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

Tectonic Fabric of the Atlantic and Indian Oceans and Continental Drift

B. C. Heezen and Marie Tharp

Phil. Trans. R. Soc. Lond. A 1965 **258**, 90-106
doi: 10.1098/rsta.1965.0024

VIII. Tectonic fabric of the Atlantic and Indian oceans and continental drift*

By B. C. Heezen and Marie Tharp

Department of Geology and Lamont Geological Observatory,
Columbia University, Palisades, New York

The floor of the Indian Ocean is dominated by (1) the seismically active Mid-Oceanic Ridge, (2) scattered linear micro-continents (mostly meridional), and (3) fracture zones (some displace the axis of the Mid-Oceanic Ridge and others parallel the micro-continents). The pattern suggests that movement along the Diamantina Fracture Zone has displaced Australia to the east relative to Broken Ridge. In the Arabian Sea north-northeast trending fracture zones have displaced the axis of the Carlsberg Ridge. The complex tectonic fabric of the Indian Ocean is difficult to explain in terms of a simple pattern of convection currents.

The location and origin of the Mid-Oceanic Ridge, of oceanic rises, aseismic ridges and transcurrent fault systems must be accounted for in any hypothesis of continental displacement despite unique or exotic assumptions as to strength, viscosity or composition of the oceanic crust and mantle.

Introduction

Continental drift was first proposed as an explanation of the rather precise geometrical fit between South America and Africa. Wegener (1924) impressed by this fit, collected various other evidence (palaeoclimatic, palaeobiological, stratigraphic) that these continents were formerly joined into one ancient Pangea. du Toit collected further evidence

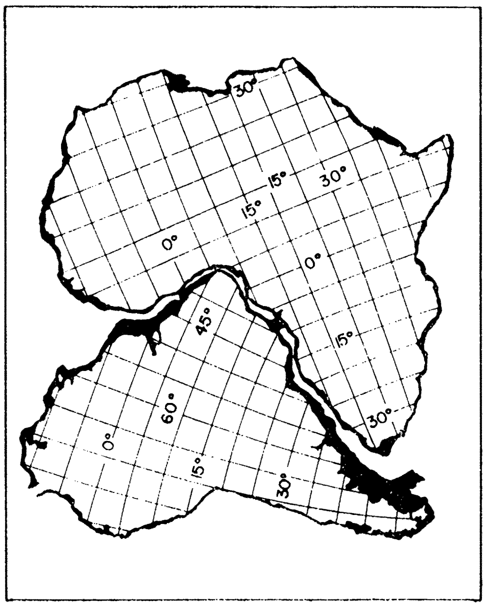

Figure 1. Fit of South America and Africa. Dark edging of the continents is the continental shelf. (After Carey 1958, p. 223.)

and arrived at a somewhat more refined reconstruction. Although continental drift was accepted by some Earth scientists, it remained a highly controversial subject until the 1950's when palaeomagnetic studies seemed to provide support not only for polar wandering

* Lamont Biological Observatory Contribution, No. 788.

but for continental drift. Although there formerly was some scepticism about how good the fit between South America and Africa really is, it has been amply demonstrated by Carey (1958) and by Bullard, Everett & Smith (1965, this Symposium) that the fit is indeed good (figure 1).

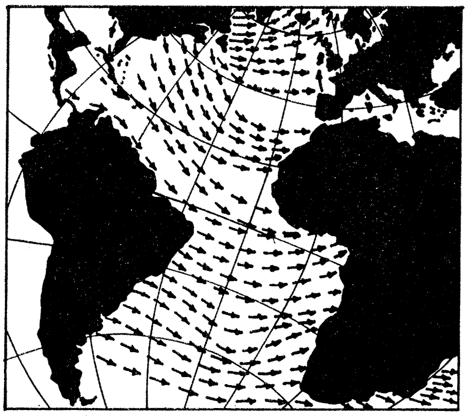

FIGURE 2. Displacement flow lines North and South Atlantic. (After Carey 1958, p. 275.)

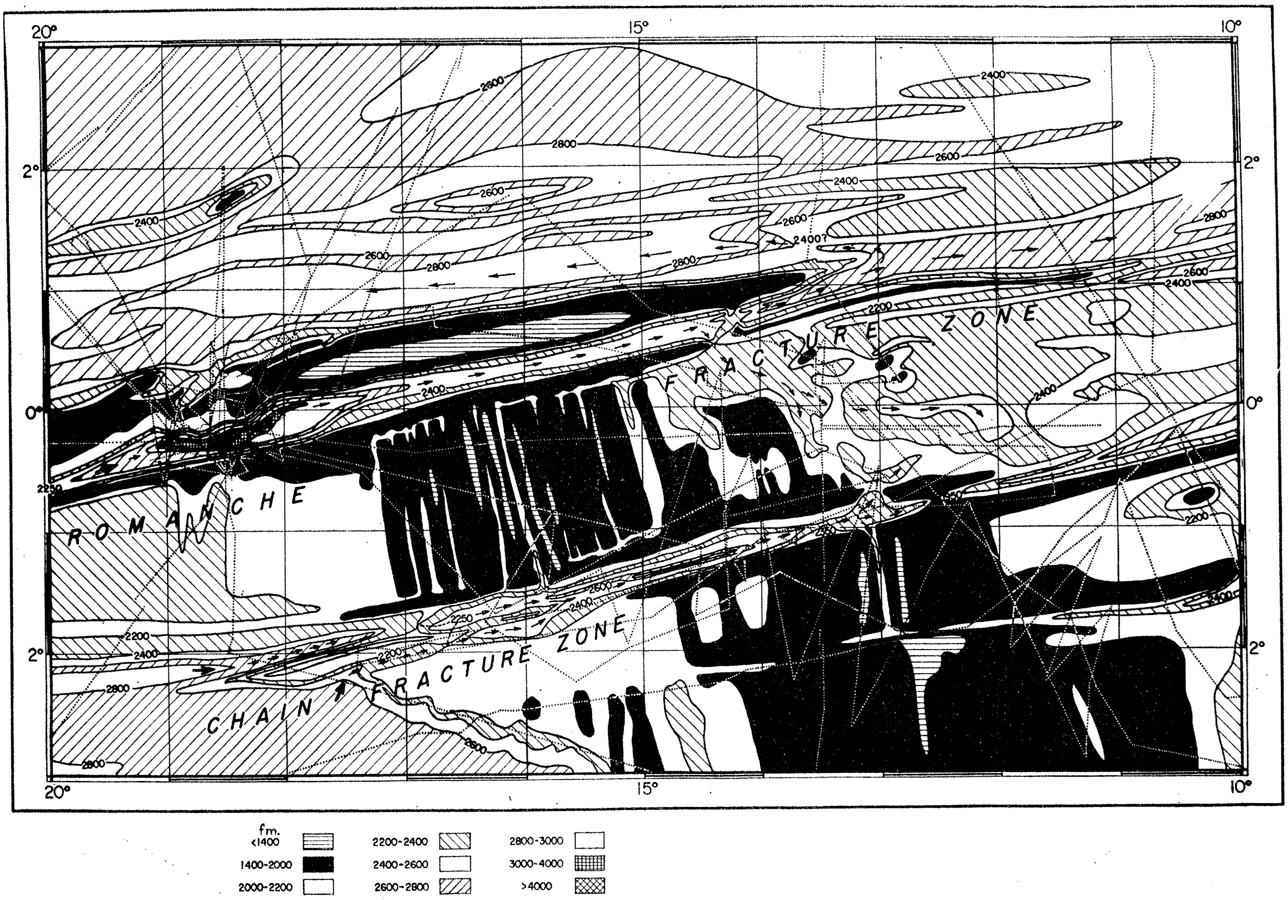

FIGURE 3. Bathymetric sketch of portions of the Chain and Romanche Fracture Zones. All available sounding lines are indicated by dotted lines. Basic contour interval is 200 fm., except below 3000 fm. where the slopes are too steep for contour portrayal at this scale and between 1400 and 2000 fm. where topography is too irregular to permit detailed contours. Arrows indicate suggested pattern of bottom water flow. (After Heezen *et al.* 1964*a*, p. 14.)

