Continental Displacement and Expansion of the Earth during the Mesozoic and Cenozoic

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CONTINENTAL DISPLACEMENT AND EXPANSION OF THE EARTH DURING THE MESOZOIC AND CENOZOIC

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CONTENTS

Most reconstructions of Pangaea, the early Mesozoic supercontinent, assume an Earth of modern dimensions. Such reconstructions produce major geometric and geological fit inconsistencies particularly in areas such as the Arctic, Caribbean, Mediterranean, and southeast Asia and Indonesia. The ocean floor spreading history of these regions and the adjacent oceans indicates that they have grown by areal expansion since their initiation. In contrast, the various reconstructions of Mesozoic and Cenozoic stages which assume an Earth of constant dimensions, require that these regions, either initially or during their development, should contract in area. The geological evidence from the continental margins and from the Earth's oceans does not support the amount of subduction, either in whole or in part, required by the constant dimension hypothesis.

It is shown that an exact fit of the various continental fragments together to reform Pangaea, which agrees with the geometric and geological matches, is obtained when the value of the Earth's surface curvature is increased to the point at which the diameter of the globe is 80 % of its current mean value. This corresponds in time to the late Triassic–early Jurassic. It is asserted that the early Upper Jurassic to Recent ocean floor spreading data now available, displayed here in maps, also demonstrate progressive global expansion commensurate with an increase in diameter of 20 % of the Earth's current mean value.

Series of maps employing a zenithal equidistant projection are used to illustrate stages in the inferred development of certain regions during the Mesozoic and Cenozoic according to the ocean floor spreading data. The global expansion deduced from the geometric requirements of the spreading data in these maps permits a much more straightforward reading of the development of ocean basins and associated displacement of continents; one which accords with the field evidence. The inconsistencies seen in constant dimensions reconstructions do not arise. The results are summarized in outline hemisphere maps for which a new cartographic projection has been developed.

1. Introduction

Most reconstructions of Wegener's late Palaeozoic–early Mesozoic super-continent Pangaea are made on a globe of modern dimensions (see, for example, Carey 1958; Dietz & Holden 1970; Robinson 1971; Smith 1971; Smith, Briden & Drewry 1973). The fit of the continents together in such reconstructions is far from perfect. Although the fit of the North West African continental margin into the corresponding North American East Coast embayment is reasonably precise, the accuracy of the fit deteriorates away from this region (figure 1). It has long been recognized that the simple expedient of increasing the value of surface curvature, and thus reducing the Earth's diameter, produces a better fit of the continents together (see, for example, Carey 1958; Hilgenberg 1966; Meservey 1969; and see Jeffreys 1962). However, without reasonably detailed information on the history of development of the oceanic crustal regions which form some 70 % of the Earth's total surface area, no precise work could be attempted to ascertain whether or not the Earth has expanded during its history. A review of previous work advocating global expansion has been given by Carey (1975).

Sufficient data are now available from the mapping of the magnetic anomaly patterns in the crust of the oceanic basins to apply a spherical geometric test to determine whether or not the Earth has expanded since the start of their formation. The bulk of the ocean floor spreading data published up to the end of 1974 is shown in figures 2–4, and the chronological table of numbered reversed magnetic anomaly lineations during the Mesozoic and Cenozoic is given in table 1. The schemes of continental dispersal proposed by authors who assume an Earth of constant dimensions during Phanerozoic time, such as Dietz & Holden (1970) and Smith *et al.* (1973), do not accord with either the geometry of the original fit of continental fragments together, the ocean floor spreading data now available (which indicates the dispersal of these fragments), or the orogenic history of the Earth's crust during the Mesozoic and Cenozoic.

It is asserted here, that the excellent fit of the continents together in the late Triassic–early Jurassic in the reconstructions below, and the subsequent fragmentation of Pangaea according to the ocean floor spreading data rather than pre-conceived assumptions, indicates that the Earth has expanded during the last 180–200 million years (Ma) by 20 % of its modern diameter. This expansion is probably related to the general expansion of the Universe (see, for example, Hoyle 1972). There is no evidence, however, of expansion and contraction phases in the Mesozoic and Cenozoic in response to cyclical changes in the value of galactic gravity suggested by Steiner (1967).

