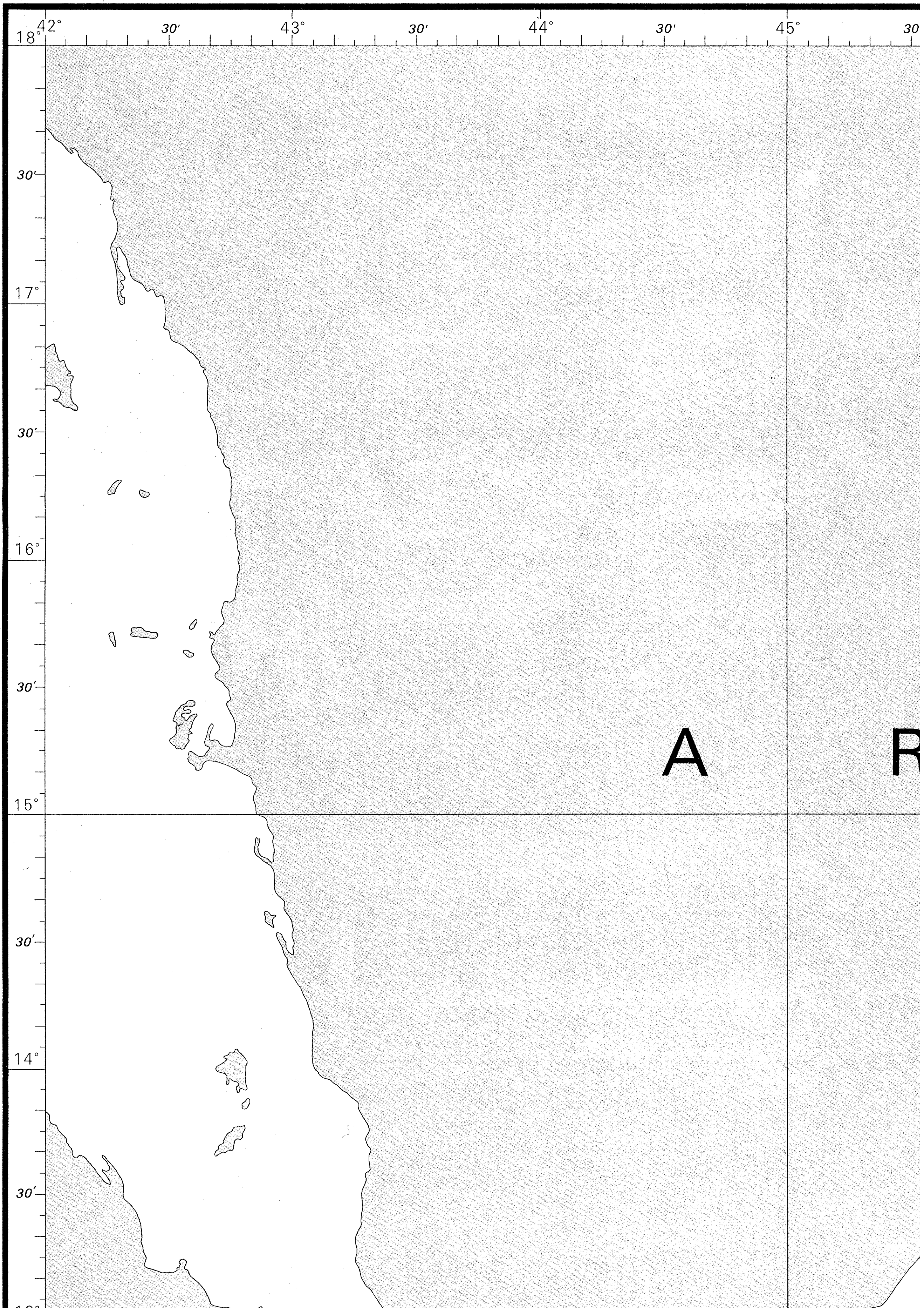
-100 —

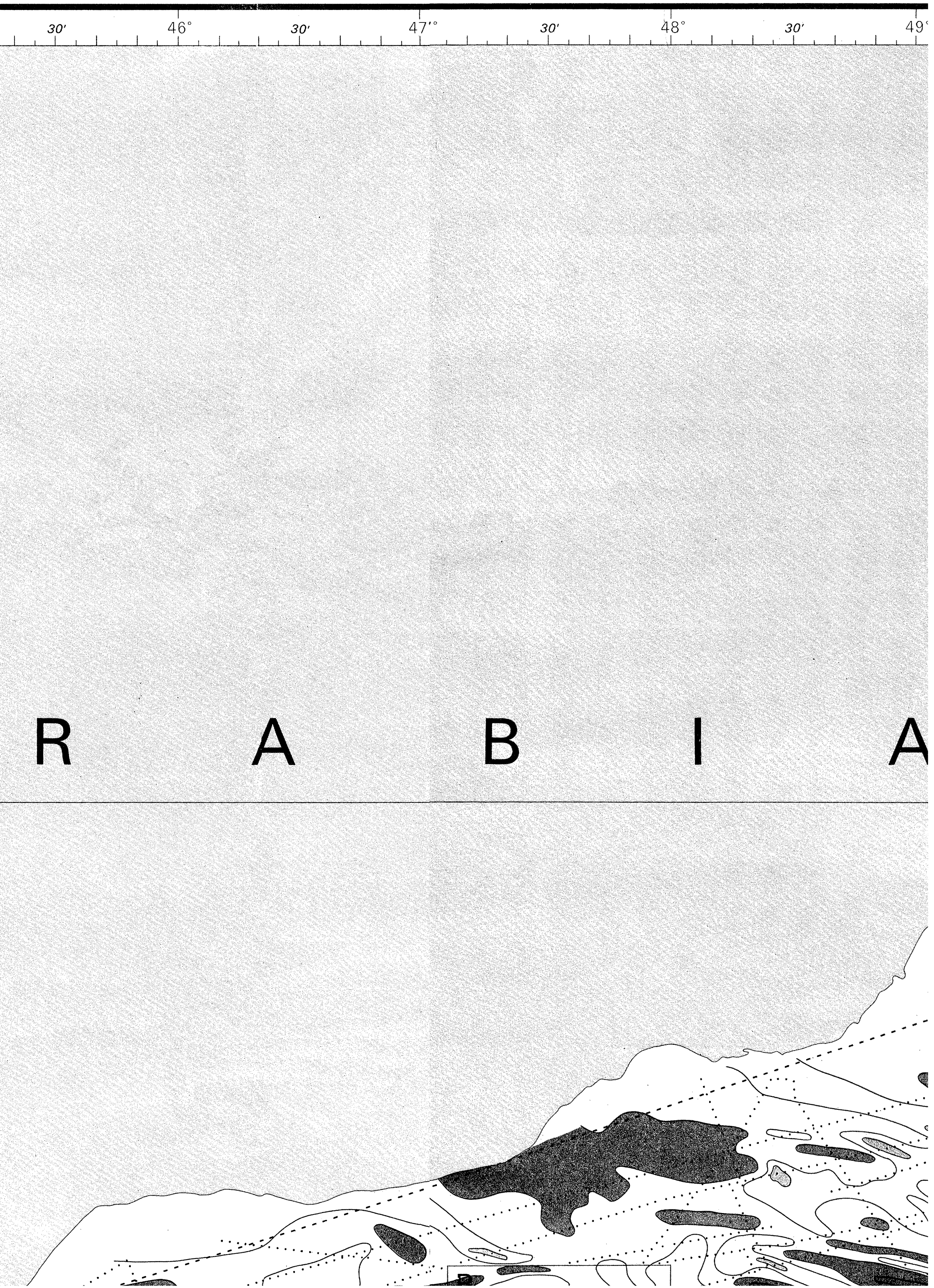
-500 isobaths (in fathoms)