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

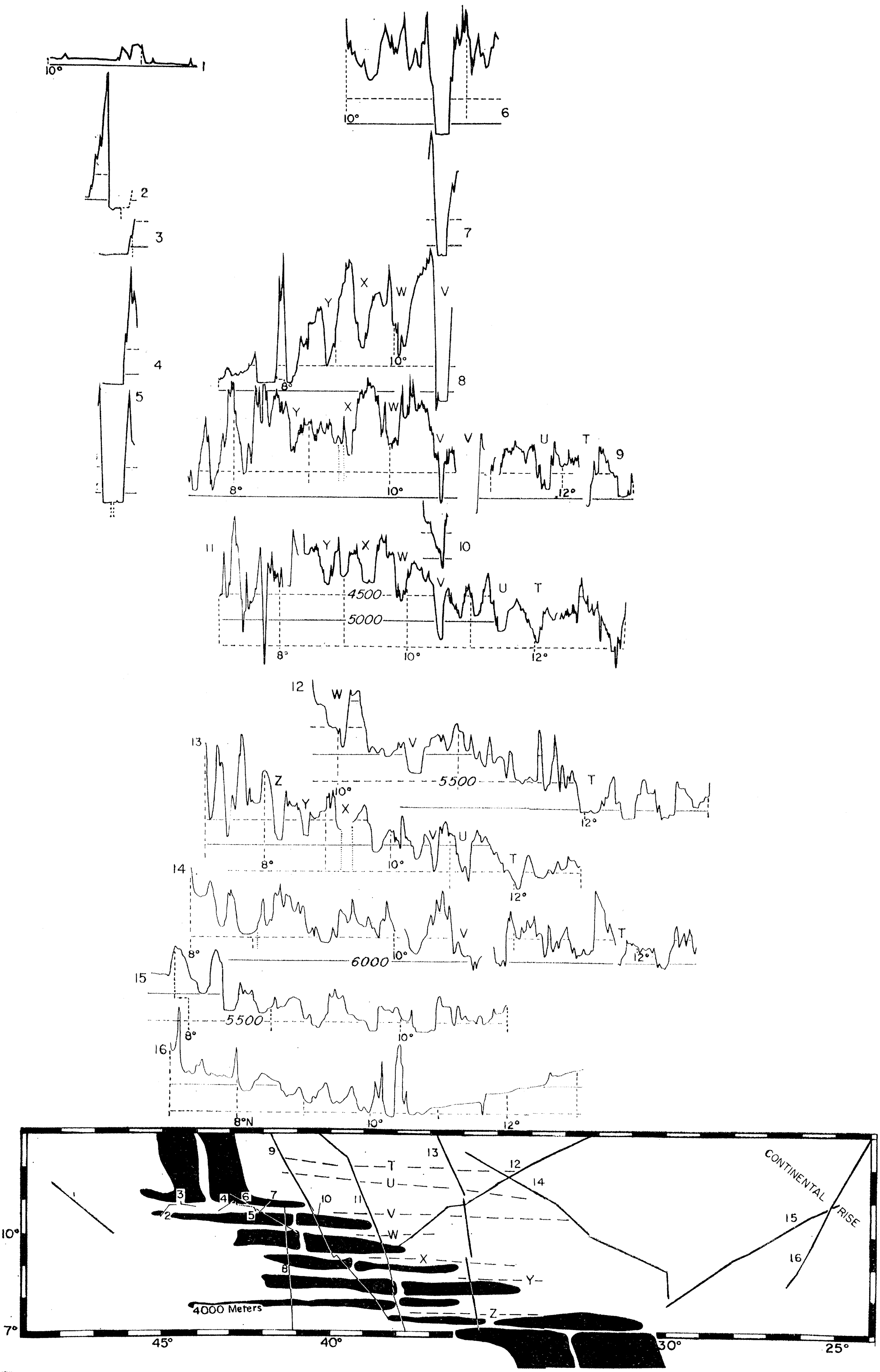

FIGURE 4. Topographic profiles in the vicinity of Vema Fracture Zone. Vema Fracture Zone indicated by letter *V*. Letters *T*, *U*, *W*, *X*, *Y* and *Z* indicate the location of possible other parallel zones. (After Heezen *et al.* 1964*b*.)

The Atlantic Ocean floor

Carey constructed displacement flow lines to represent the directions along which the continents would have to move from their present positions to reach a former contiguous position (figure 2). Although there is considerable doubt as to the former juxtapositions

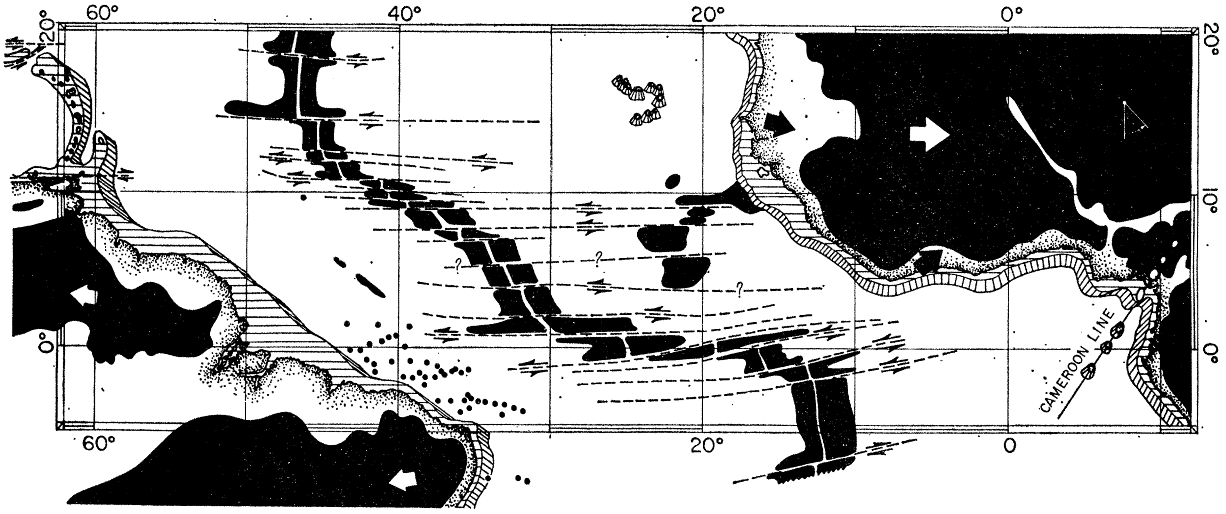

Figure 5. Fracture zones in the equatorial Atlantic. Dashed lines indicates line of displacement. Relative direction is shown by arrows. Dark area on land depicts elevation greater than 3000 m; in oceanic areas a depth less than 3000 m. Black circles are seamounts.