Global expansion has major palaeogeographical implications for the evolution and distribution not only of terrestrial life but of modern marine faunas and floras, which provide a

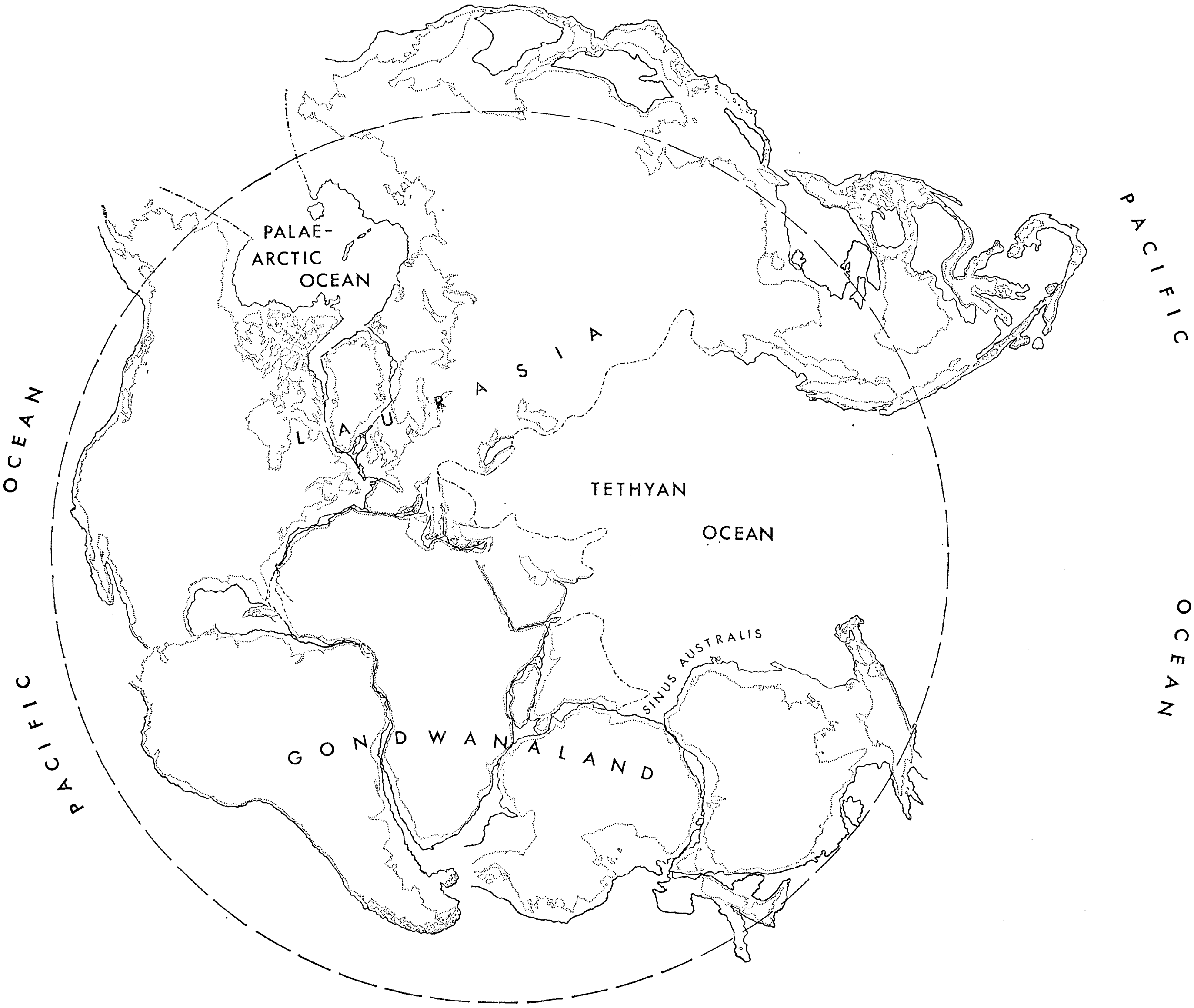
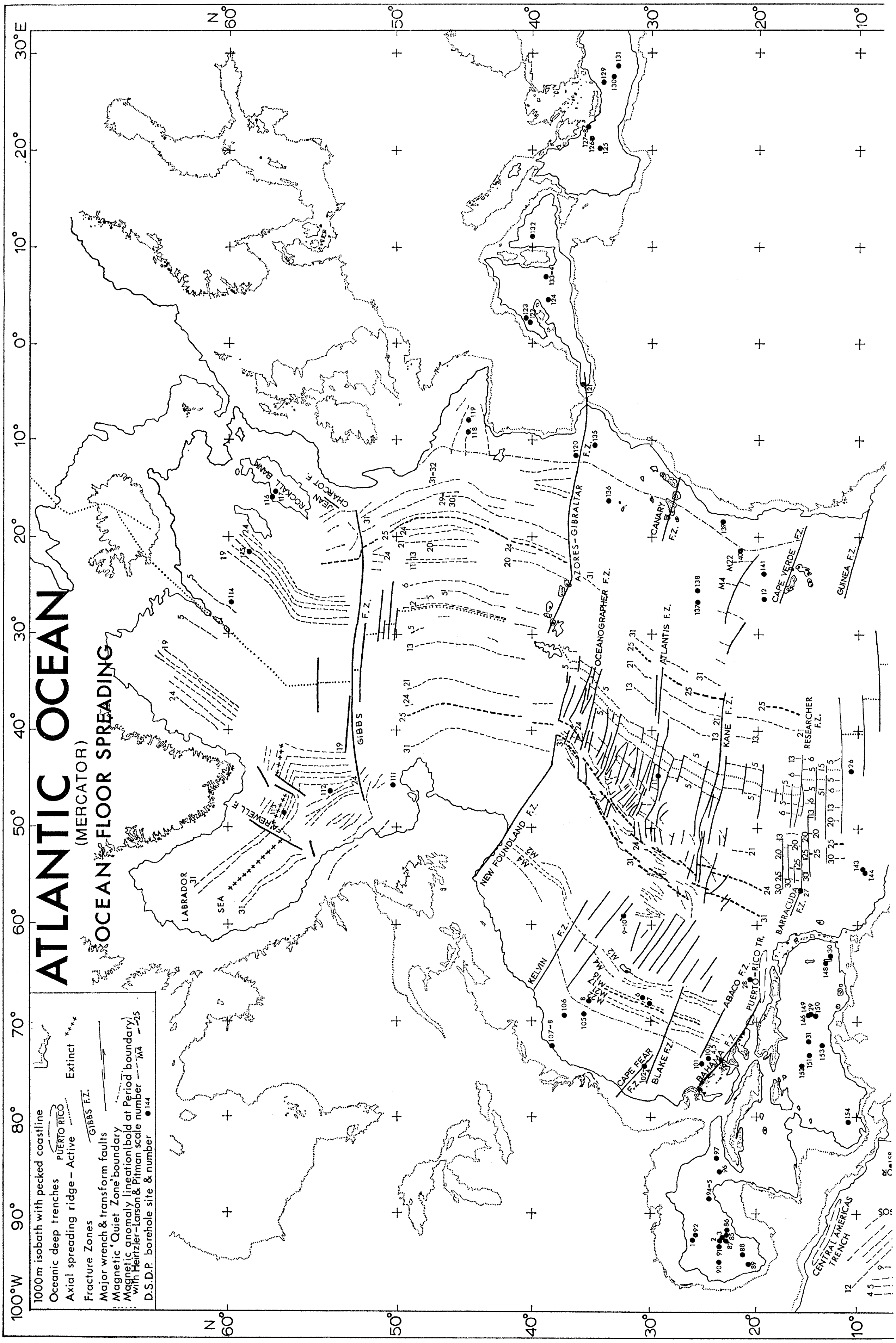