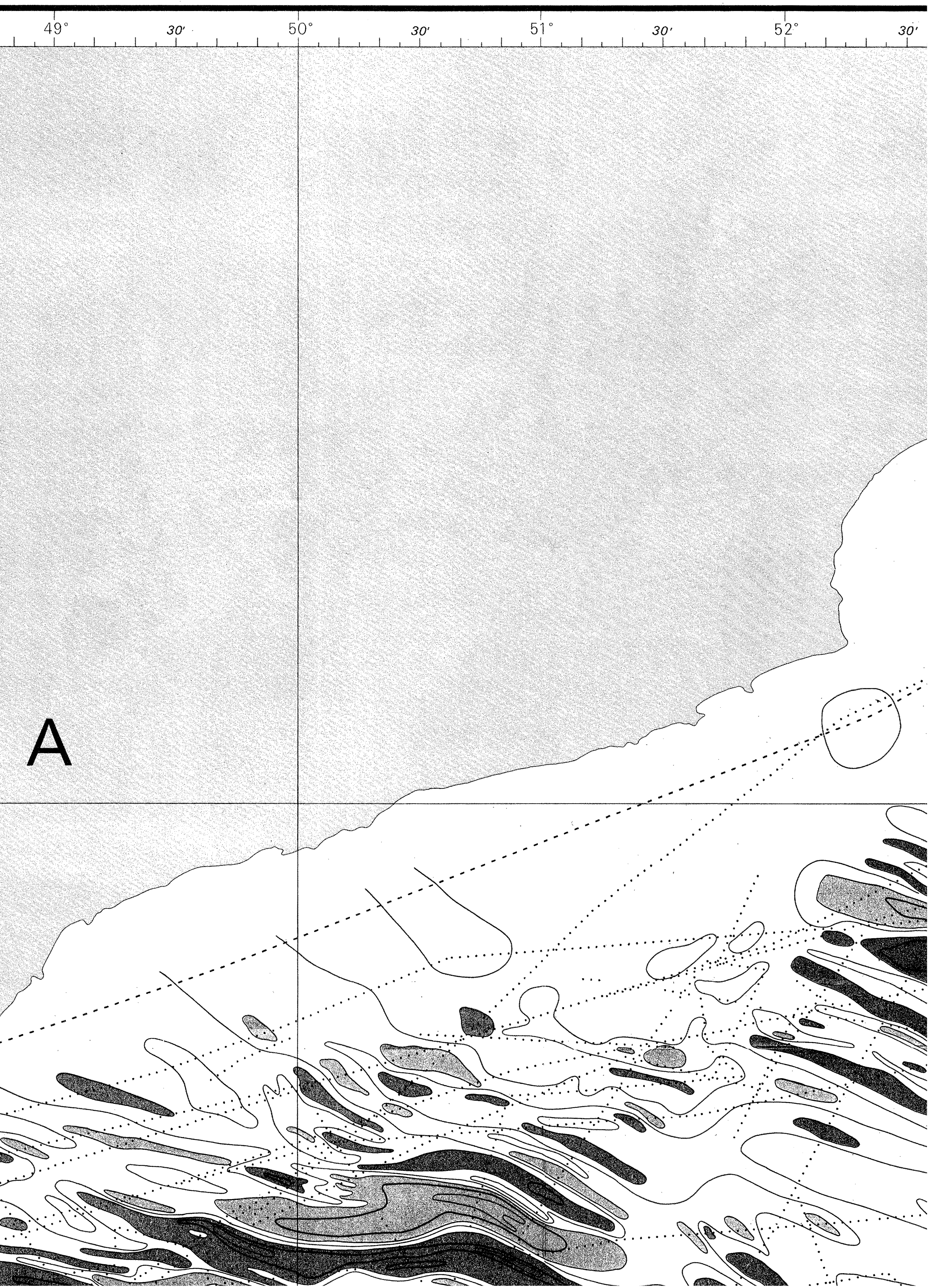
55°

Figure 3

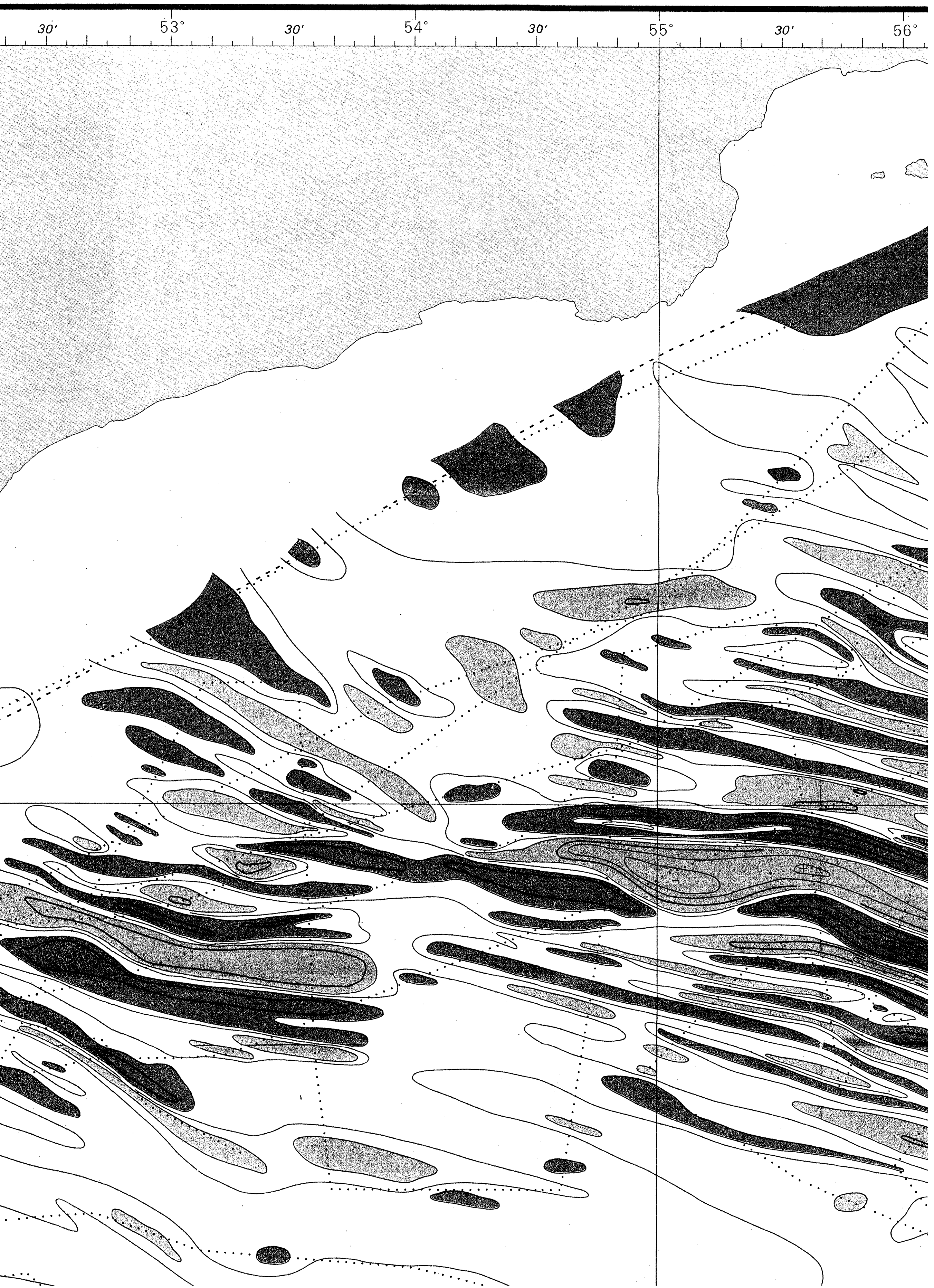
Laughton, Whitmarsh, Jones, Fig. 20, Red Sea Discussion Phil. Trans. Roy. Soc. A