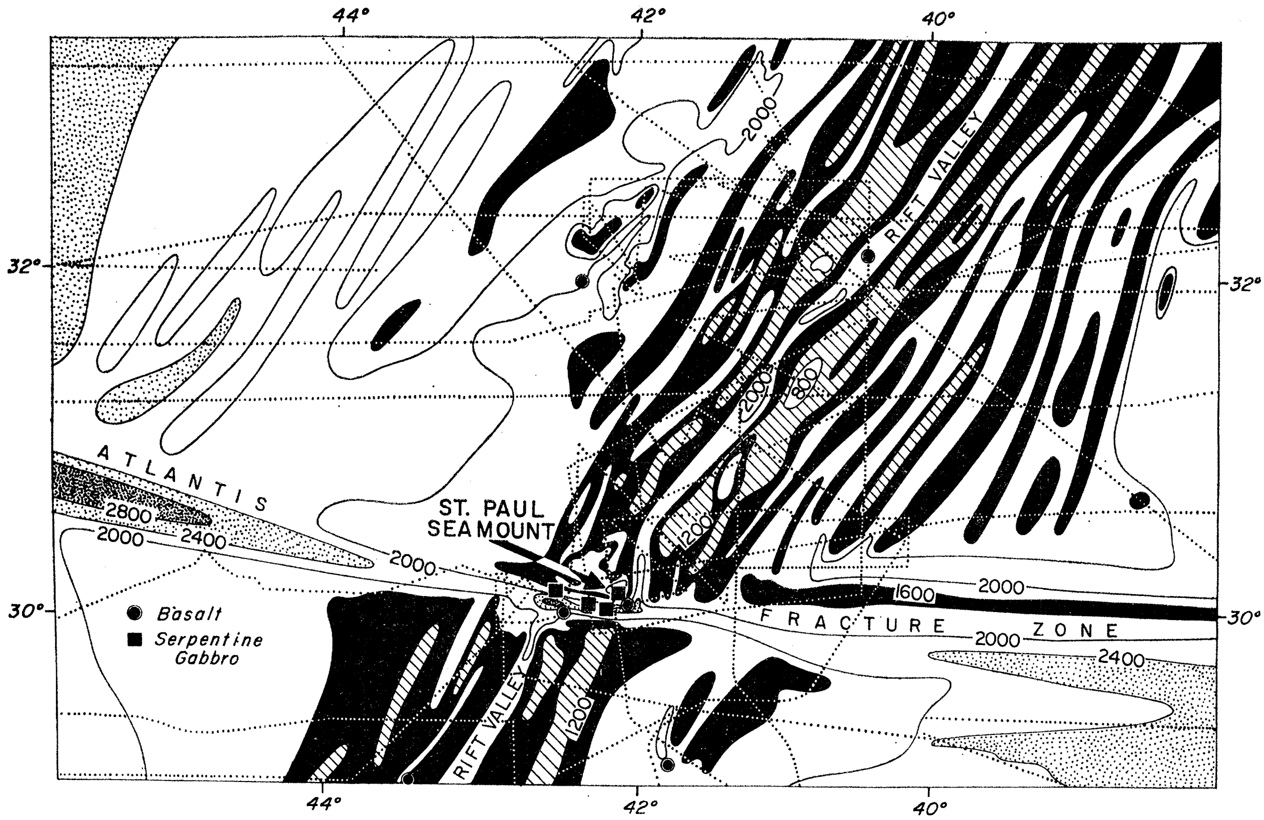

Figure 6. Bathymetric sketch of Atlantis Fracture Zone. Contour interval 400 fm. Dark area 1200 to 1600 fm. Stippled zones are depths greater than 2400 fm. All available sounding lines are indicated by dashed lines.

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

of lands in the Indian Ocean and the northern North Atlantic, there is no doubt as to the initial relative positions of the two sides of the South Atlantic, for the fit of the two continents is truly exceptional.

The displacement flow lines of Carey were drawn under the simple assumption that the rotation as well as the longitudinal displacement of the two continents proceeded approximately uniformly with time. As a surprising result of this simple exercise it is seen that the displacement flow lines are remarkably parallel to the major physiographic features of the equatorial Atlantic Ocean. Just north of the equator the flow lines trend in a east–southeast direction. This is also true of the fracture zones of the Atlantic which offset the crest of the Mid-Oceanic Ridge. Just south of the equator the fracture zones trend about 080°; just north of the equator they trend about 100°.

Two of the most prominent of the east–west faults which displace the equatorial Mid-Atlantic Ridge are the Chain and Romanche Fracture Zones (figure 3). Displacement on the Chain Fracture Zone is approximately 180 miles (Heezen, Bunce, Hersey & Tharp 1964*a*). Displacement along the Romanche Fracture Zone appears to be approximately twice as much. A prominent fracture zone at 11° N—the Vema Fracture Zone—exhibits a displacement of approximately 180 miles (Heezen, Gerard & Tharp 1964*b*) (figure 4). A fracture zone at 30° N displaces the axis of the Mid-Atlantic Ridge in a right lateral sense by 60 miles (figure 6). This fracture zone again appears to be parallel to the continental drift displacement flow lines (figure 2).

The greatest depth in each of the fracture zones so far investigated is found in the region where the axis of the Mid-Atlantic Ridge is offset (figure 3). Dredging in the vicinity of St Paul's Seamount, which lies on the northern side of the Atlantis Fracture Zone, brought up quantities of peridotite, serpentine and gabbro in addition to much basalt. St Paul's rocks, a very similar-looking mountain, lies on the St Paul's Fracture Zone and is composed of sheared dunite. Heavy mineral sands containing ultrabasic as well as metamorphic mineral suites have been brought up in cores from the Vema and Romanche Fracture Zones.

If we are to explain the similarity of the continental margins of the South Atlantic through continental displacement, the strike-slip faults of the sea floor must indicate the direction of movement of the adjacent continents. Therefore motions may be inferred for the adjacent continents from the direction and magnitude of the displacement of sea-floor fracture zones (figure 5).

The Indian Ocean floor

The Indian Ocean has recently come under the intensive investigation of the International Indian Ocean Expedition and our knowledge of this ocean is rapidly increasing. Sufficient information has now been received for the Arabian Sea that it is unlikely that the major patterns of this area will be altered by subsequent exploration. The results of this exploration, largely carried out by H.M.S. *Owen* (Anon. 1963), H.M.S. *Dalrymple* and R.V. *Discovery*, are represented in a portion of the physiographic diagram of the Indian Ocean (figure 7).

The Indian Ocean is dominated by (1) the seismic active Mid-Oceanic Ridge, (2) scattered linear micro-continents, mostly meridional, and (3) fracture zones some of