Figure 1. Conventional reconstruction of Pangaea. Stereographic projection from a globe representing a modern diameter Earth.

significant and growing amount of our food supply. The bulk of these live and reproduce in the comparatively shallow waters of the continental shelves and the few epicontinental seas which exist today, such as Hudsons Bay, the Barents Sea, North Sea and parts of the South China Sea. Epicontinental seas were very much more extensive in the past, but have shrunk greatly in area from the late Cretaceous onward. Studies of the history of development and distribution of marine faunas and floras during the Mesozoic and Cenozoic require palaeogeographic maps which reflect more accurately the distribution of land, seas and oceanic areas actually present. Maps based on the concept of a constant dimension Earth during the Mesozoic and Cenozoic not only do not accord with the ocean floor spreading data, but also produce inconsistencies in faunal distributions.


ATLANTIC OCEAN
(MERCATOR)
OCEAN FLOOR SPREADING
1000 m isobath with pecked coastline
Oceanic deep trenches PUERTO RICO
Axial spreading ridge – Active
Extinct
Fracture Zones GIBBS F.Z.
Major wrench & transform faults
Magnetic 'Quiet Zone' boundary
Magnetic anomaly lineation (bold at Period boundary) with Heirtzler–Larson & Pitman scale number M4 25
D.S.D.P. borehole site & number 144
30° E
20°
10°
0°
10°
20°
30°
40°
50°
60°
70°
80°
90°
100° W
N 60°
50°
40°
30°
20°
10°
LABRADOR SEA
FAREWELL F.Z.
GIBBS F.Z.
JEAN CHARCOT F.
ROCKALL BANK
AZORES–GIBRALTAR F.Z.
OCEANOGRAPHER F.Z.
ATLANTIS F.Z.
KANE F.Z.
CANARY F.Z.
CAPE VERDE F.Z.
GUINEA F.Z.
RESEARCHER F.Z.
BARRACUDA F.Z.
PUERTO RICO TR.
ABACO F.Z.
BAHAMA F.Z.
BLAKE F.Z.
CAPE FEAR F.Z.
KELVIN F.Z.
NEW FOUNDLAND F.Z.
CENTRAL AMERICAS TRENCH
M4
M22
M21