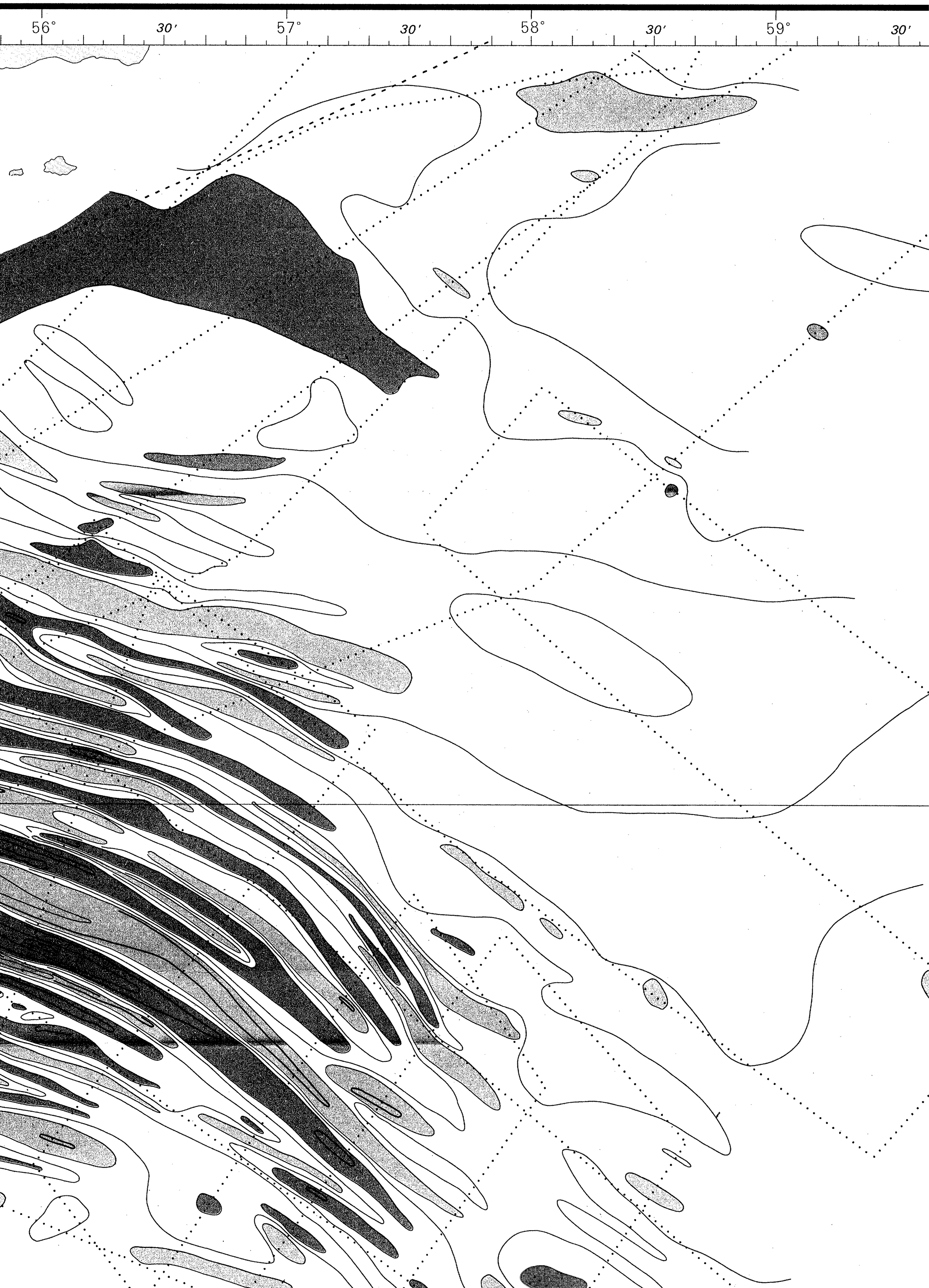

30'
46°
30'
47°
30'
48°
30'
R A B I A

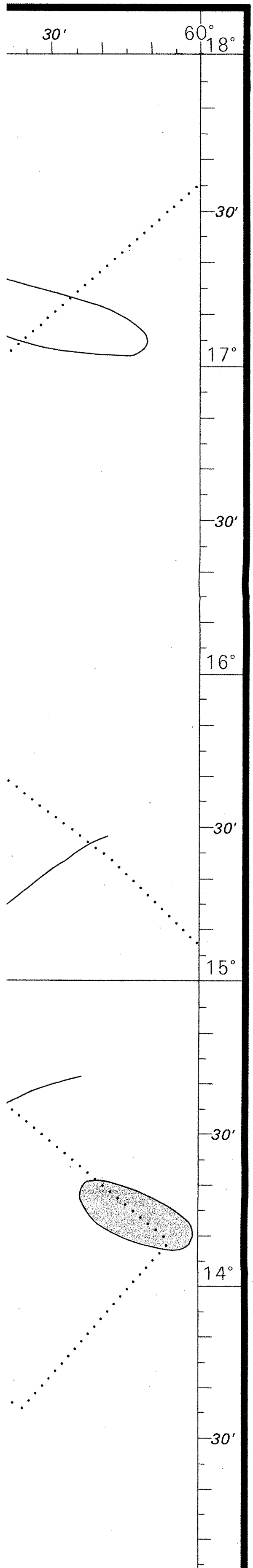


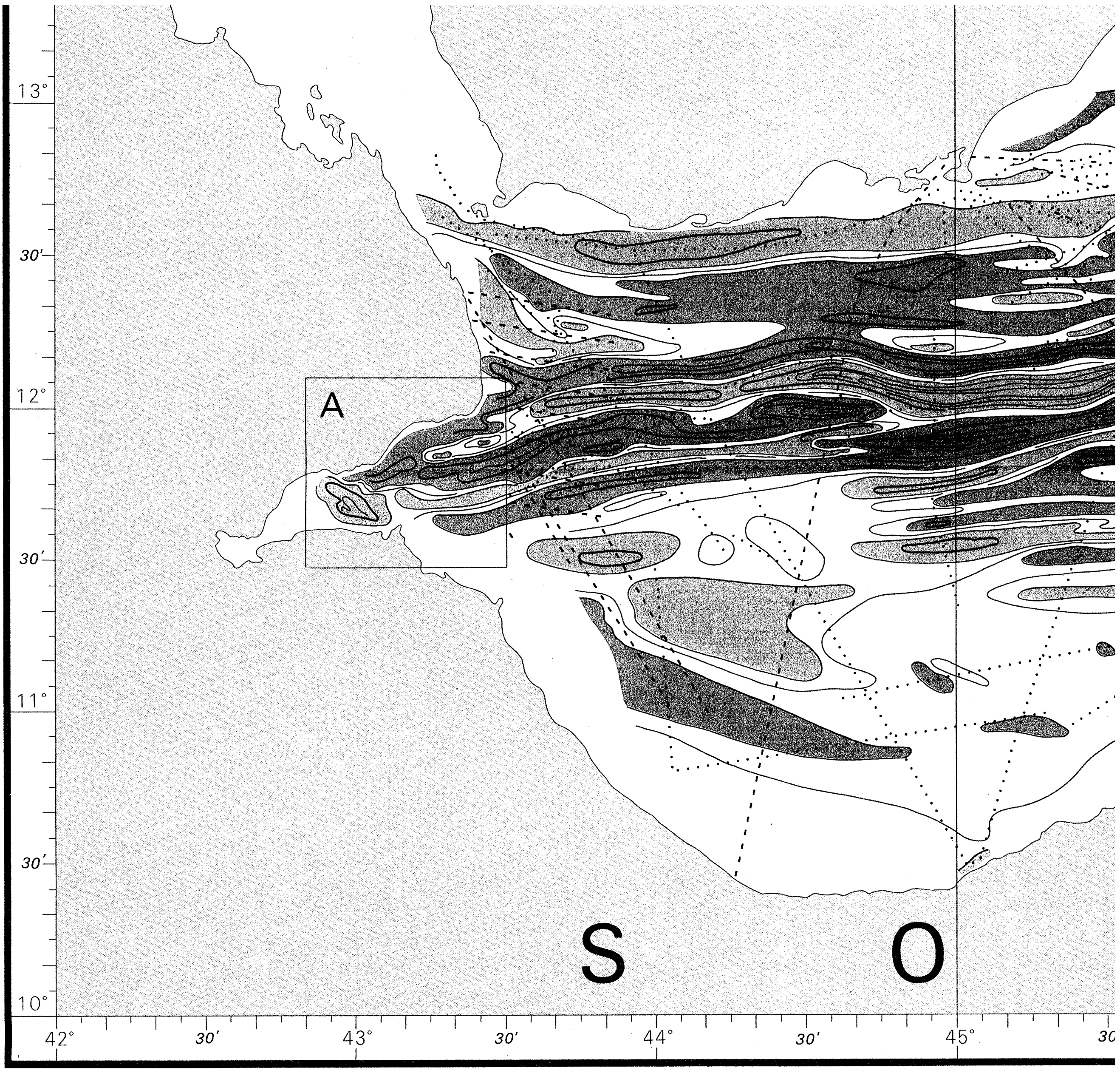
49°
30'
50°
30'
51°
30'
52°
30'
A



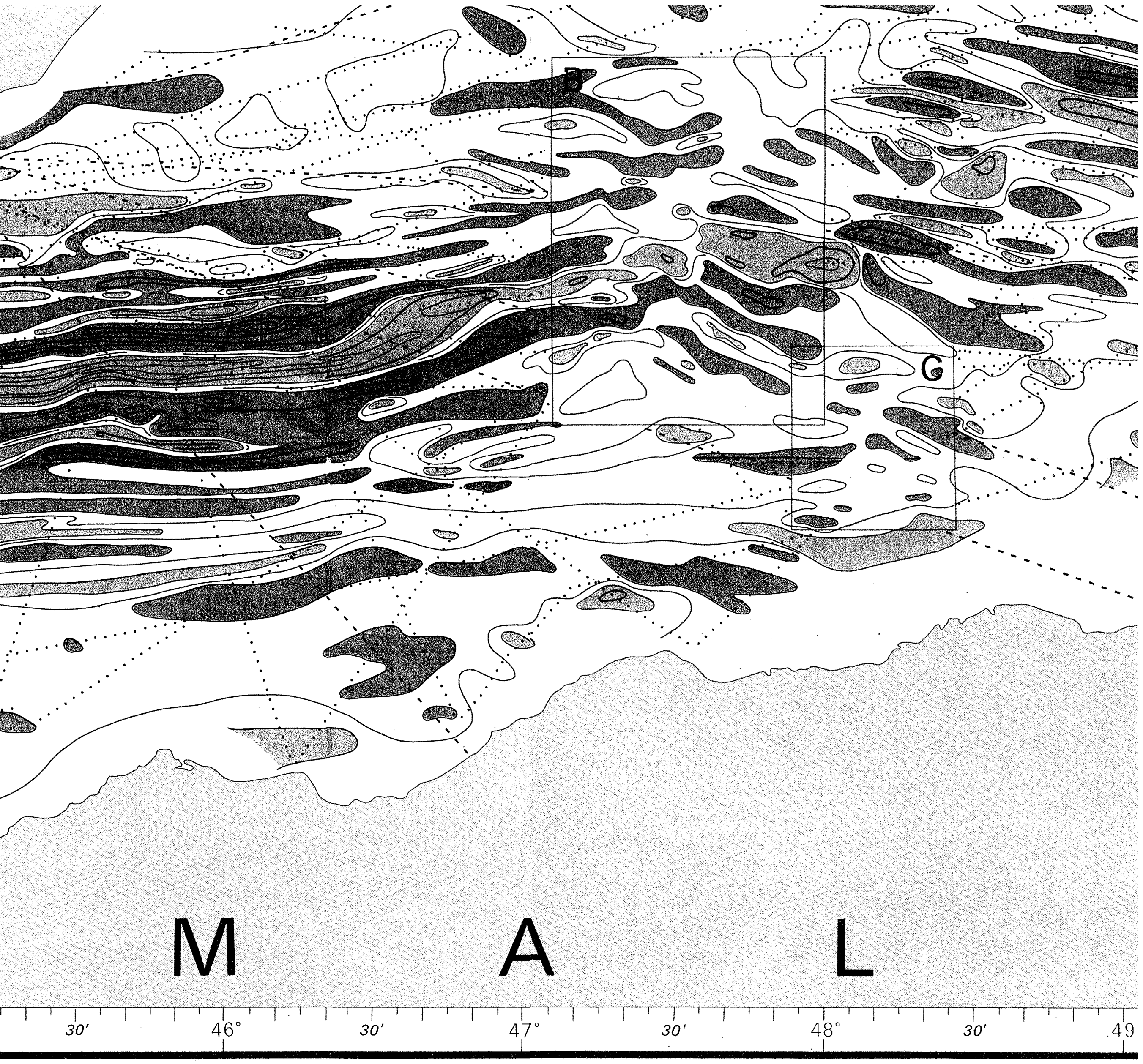
30'
53°
30'
54°
30'
55°
30'
56°


56°
30′
57°
30′
58°
30′
59°
30′

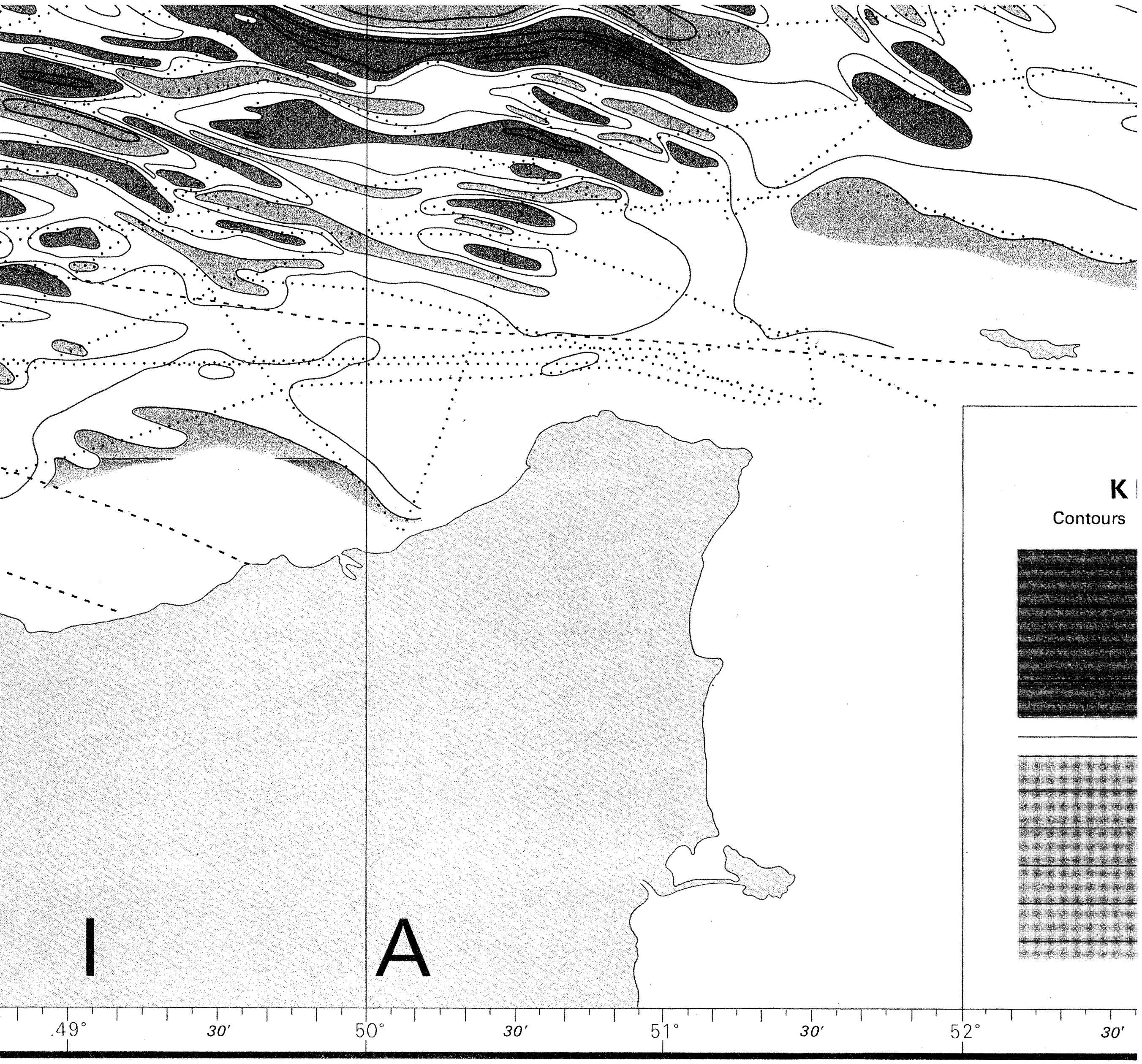

30′
60°
18°
30′
17°
30′
16°
30′
15°
30′
14°
30′



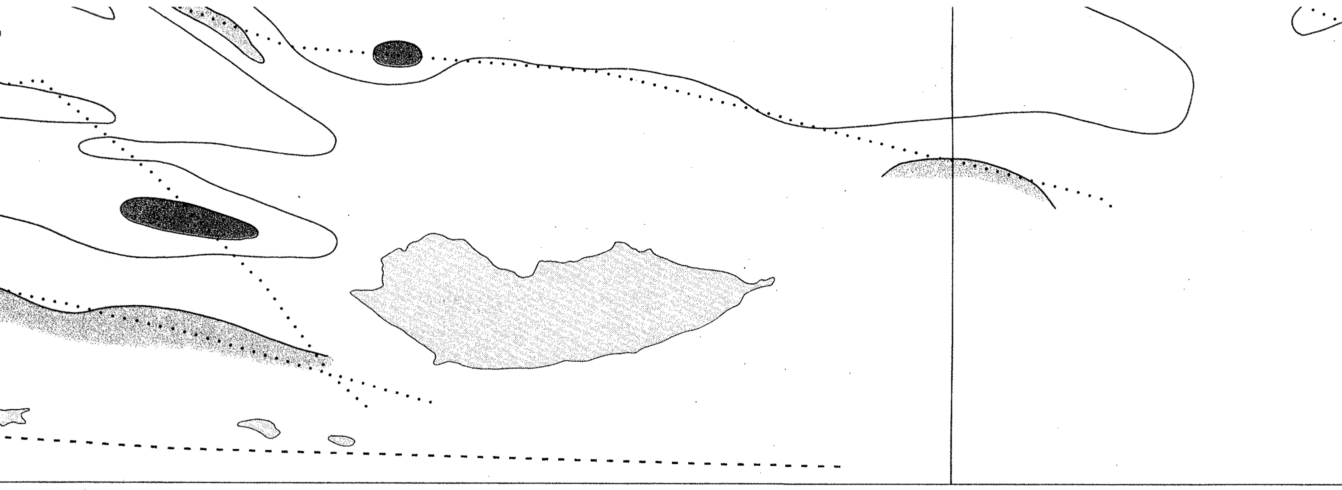
13°
30'
12°
A
30'
11°
30'
10°
S
O
42°
30'
43°
30'
44°
30'
45°



B
C
M
A
L
30'
46°
30'
47°
30'
48°
30'
49°

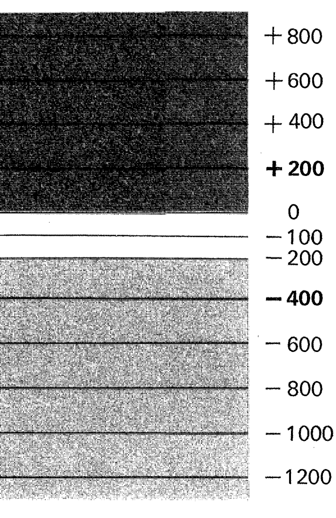


I
A
K
Contours
49°
30′
50°
30′
51°
30′
52°
30′



KEY

Contours in Gammas



MAGNETIC ANOMALY CHA

GULF OF A

By R.B. WHITMARSH

National Institute of Oceanograph

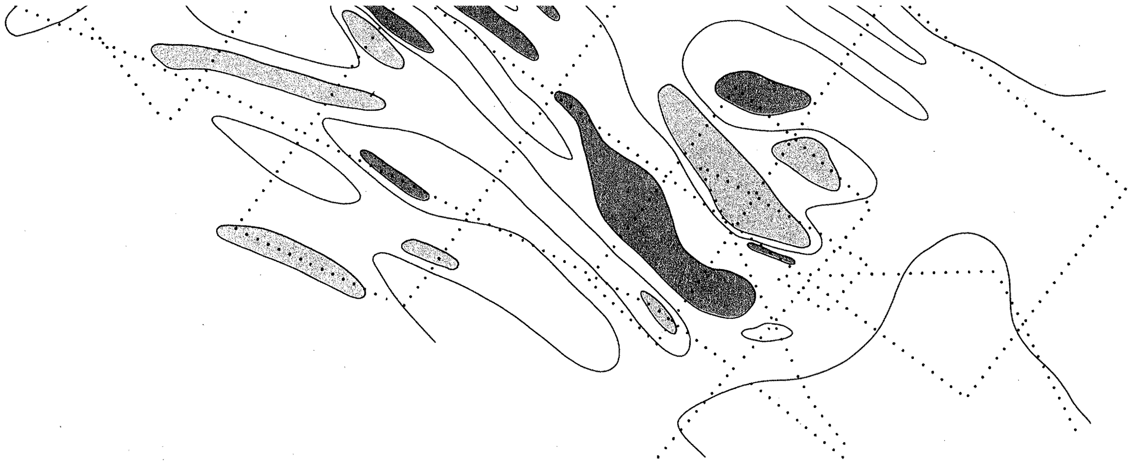
May 1969

SCALE 1:2,000,000 at 33°N

Regional Field: International Geomagnetic Reference Field

Projection: Mercator

30′ 53° 30′ 54° 30′ 55° 30′ 56°



HART OF THE

ADEN

graphy

3°N

ce Field Epoch 1965·0

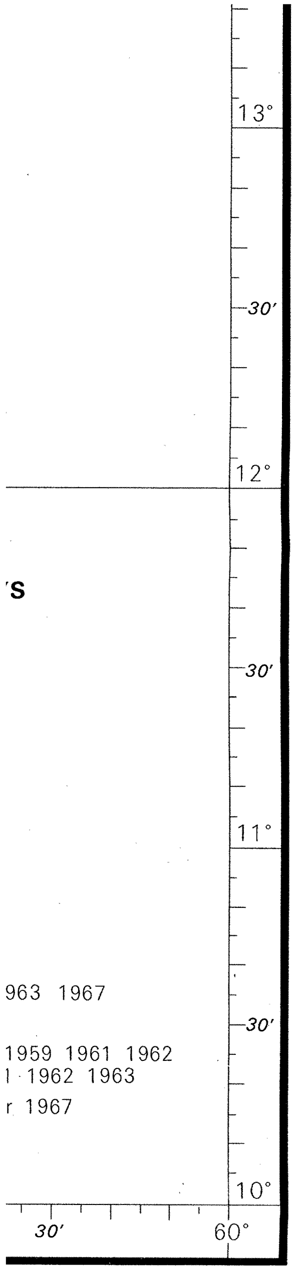
KEY TO MAGNETIC TRACKS AND SURVEYS

- - - - - - - - - -	Aircraft Tracks
. . . .	Ship Tracks
▭	Special Survey Areas
A	Gulf of Tadjura
B	One Degree Square Fig. 18
C	Half Degree Square Fig. 19

Sources of data

Deutsches Hydrographisches Institut	R.V.Meteor 1967
Lamont - Doherty Geological Observatory	R.V. Vema 1958 R.V. Conrad 1965
National Institute of Oceonography	R.R.S. Discovery 1963 1967