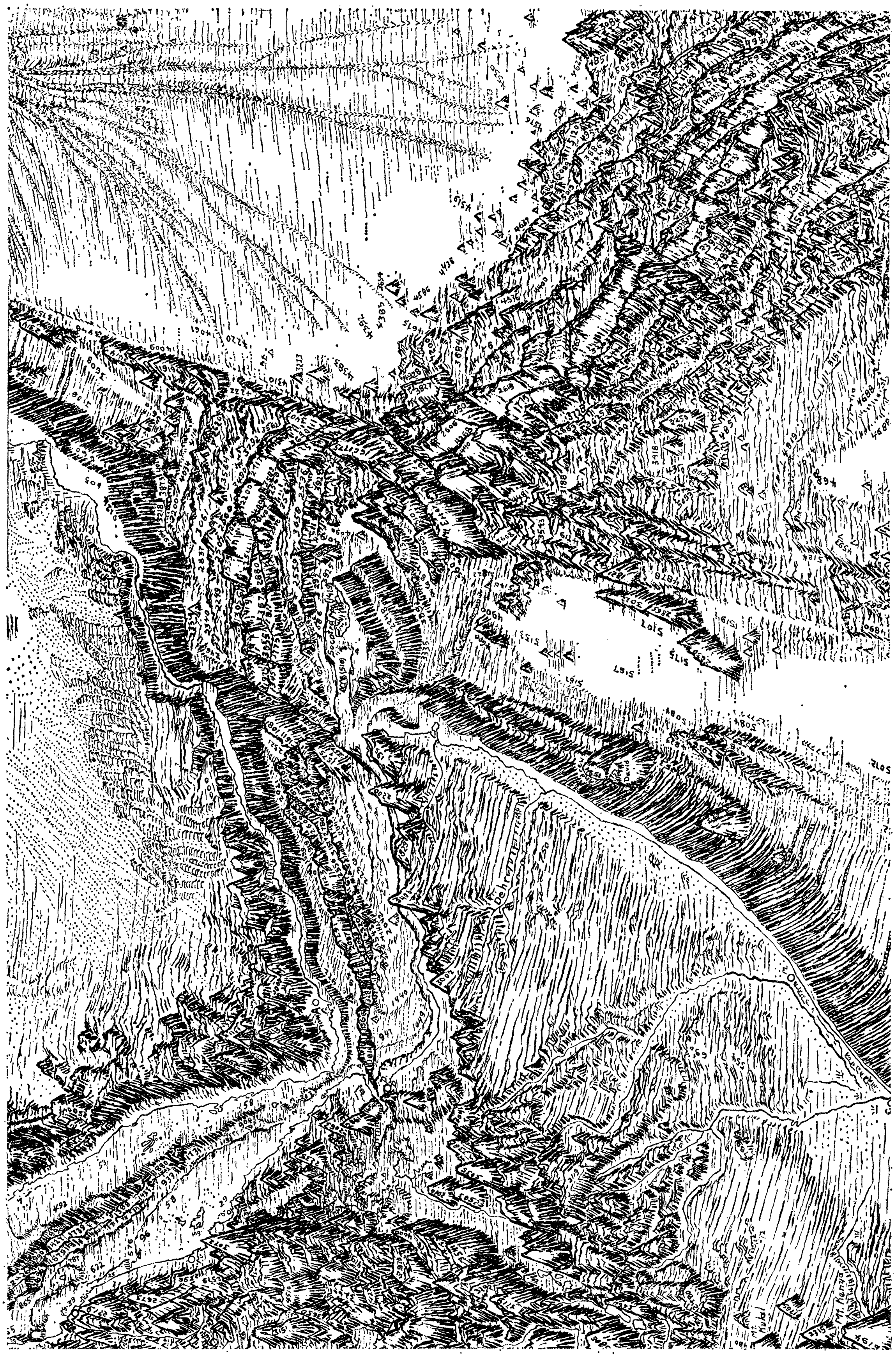

FIGURE 7. Arabian Sea, Red Sea, and Gulf of Aden. This is a portion of the Physiographic Diagram of the Indian Ocean published by the Geological Society of America. (Copyright 1964 Bruce C. Heezen and Marie Tharp; reproduced by permission.)

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

FIGURE 8. Madagascar Ridge, Mozambique Ridge and Mid-Oceanic Ridge. This is a portion of the Physiographic Diagram of the Indian Ocean published by the Geological Society of America. (Copyright 1964 Bruce C. Heezen and Marie Tharp; reproduced by permission.)

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

which displace the axis of the Mid-Oceanic Ridge and others which parallel the micro-continents. Probably the most striking features of the Indian Ocean are the north–north-east trending aseismic ridges, the most remarkable of which is Ninetyeast Ridge which extends from 15° N to 35° S in a nearly straight line. Its linearity is most striking and in profile it is seen to be a large, blocky feature with a relatively smooth top. The Laccadive-Maldive Ridge is a similar feature studded with islands, but is shorter. The Seychelles-Mascarene Ridge which runs from about a degree north of Mauritius to north of the

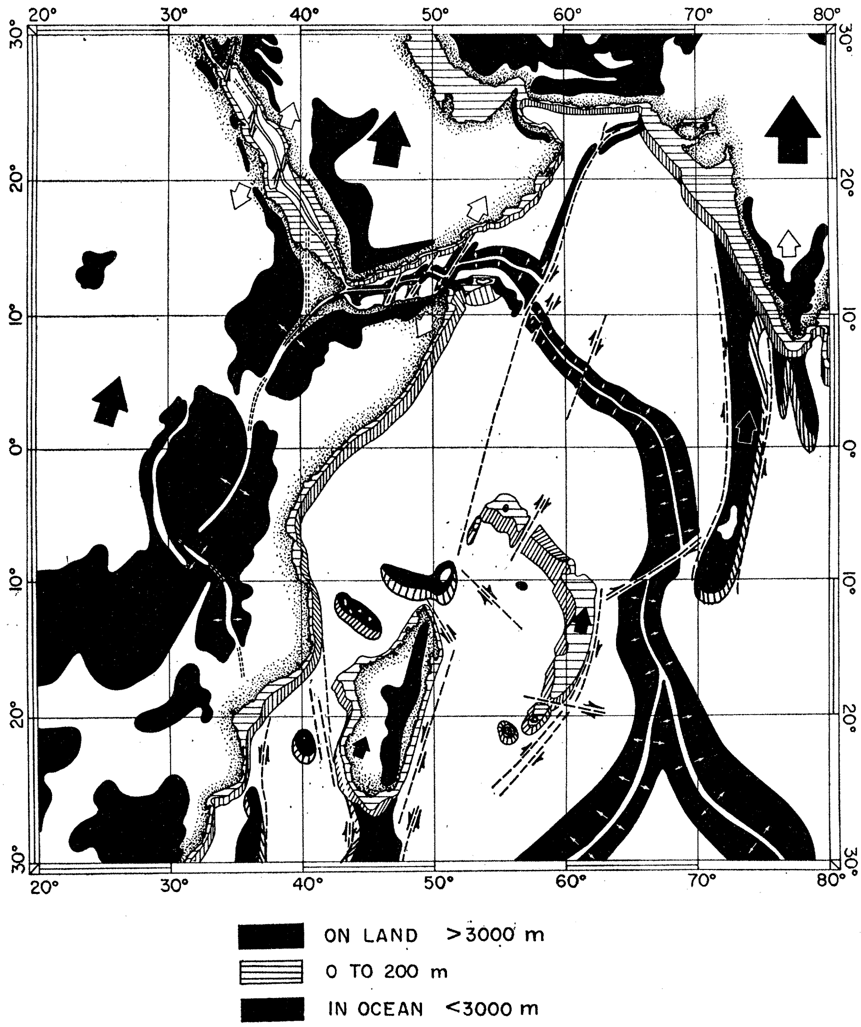

FIGURE 9. Northwest Indian Ocean. Dashed line indicates line of displacement. Relative direction is shown by arrows. Dark area on land depicts elevation greater than 3000 m; in oceanic areas a depth less than 3000 m.

Seychelles is high, flat-topped with abrupt sides but has a less obvious north–south lineation. Madagascar and the Madagascar Ridge is a wide, broad feature which extends for over 1500 miles. South of Mozambique another linear north–south ridge extends along the west side of the Mozambique Channel. The Kerguelen Plateau in the southern part of the Indian Ocean is a broad, relatively flat-topped feature. There is another similar but little known plateau near the Crozet Islands. Thus the Indian Ocean

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

has many blocky features, which owing to their height and size, must have crustal thicknesses of continental proportions. Seismic-refraction measurements on some of these features by Raitt & Shor (not yet published) tends to support this conclusion.