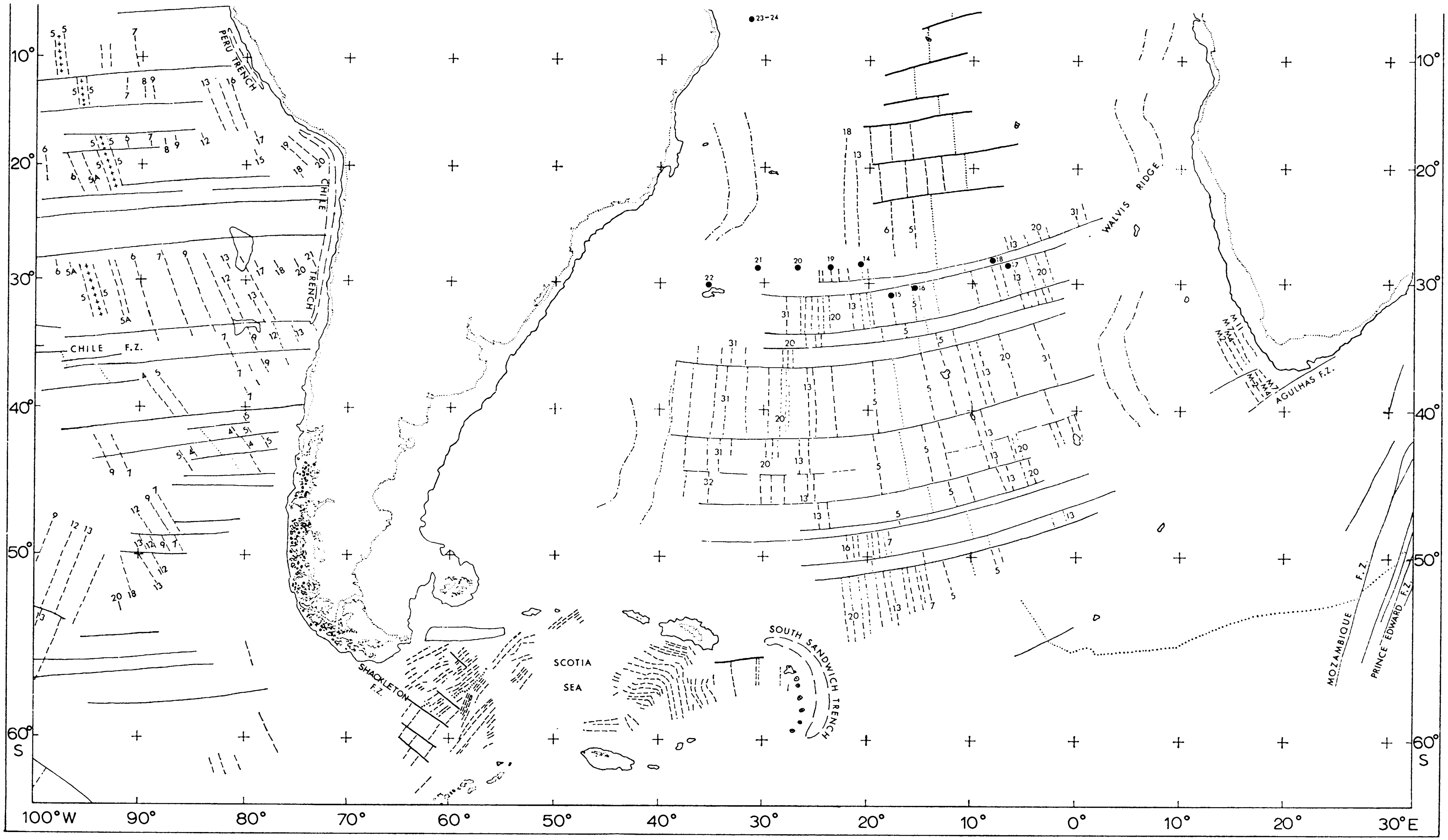


Figure 2. Atlantic Ocean (Mercator's) showing ocean floor spreading data and Deep Sea Drilling Project (D.S.D.P.) borehole sites, compiled essentially from Barker (1970, 1972*a*,*b*); Dickson, Pitman & Heirtzler (1968), Larson & Pitman (1972), Laughton (1971), Le Pichon & Fox (1971), Le Pichon & Hayes (1971), Pitman, Talwani & Heirtzler (1971), Vogt, Anderson & Bracey (1971), Vogt & Johnson (1971), Vogt & Ostenso (1970), Williams & McKenzie (1971), Mascle & Phillips (1972), Ladd, Dickson & Pitman (1973), Larson & Ladd (1973), Peter, Lattimore, De Wald & Merrill (1973), Lattimore, Rona & De Wald (1974), and JOIDES. The magnetic reversal anomaly sequence is given in table 1 (p. 228) with approximate ages.

The maps given in figures 2–4 employ the conventional Mercator's projection, while those given in figures 6–10 are projected by using either the polar or equatorial cases of the zenithal equidistant projection. In order to produce hemisphere maps of various stages in continental displacement on an expanding globe, with as little distortion as possible, and at the same time providing little distorted representations of the vitally important polar regions, it became