Scripps Institution of Oceanography	R.V. Horizon 1962
U.K. Hydrographic Dept. Ministry of Defence (Navy)	H.M.S. Dalrymple 1959 1961 H.M.S. Owen 1961 · 1962 19
U.S. Coast and Geodetic Survey	R.V. Oceanographer 1967
Woods Hole Oceanographic Institution	R.V. Chain 1964

56° 30′ 57° 30′ 58° 30′ 59° 30′


13°
30′
12°
'S
30′
11°
963 1967
1959 1961 1962
l 1962 1963
r 1967
30′
10°
30′
60°


GEOLOGICAL MAP
NORTHERN SOMALIA AND SOCOTRA, GULF OF ADEN
Compiled by Z.R.BEYDOUN (see Figure 1 for sources)
MILES 10 0 20 40 60 80 100 MILES
METRES 10000 0 50 100 150 KILOMETRES
Lambert Conical Orthomorphic Projection
Quaternary undifferentiated
Oligocene–Miocene–Pliocene
Oligocene s.str. with Lr Miocene
Middle Eocene (to Ur Eocene east of longitude 49° E) Karkar Series
Lower-Middle Eocene Gypsum-anhydrite and Taleh Series
Palaeocene–Lr Eocene Auradu Series
Cretaceous undifferentiated
Jurassic undifferentiated
Precambrian metasediments
Precambrian and Lr Palaeozoic granites
? Precambrian–Lr Palaeozoic volcanics
Precambrian undifferentiated
Pliocene–Pleistocene Aden Volcanic Series
Ur Cretaceous–Miocene Trap Series
principal faults
Basement grain (foliation dykes, etc.)
isobaths (in fathoms)
DJIBOUTI
Ali Sabieh
Aisha
Borama
Hargeisa
Bulhar
Berbera
Sheikh
Burao
Karin
Ankhor
Heis
Mait
Erigavo
Las Khoreh
Bandar Cassim
Candala
Alula
C. Guardafui (Ras Aseir)
Ras Hantara
Ras Binnah
Hafun
Darror Valley
Abd al Kuri
Samha
Darsah
Hadibu
SOCOTRA
500 fathoms (1000 m)
100 fathoms (200 m)