We may, of course, in referring to these aseismic ridges as micro-continents, infer that they are either (1) fragments of former continents, or (2) nuclei of growing continents. The age of the granite on the Seychelles and the geology of Madagascar suggest that at

FIGURE 10. Diamantina Fracture Zone, Broken Ridge, Ninetyeast Ridge in the east central Indian Ocean. This is a portion of the Physiographic Diagram of the Indian Ocean published by the Geological Society of America. (Copyright 1964 Bruce C. Heezen and Marie Tharp; reproduced by permission.)

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

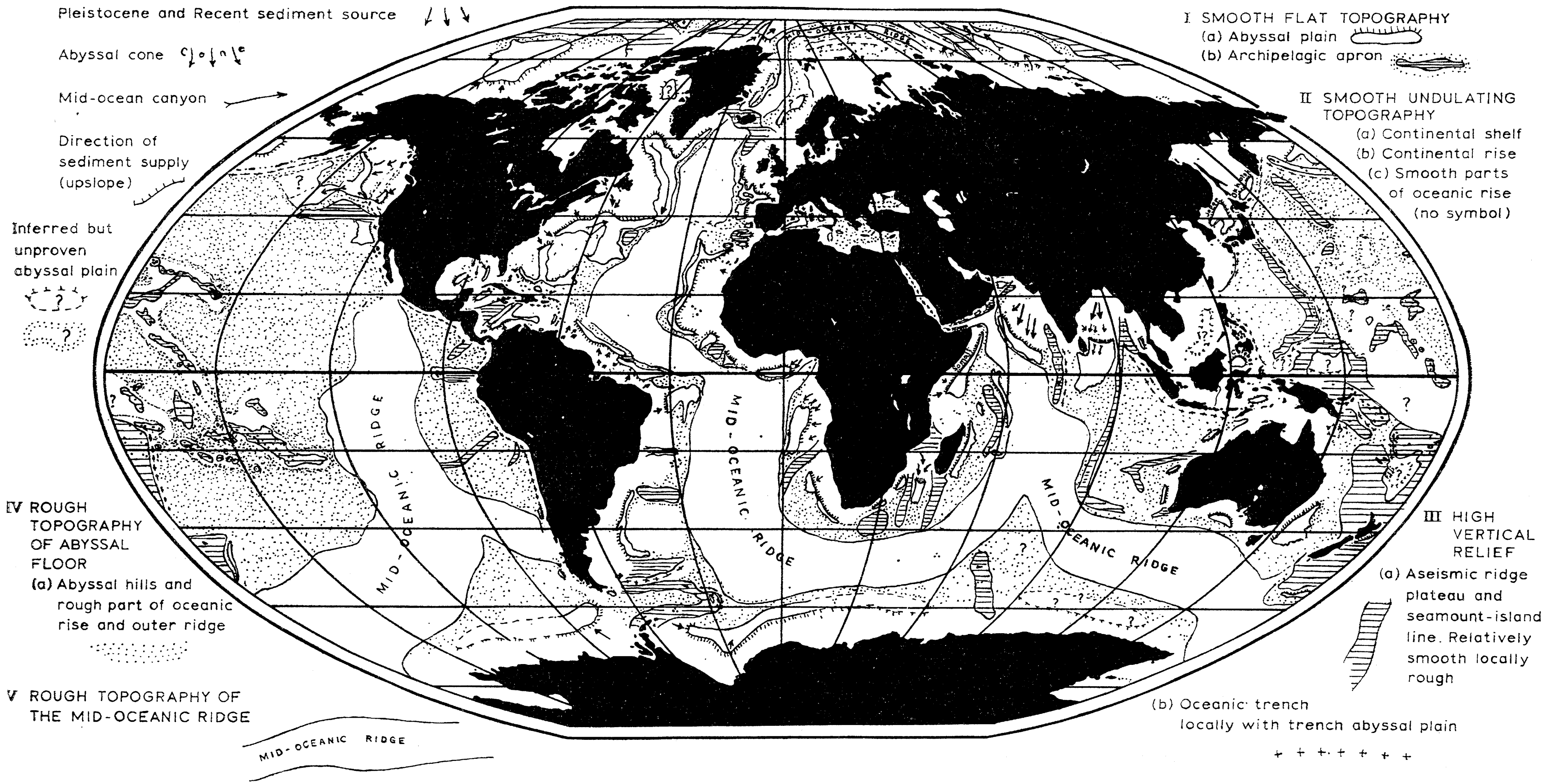

FIGURE 11. Distribution of smooth and rough topography in the world oceans. (North Atlantic, after Heezen, Tharp & Ewing 1959; South Atlantic after Heezen & Tharp 1961; Indian Ocean after Heezen & Tharp 1964; Pacific Archipelago Aprons after Menard 1956; Arctic after Dietz & Shumway 1961.)

least these two micro-continents are of great age (Baker & Miller 1963) and if these are growing continents the rate of growth is indeed small. It seems more reasonable to assume that the micro-continents which are distributed in such a strikingly meridional pattern throughout the Indian Ocean are fragments of continental crust. These features are similar in form and probably in origin to the Walfisch Ridge of the South Atlantic and it is perhaps significant that the Walfisch Ridge is, in general, parallel to the aseismic ridges of the Indian Ocean.

Winding its way between this pattern of ridges is the forked Mid-Oceanic Ridge. The ridge is cut by strike-slip faults some of which have been studied, others inferred, and in other areas the data are too scarce to even speculate on the presence or absence of fracture zones. The topography of the Mid-Oceanic Ridge exhibits marked variations in texture which are probably in part due to variations in sediment thickness.

In the southeastern Indian Ocean the relief on the Mid-Oceanic Ridge is subdued except in the crest zone where the typical rugged nature of the ridge is observed. In the region of the Indian Ocean north of 40° S sediment is nearly lacking on the ridge and the topography is rugged.

The most obvious fracture zones, those which displace the axis of the Mid-Oceanic Ridge, are reflected both in the earthquake-epicentre belt and in the topography. A large, prominent fracture zone lies east of the mouth of the Gulf of Aden (Matthews 1963). The Vema Trench near 9° S forms a prominent offset in the axis of the ridge (Heezen & Nafe 1964). Other fracture zones have been inferred in the southwestern branch of the Mid-Oceanic Ridge (Ewing & Heezen 1961).

A prominent fracture zone extends from south of the southwestern corner of Australia to the west–northwest along the south side of the Broken Ridge. Although no topographic patterns nor magnetic anomaly patterns have been matched across this fracture zone, it seems that strike-slip motion is likely to be found along this long linear feature. An extrapolation of the trend of the western end of this fracture zone crosses the Ninetyeast Ridge. This fracture zone, known as Diamantina Fracture Zone, is named after the Australian Naval Research Vessel *Diamantina*. If strike-slip motion has occurred along this fracture zone it must have been in such a sense that the south side of the fracture zone was displaced to the east, for otherwise it would seem necessary that some displacement of the southern tip of the Ninetyeast Ridge would have taken place and no such displacement is evident.

The long linear trend of the Ninetyeast Ridge seems also to indicate strike-slip motion. Although no obvious topographic displacements are observed, the striking linearity of the Ninetyeast Ridge at least suggests strike-slip motion. If such offset occurred it would seem that the area to the west of the Ninetyeast Ridge must have moved to the north.

A northward drift of India is suggested by palaeomagnetic measurements. From the patterns seen in the sea floor it would appear that the last phases of this movement must have been in a direction parallel to the Ninetyeast Ridge and the Owen Fracture Zone of the Arabian Sea which displaces the present seismically active crest of the Mid-Oceanic Ridge.

The Mid-Oceanic Ridge appears to be a feature created by extension of the Earth's crust and the emplacement of new material from the mantle below. The aseismic ridges of the Indian Ocean appear to be micro-continents and to owe their long linear orientation to strike-slip faulting. Thus several systems of motion can be inferred. The active rift valley of the Mid-Oceanic Ridge indicates divergent movement from the crest of the ridge which resulted in the creation of the rift valley and the minor ridges which parallel the rift valley and gave the Mid-Oceanic Ridge such a striking grain parallel to its axis. Superimposed on this grain are strike-slip faults which offset the axis of the ridge. The orientation of these strike-slip faults is in general parallel to the inferred divergent motion at the crest of the ridge. The micro-continents of the Indian Ocean are oriented largely north–northeast, south–southwest. In the equatorial Indian Ocean the Mid-Oceanic Ridge lies generally parallel to the aseismic ridges, but a little north of the equator it cuts across the trend of the aseismic ridges as it does even more dramatically south of 35° S.

In recent years there has been much speculation concerning the origin of the Mid-Oceanic Ridge. Many authors now attribute the extensional topography of the Mid-Oceanic Ridge to the effects of convection cells which rise beneath the ridge, carrying the ocean floor away from the ridge towards the adjacent continents. The creation of new crust along the crest of the ridge and folding along the continental margins are considered to be the result of this convection. In an ocean such as the North Atlantic or South Atlantic the nearly precise symmetry of these oceans and the lack of any extensive aseismic ridges make such a pattern indeed attractive. However, in the Indian Ocean the existence of such divergent trends and the scattered ancient micro-continents make such explanation extremely difficult. If one were to imagine that the Carlsberg Ridge were formed by a rising convection cell, then it is difficult to imagine why the Seychelles and the Laccadives would not have been carried away and forced into the adjacent continents rather than existing as they do as scattered linear micro-continents in the centre of the sea. The radical difference in inferred motions along the fracture zones paralleling the ancient micro-continents and the motions along the crest of the Mid-Oceanic Ridge inferred from the form of the modern topography and the displacement of the fracture zones, seem also difficult to reconcile with the concept of convection currents. Indeed the extension of the Mid-Oceanic Ridge belt into the Red Sea and to the rift valleys of Africa seems also to raise serious if not fatal objections to the convection current hypothesis.

It has been recognized for some years that the smooth form of the abyssal plains and adjacent continental rise is due in large part to the smoothing effects of turbidity-current deposition. Recent continuous seismic-reflexion profiles (Ewing, Ewing & Talwani 1964; and other papers) have shown that the rugged topography of the Mid-Oceanic Ridge is, as might be expected, mantled with a negligible amount of sediment, often too little to measure with present techniques, and that the sediment which is found is in general collected into basins. In general, the Mid-Oceanic Ridge is devoid of sediments throughout most of its length. However, certain regional variations in topographic form have been noted in the ridge, some of which may be related to variations in the thickness of sediments.

The four major factors affecting the thickness of sediment in any one place are: (1) the organic productivity of the area, (2) the availability and transport of terrigenous sediments, (3) the depth of water (which is related to the preservation of soluble contituents), and (4) the age of the ocean floor in the particular area under consideration. Abyssal plains are found adjacent to major sediment sources and appear to be in part due to the effects of

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

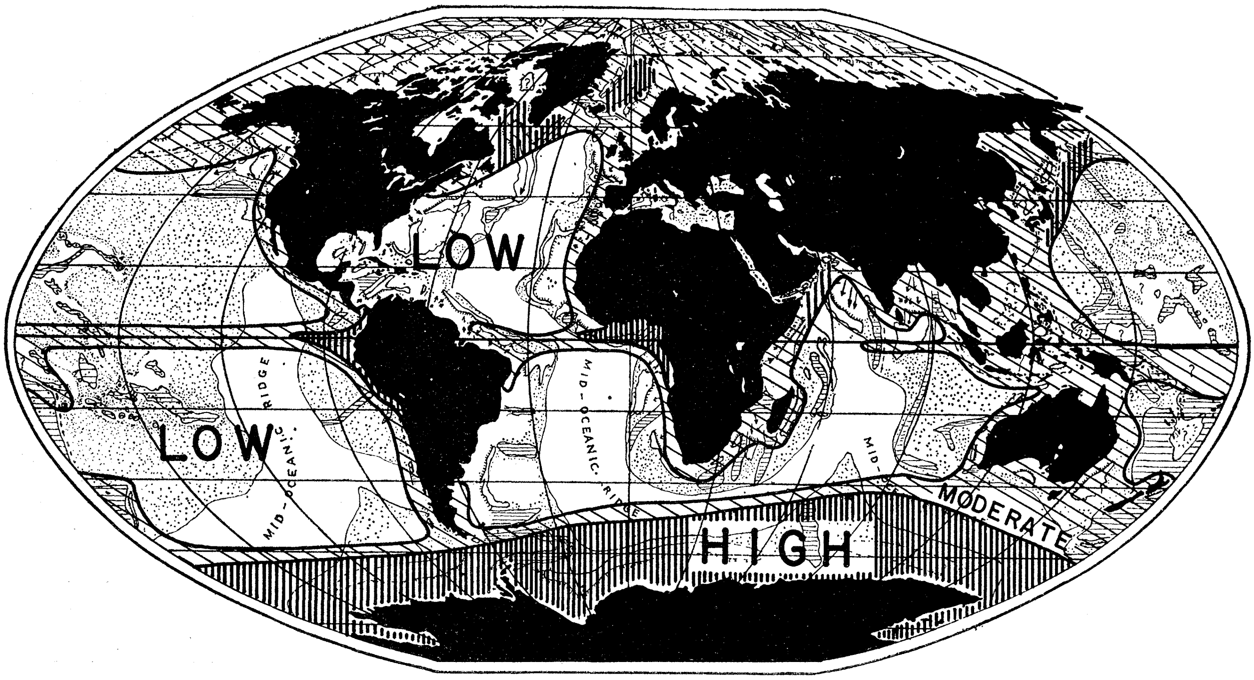

FIGURE 12. Organic productivity of the world ocean; a generalized interpretation based largely on oceanic circulation patterns.