Figure 3

12°
43°
44°
100 fathoms (200m)
DJIBOUTI
Ali Sabieh
11°
Aisha
10°
Buramo
Hargaisa

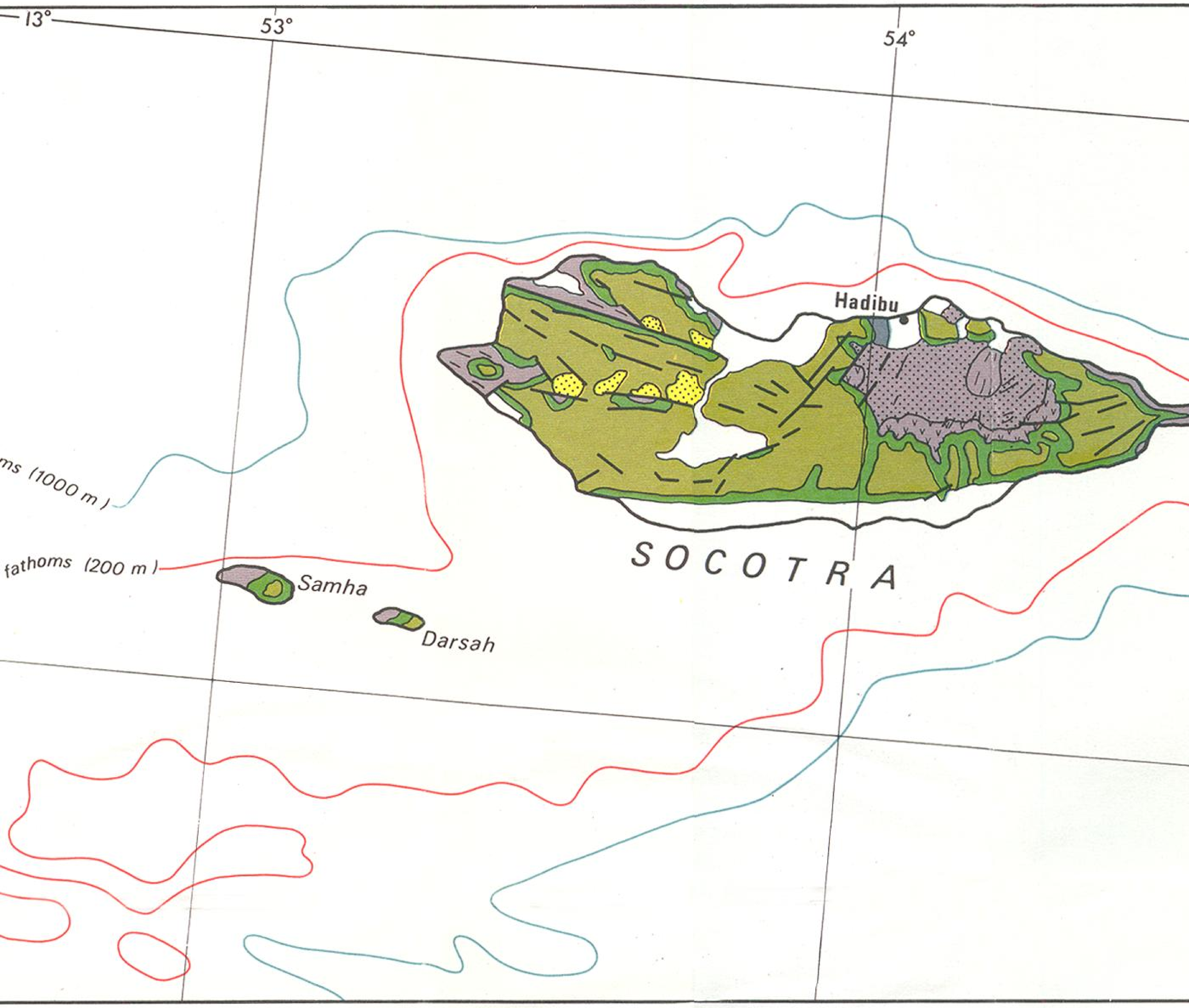
44°
45°
500 fathoms (1000 m)
Karin
Bulhar
Berbera
Bihendula


46°
47°
1st. Lst/PC
Mait
2nd. Lst/PC
Onkhor
Hais
Erigavo
Asseh

48°
49°
Las Khoreh
Bandar Cassim

50°
Alula
Ras Hantara
Candala
Darror Valley


51°
52°
13°
500 fathoms (1000
100 fathoms
Abd al Kuri
C. Guardafui
(Ras Aser)
Ras Binnah
Hafun
500 fathoms
(1000 m)
100 fathoms
(200 m)
NORTH
Quatern
Oligocen
Oligocen
Middle
longitud
Lower-M
Gypsum
Palaeoc
Auradu



GEOLOGICAL MAP
RTHERN SOMALIA AND SOCOTRA, GULF

Compiled by Z.R. BEYDOUN (see Figure 1 for sources)

MILES 10 0 20 40 60 80 10

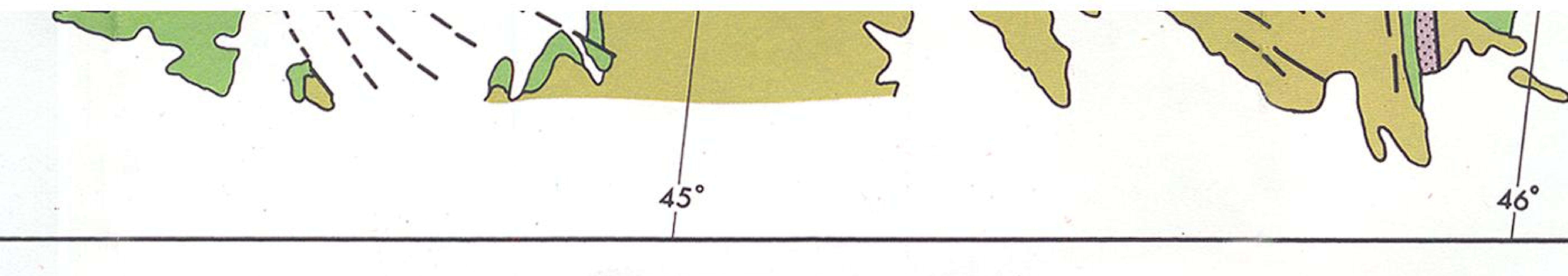
METRES 10000 0 50 100 150 K

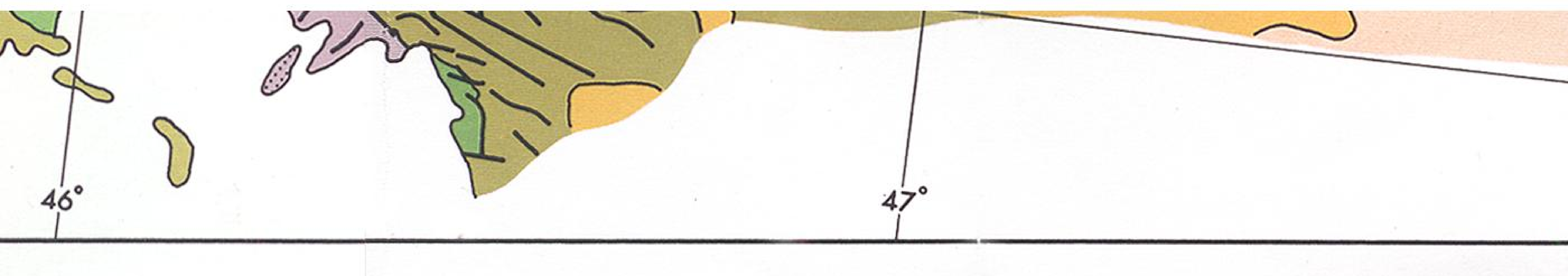
Lambert Conical Orthomorphic Projection

- Quaternary undifferentiated
- Oligocene–Miocene–Pliocene
- Oligocene *s.str.* with Lr Miocene
- Middle Eocene (to Ur Eocene east of longitude 49° E) Karkar Series
- Lower-Middle Eocene Gypsum-anhydrite and Taleh Series
- Palaeocene–Lr Eocene Auradu Series
- Cretaceous undifferentiated
- Jurassic undifferentiated
- Precambrian metasediments
- Precambrian and Lr Palaeozoic granites
- ? Precambrian–Lr Palaeozoic volcanics
- Precambrian undifferentiated


55°
13°
12°
11°
ULF OF ADEN
100 MILES
150 KILOMETRES
Pliocene–Pleistocene
Aden Volcanic Series
Ur Cretaceous–Miocene
Trap Series
principal faults
Basement grain
(foliation dykes, etc.)
100
500
isobaths (in fathoms)