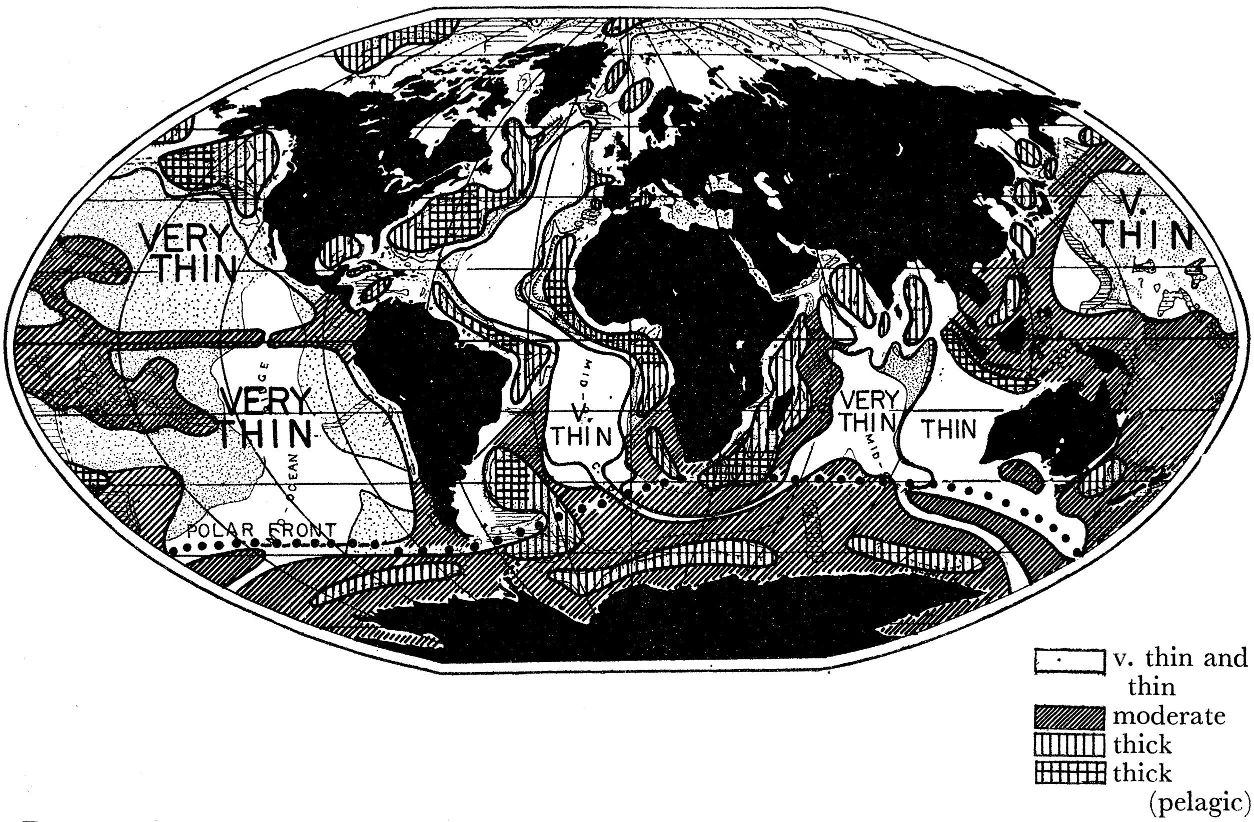

FIGURE 13. Sediment thickness. Based in part on seismic reflexion measurements of Ewing *et al.* (1962, 1963, 1964) and others; on seismic refraction measurements of Raitt (1956) and others, and generalized on the basis of the distribution of abyssal plains, oceanic rises and smooth areas of the Mid-Oceanic Ridge as observed on precision high resolution echograms.

turbidity-current deposition, and in part due to the transport by other means from the adjacent sediment sources.

The organic productivity of the surface waters of the ocean exerts a major control on the rate of deposition of organic oozes. The high productivity areas of the Antarctic are characterized at the present time by rapidly deposited diatomites. Near the equator radiolaria and carbonate oozes are characteristically found. However, in the deeper waters of the North Pacific and South Pacific, North Atlantic and South Atlantic the abyssal red clays represent the residue left after the dissolution of the majority of the organic components.

A comparison of figures 12 and 13 indicates that the relatively greater sediment thicknesses which lie on the Mid-Oceanic Ridge and oceanic rises in the circum-Antarctic belt are probably due to the influence of the high productivity of the Antarctic. A belt of thinner sediments follows the crest of the Mid-Oceanic Ridge through the centre of this high productivity area in the southern Indian Ocean. The marked similarity in the patterns of productivity and of sediment thickness suggests that a large proportion of the sediments measured in the reflexion profiles and inferred from the smoothing effects observed in echo-grams were laid down during recent geological time under climatic and oceanic circulation systems similar to the present. It would seem likely that there has always been a higher productivity in the Antarctic and equatorial belts, although the contrast between the productivity of these areas and that of the lower productivity areas may have been smaller in former non-glacial times. The high productivity of the Antarctic is at the present time related to an intense vertical circulation, the present form of which is in large part dependent on the glacial conditions which prevail in the Antarctic seas. The thin sediment along the crest of the Mid-Oceanic south of Africa and south of Australia indicates a relatively recent age of this topography and perhaps deformation during the Pleistocene. The narrow belt of somewhat thicker sediments in the equatorial Pacific has been investigated by Riedel of Scripps Institution of Oceanography and was first recognized in the eastern equatorial Pacific by Arrhenius (1952). Arrhenius noted a northward shift of the belt of carbonate sediments in the early Pleistocene which may represent either the commencement of more vigorous circulation at the equator or a northward shift of the equatorial current system.

An intensive study of the Pacific Ocean in search of the past position of this equatorial belt might be extremely informative in terms of polar wandering. This belt, which is so closely tied to the present equator, should show a recognizable shift with time if polar wandering has occurred.

The very thin sediment on the Mid-Oceanic Ridge of the southeast Pacific and of the Atlantic might be evidence of relatively recent origin of these features, but on the other hand may simply reflect the very low productivity of these areas. The thick sediments of the Argentine Basin (Ewing, Ludwig & Ewing 1964) and of the North America Basin (Ewing 1963) appear to be composed largely of pelagic deposits. These thick deposits constitute real anomalies in the distribution pattern, since they occur beneath areas of particularly low present productivity. The thick sediments associated with the continental rise and the abyssal plains can be assumed to be largely terrigenous and therefore have little or no bearing on shifting zonal productivity patterns. However, it would seem that