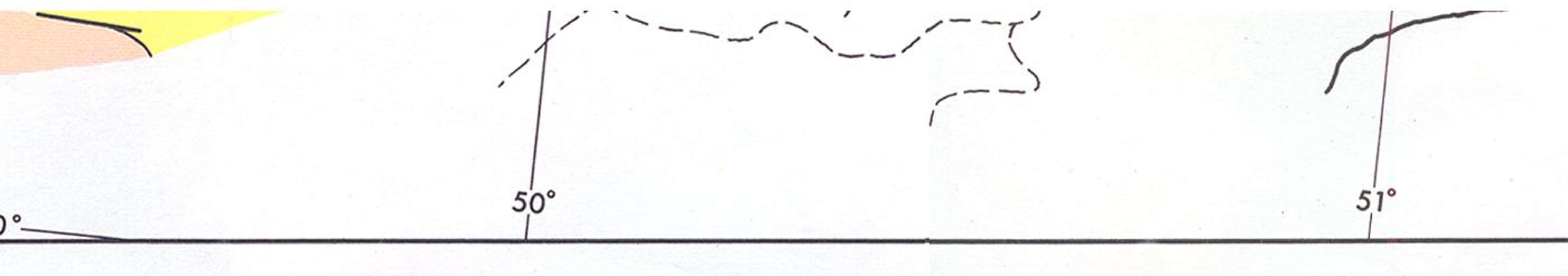

Hargaisa
43°
44°
ReP

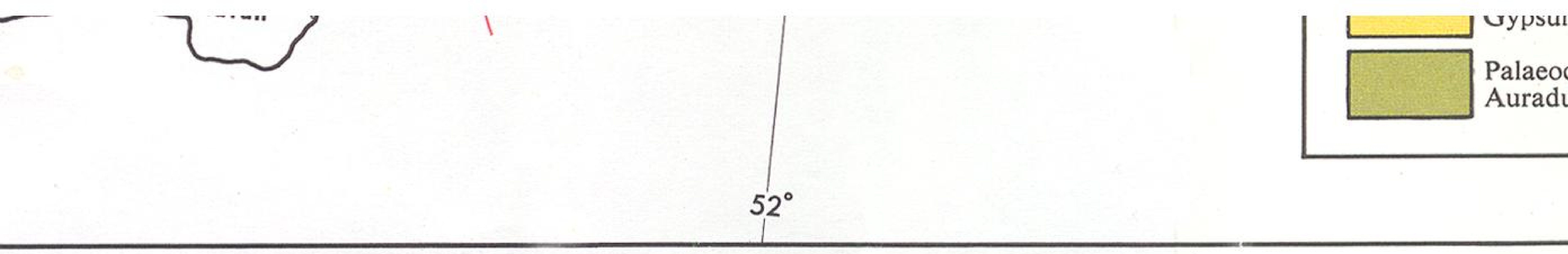

45°
46°

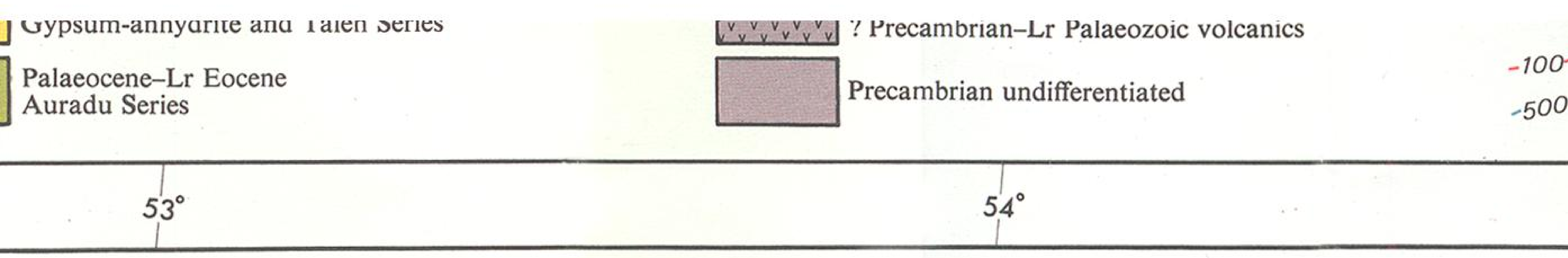


46°
47°


48°
49°
10°


50°
51°


52°


Gypsum-anhydrite and Taleh Series
Palaeocene–Lr Eocene
Auradu Series
? Precambrian–Lr Palaeozoic volcanics
Precambrian undifferentiated
100
500
53°
54°

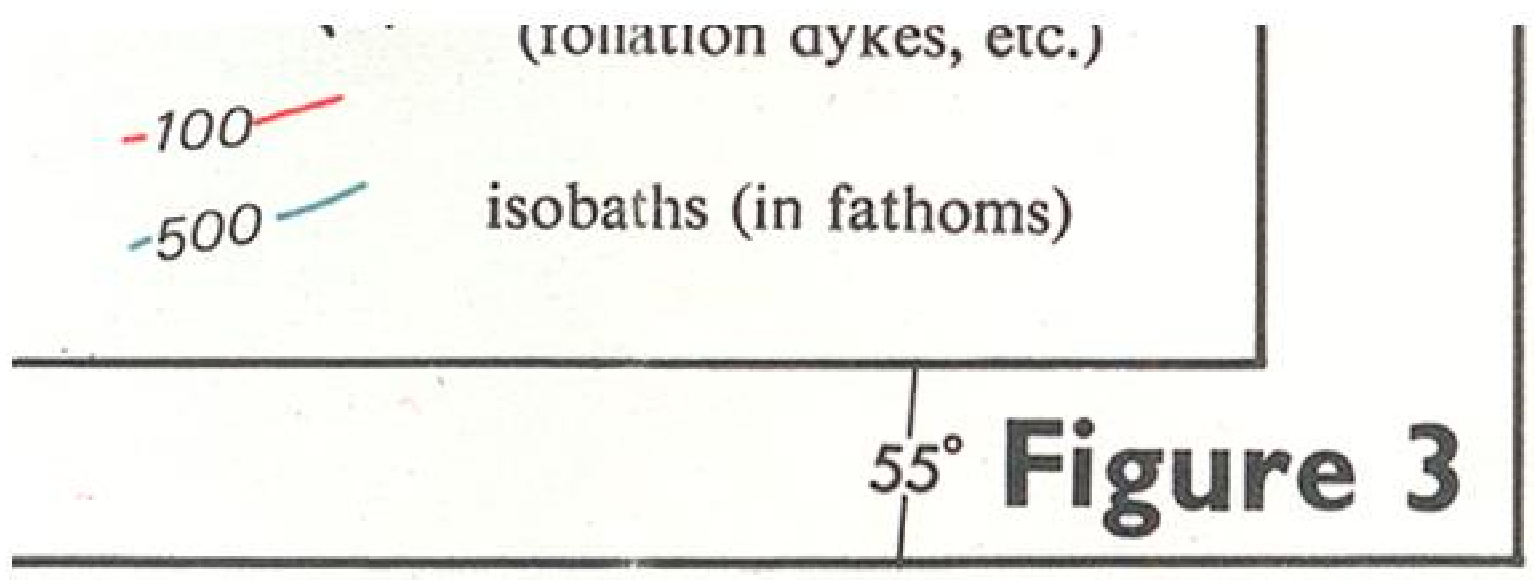


Figure 3

Laughton, Whitmarsh, Jones, Fig 20, Red Sea Discussion Phil. Trans. Roy. Soc. A

Laughton, Whitmarsh, Jones, Fig. 20, Red Sea Discussion Phil. Trans. Roy. Soc. A


30′
46°
30′
47°
30′
48°
30′
49°
R A B I A

49°
30′
50°
30′
51°
30′
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30′
A


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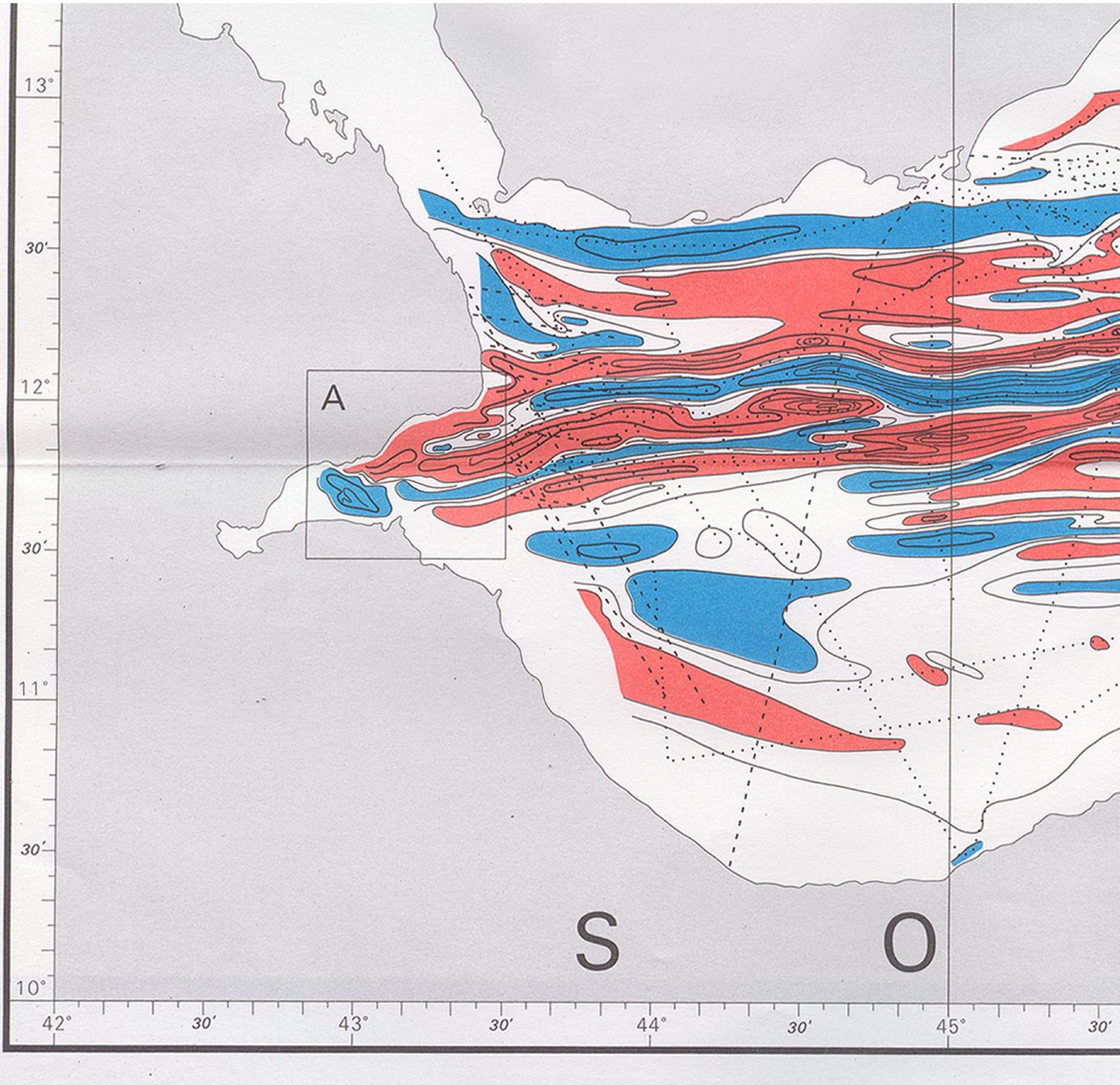