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

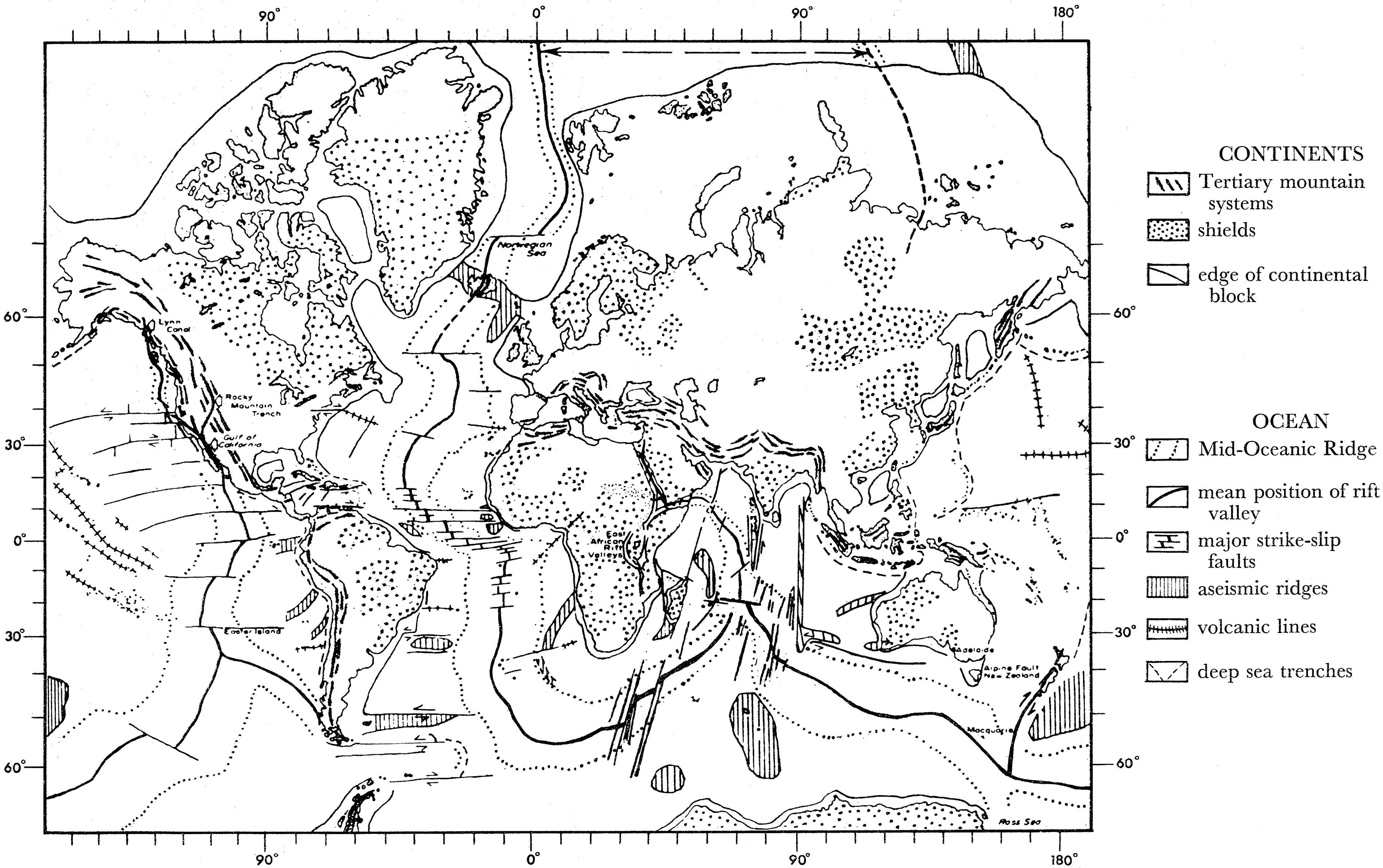

FIGURE 14. Tectonic chart of the world.

the large contrast in thickness between the essentially pelagic deposits of these basins and thin deposits of the adjacent ridge would suggest a greater age for the oceanic rises than for the Mid-Oceanic Ridge despite the fact that active currents are known to sweep the ridge and would tend to concentrate the finer sediments in the basin.

At the present time the sediment distribution patterns cannot be used in any definite way to infer polar wandering. However, the method seems to have potential. One conclusion which seems to be supported by the present data is that the present productivity patterns and the present continental terrigenous sources dominate the present distribution of unconsolidated sediments, and on this basis point away from many radical reorientations of the sea floor in the time during which the majority of the sediments now seen on the ocean floor were deposited. This may mean that the oceanic sedimentation commenced relatively recently, perhaps in the early Tertiary, or that the ocean floor is relatively young. Since palaeomagnetism points to no very radical Tertiary changes in pole position, it would seem that the sediment thicknesses we see are primarily Tertiary in age.

A tectonic sketch of the world is shown in figure 14. The motions of the continents inferred from adjacent strike-slip faults are shown by large black arrows. The motions inferred from sea-floor features are consistent in a general way with palaeomagnetic reconstructions. A simple convection current pattern is not favoured for the explanation of these features. The tectonic pattern of the Indian Ocean floor seems particularly difficult to explain in terms of oceanic spreading (Dietz 1961; Wilson 1963).

Although there are many unsolved problems and some evidence which apparently is adverse to this concept, the writer believes that a general expansion of the earth better explains the sea floor tectonic fabric than the recently popular convection current hypothesis.

References (Heezen & Tharp)

Anon. 1963 *Bathymetric magnetic and gravity investigations H.M.S.* Owen, 1961–1962: *Admiralty Mar. Sci. Publ.* no. 4, pt. 2, Hydrographic Department, Admiralty, London, 35 p.

Arrhenius, G. 1952 Sediment cores from the East Pacific. *Rep. Swed. Deep-Sea Expedition*, vol. v, nos. 1, 2, 3 and 4.

Baker, B. H. & Miller, J. A. 1963 Geology and geochronology of the Seychelles Islands and structure of the floor of the Arabian Sea. *Nature, Lond.*, **199**, 346–348.

Bullard, E., Everett, J. E. & Smith, A. Gilbert 1965 The fit of the continent around the Atlantic. *Phil. Trans.* A, **258**, 41 (this Symposium).

Carey, S. W. 1958 A tectonic approach to continental drift. In *Continental drift, a Symposium*, 1956 (S. W. Carey, convener), p. 177. Hobart: University of Tasmania.

Dietz, R. S. 1961 Continent and ocean-basin evolution by spreading of the sea floor. *Nature, Lond.*, **190**, 854–857.

Dietz, R. S. & Shumway, G. 1961 Arctic basin geomorphology. *Geol. Soc. Amer. Bull.* **72**, 1319–1330.

du Toit, A. L. 1937 *Our wandering continents*, 366 pp. Edinburgh: Oliver and Boyd.

Ewing, J. & Ewing, W. M. 1962 Reflection profiling in and around the Puerto Rico Trench. *J. Geophys. Res.* **67**, 4729–4739.

Ewing, W. M. 1963 Sediments of ocean basins. In *Man, science, learning and education*, pp. 41–59. William Marsh Rice University.

Ewing, W. M., Ewing, J. I. & Talwani, M. 1964 Sediment distribution in the oceans: the Mid-Atlantic Ridge. *Geol. Soc. Amer. Bull.* **75**, 17–36.

Ewing, W. M. & Heezen, B. C. 1960 Continuity of Mid-Oceanic Ridge and Rift Valley in the south-western Indian Ocean confirmed. *Science*, **131**, 1677–1679.

Ewing, W. M., Ludwig, W. J. & Ewing, J. I. 1964 Sediment distribution in the oceans: the Argentine Basin. *J. Geophys. Res.* **69**, 2003–2032.

Heezen, B. C., Bunce, E. T., Hersey, J. B. & Tharp, M. 1964*a* Chain and Romanche Fracture Zones: *Deep-Sea Res.* **11**, 11–33.

Heezen, B. C., Gerard, R. D. & Tharp, M. 1964*b* Vema fracture zone: equatorial Atlantic. *J. Geophys. Res.* **69**, 733–739.

Heezen, B. C. & Nafe, J. E. 1964 Vema trench: Western Indian Ocean. *Deep-Sea Res.* **11**, 79–84.

Heezen, B. C. & Tharp, M. 1961 *Physiographic diagram of the South Atlantic, the Caribbean, the Scotia Sea, and the Eastern margin of the South Pacific Ocean.* New York: Geol. Soc. Amer.

Heezen, B. C. & Tharp, M. 1964 *Physiographic diagram of the Indian Ocean, the Red Sea, the South China Sea, the Sulu Sea and the Celebes Sea.* New York: Geol. Soc. Amer.

Heezen, B. C., Tharp, M. & Ewing, M. 1959 *The floors of the oceans.* I. *The North Atlantic.* New York: Geol. Soc. Amer., 122 p.

Matthews, D. H. 1963 A major fault scarp under the Arabian Sea displacing the Carlsberg Ridge near Socotra. *Nature, Lond.*, **198**, 950–952.

Menard, H. W. 1956 Archipelagic aprons. *Amer. Assoc. Petrol. Geol. Bull.* **40**, 2195–2210.

Raitt, R. W. 1956 Seismic refraction studies of the Pacific Basin. I. *Geol. Soc. Amer. Bull.* **67**, 1623–1640.

Wegener, A. 1924 *Origin of continents and oceans*, 212 p. New York: Dutton.

Wilson, J. Tuzo 1963 Hypothesis of earth's behaviour. *Nature, Lond.*, **198**, 925–929.

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