13°
30'
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O
42°
30'
43°
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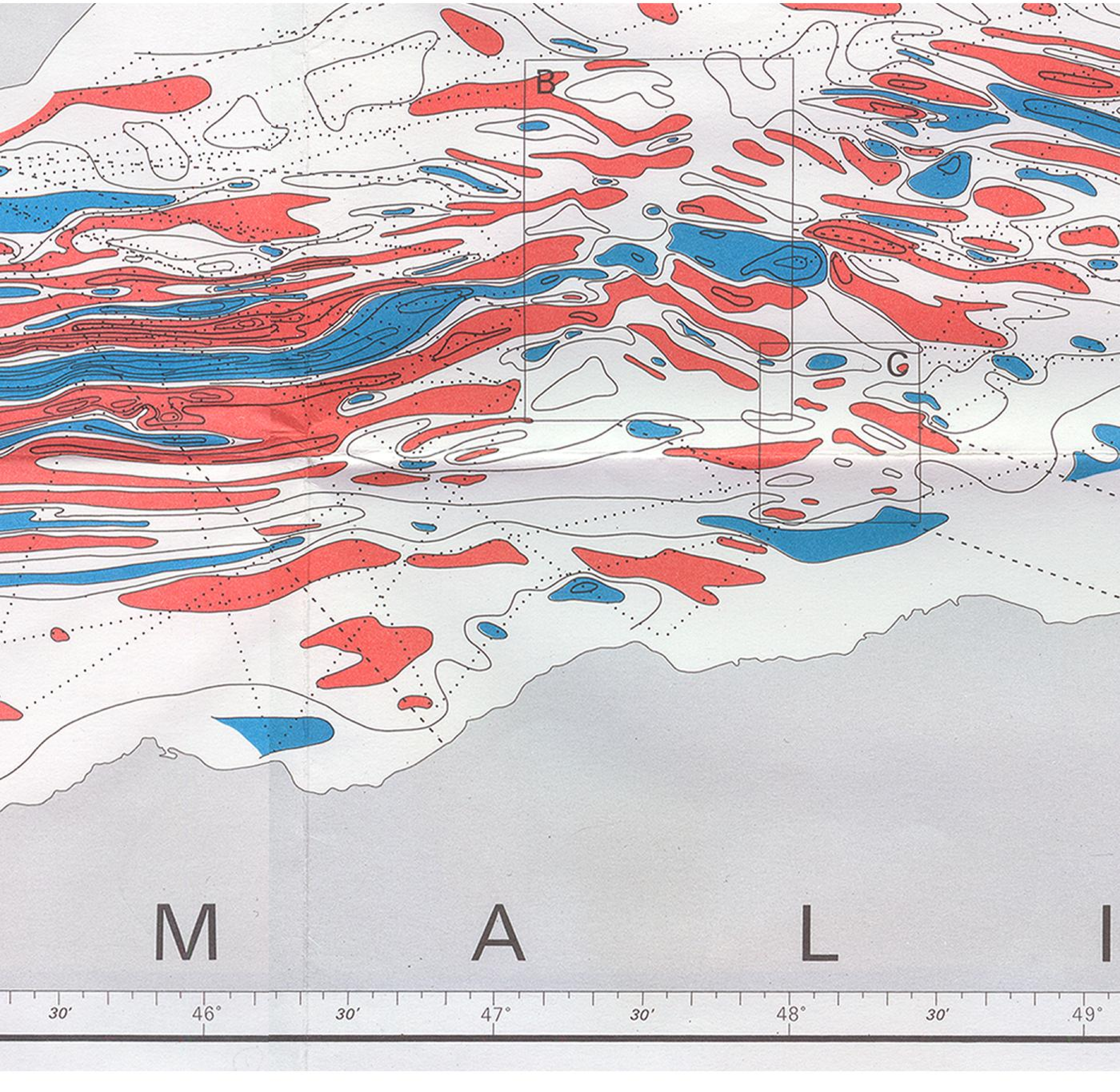
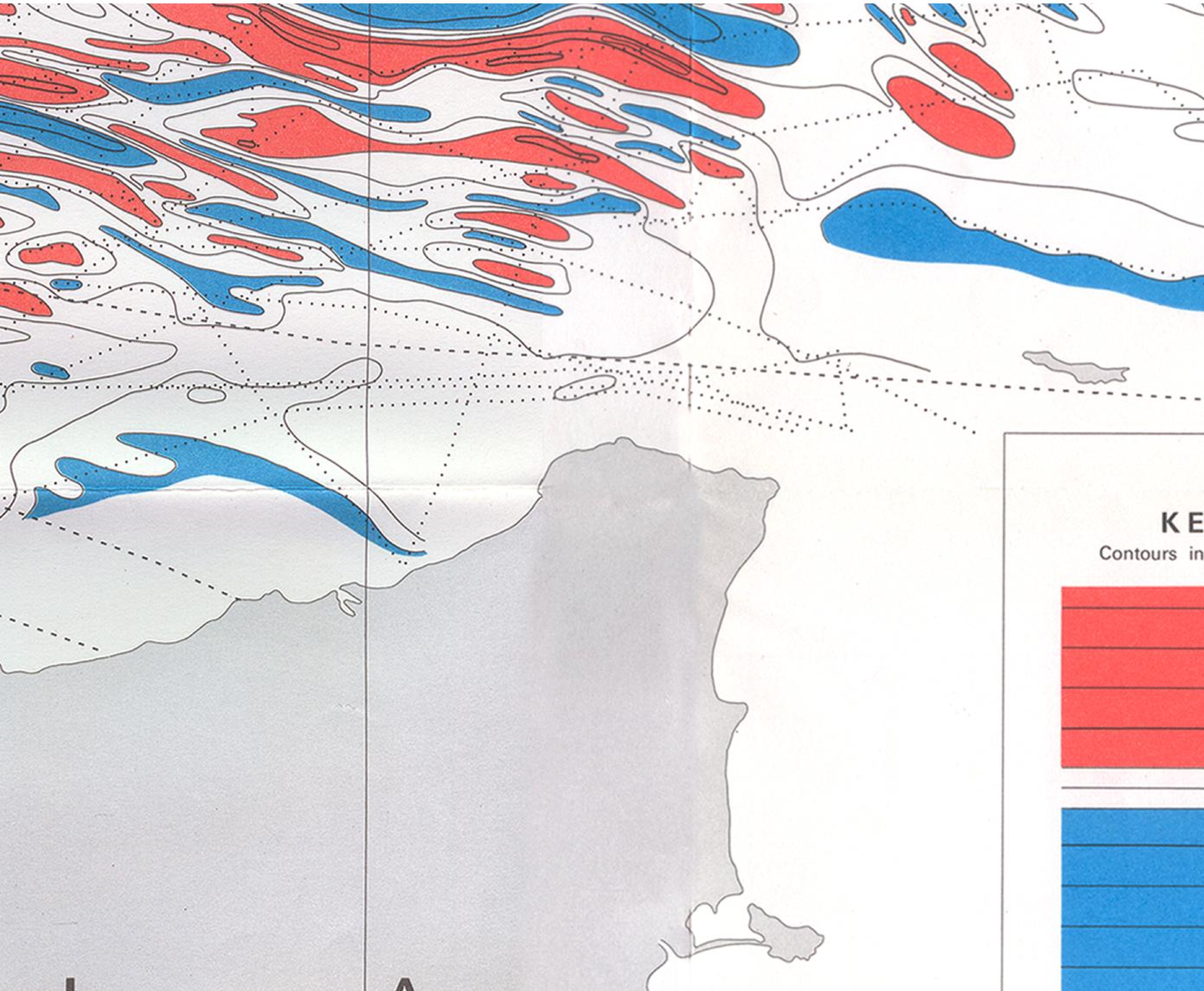
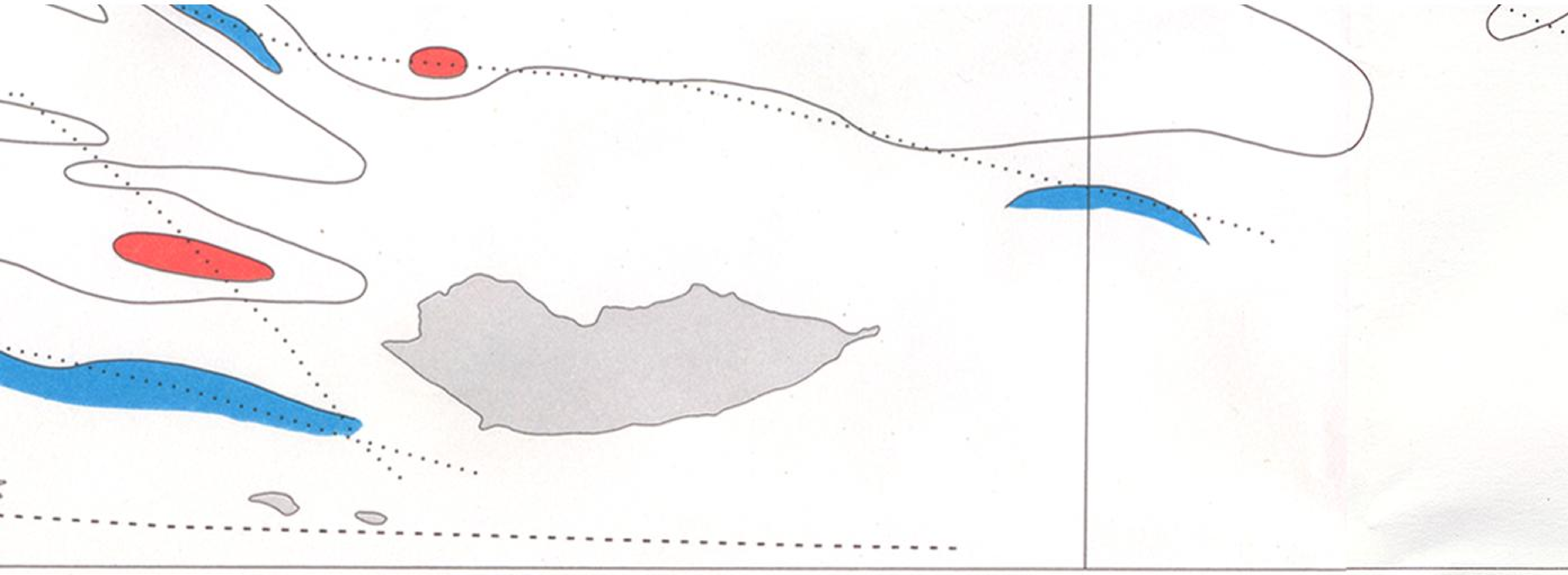
44°
30'
45°
30'



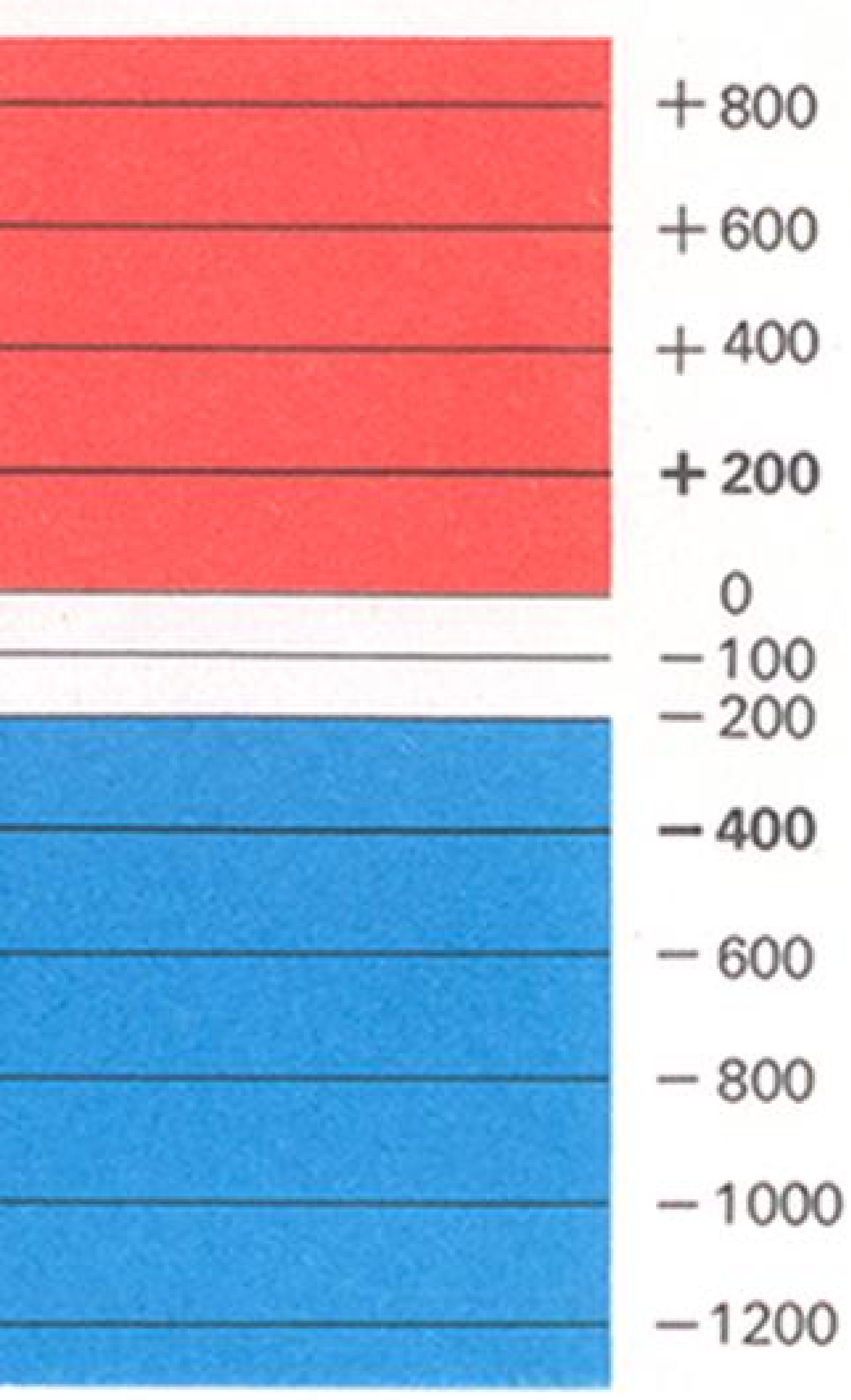
B
C
M A L I
30′
46°
30′
47°
30′
48°
30′
49°


KEY
Contours in
I
A
49°
30′
50°
30′
51°
30′
52°
30′



KEY

ntours in Gammas



MAGNETIC ANOMALY CHAR

GULF OF AD

By R.B. WHITMARSH

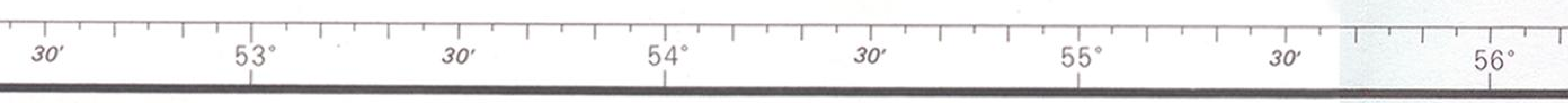
National Institute of Oceanography

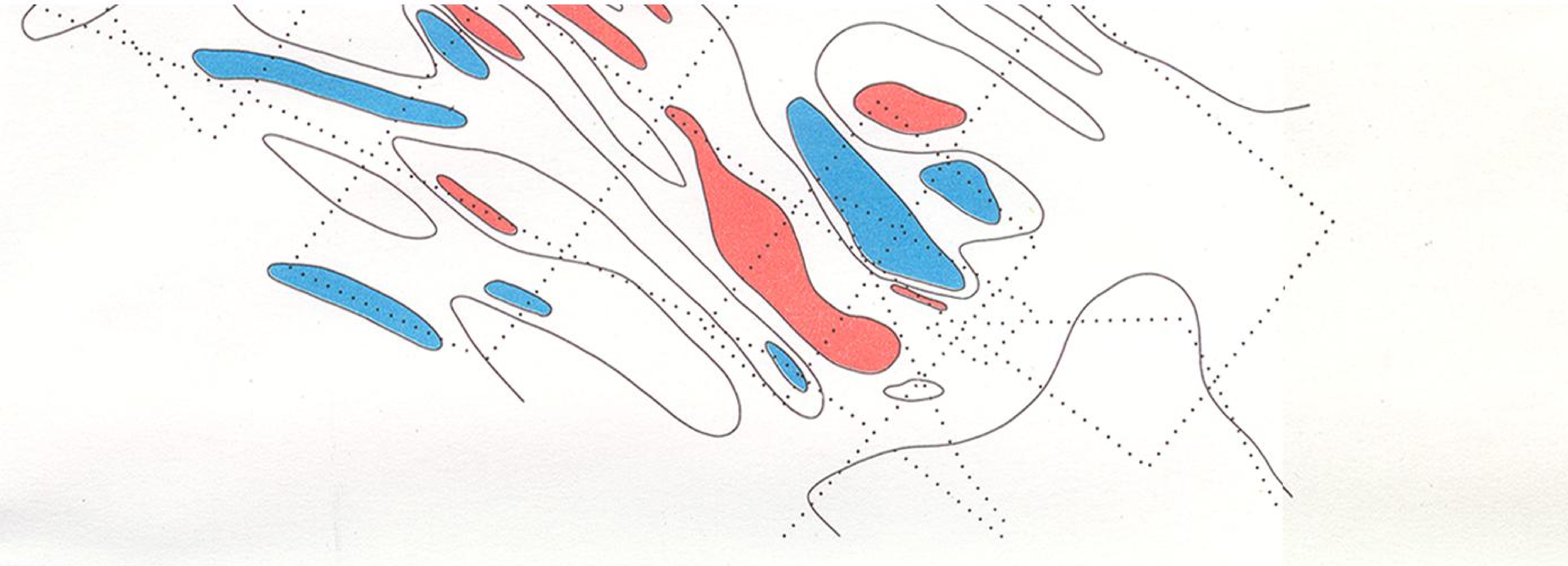
May 1969

SCALE 1:2,000,000 at 33°N

Regional Field: International Geomagnetic Reference Field Ep

Projection: Mercator





HART OF THE

ADEN

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N

Field Epoch 1965·0

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- - - - - - - - - -	Aircraft Tracks
. . . .	Ship Tracks
▭	Special Survey Areas
A	Gulf of Tadjura
B	One Degree Square Fig. 18
C	Half Degree Square Fig. 19

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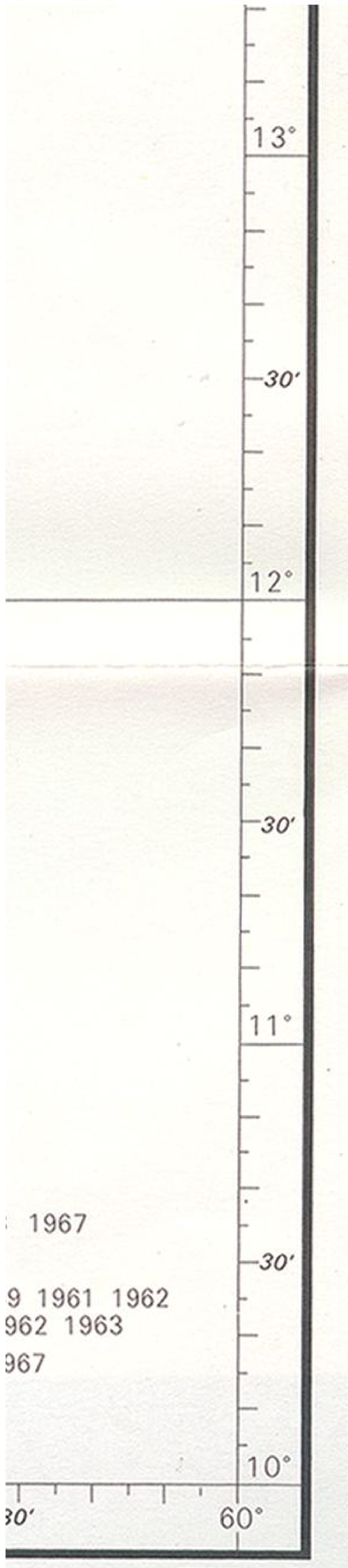
Woods Hole Oceanographic Institution	R.V. Chain 1964

56° 30′ 57° 30′ 58° 30′ 59° 30′


13°
30′
12°
30′
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1967
30′
9 1961 1962
962 1963
967
10°
30′
60°