TABLE 1. TABLE OF NUMBERED REVERSED MAGNETIC ANOMALIES GROUPED IN STAGES WITH APPROXIMATE RADIOMETRIC AGE OF EACH

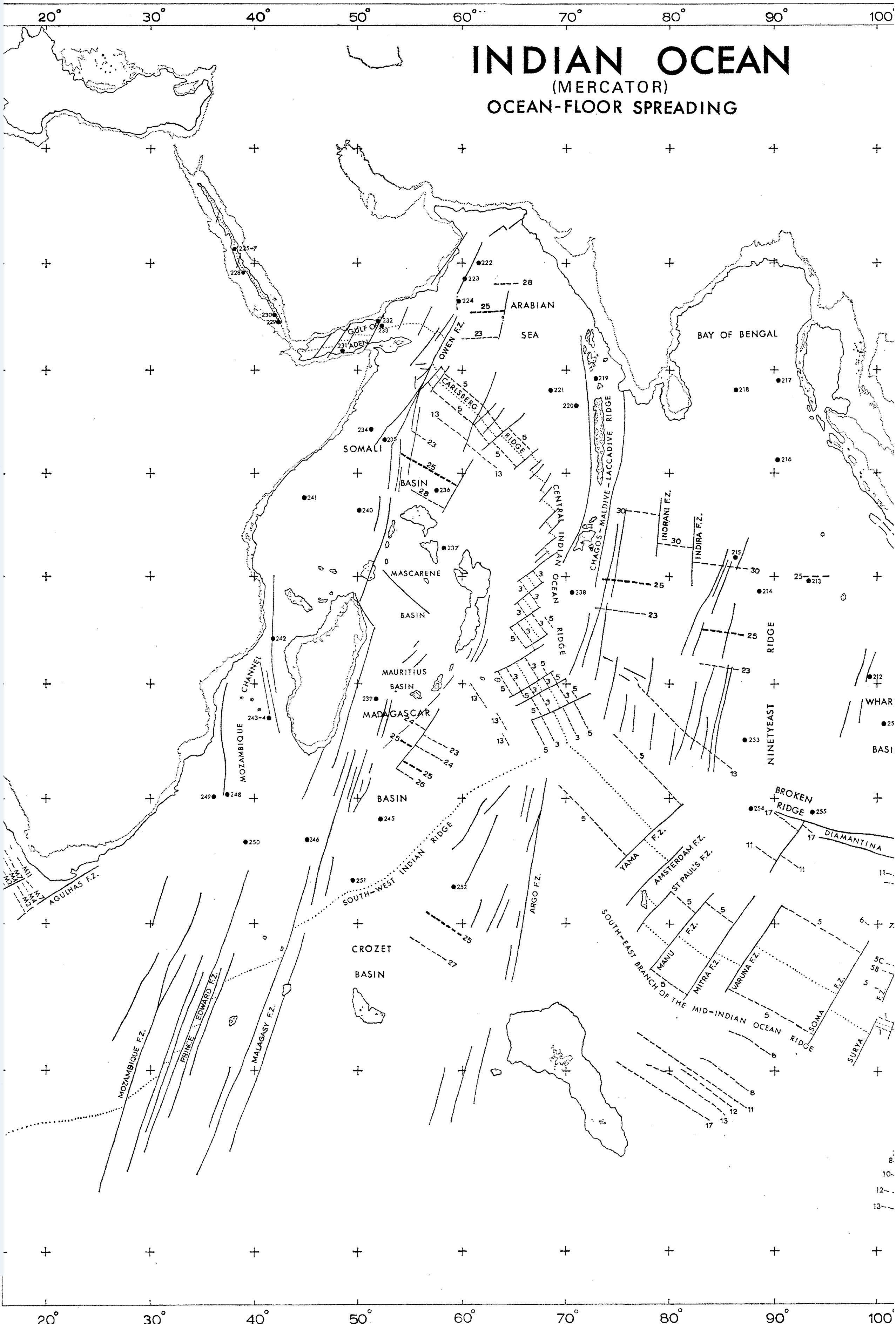
(Compiled from Heirtzler *et al.* (1968); Weissel & Hayes (1972); and Larson & Pitman (1972).)

anomaly no.	estimated age/Ma†	Stage	anomaly no.	estimated age/Ma†	Stage
1	0.5	Pleistocene	30	70–71	Campanian
2	2		31	72	
3	5	Pliocene	32	77	Santonian
			33	82	
4	7–8	Miocene			
5	9		34	85	Coniacian
5A			35	?	
5B			36‡	?	
5C					
6	21		M1	112	Barremian
			M2	113	
7	27	Oligocene	M3	114	
8	29		M4	116	
9	30				
10	32		M5	118	Hauterivian
11	33–34		M6	118–119	
12	35		M7	119–120	
			M8	120–121	
13	37	Eocene	M9	121–122	
14	39		M10	122–123	
15	40				
16	42		M11	124–125	Valanginian
17	43		M12	126–127	
18	46		M13	128–129	
19	47		M14	129–130	
20	49				
21	53–54		M15	131	Ryazanian
			M16	133–134	
22	56–57	Palaeocene	M17	135–136	
23	58–59				
24	60		M18	137	'Purbeckian'
25	63		M19	139	
26	64–65				
			M20	141–142	Portlandian
27	67	Maestrichtian	M21	143–144	
28	68				
29	69		M22§	147–148	Kimmeridgian

† Estimated age in millions of years before present (B.P.) to the nearest million, or to a position within age points.

‡ The period between 85 Ma B.P. and 110 Ma B.P. from the Coniacian back through the Upper Cretaceous, and the Albian and much of the Aptian Stages of the Lower Cretaceous, constituted a long interval of normal polarity. Crust generated during this period is magnetically 'quiet'.

§ The Upper Jurassic backward in time from about 148 Ma B.P. also formed a long period of normal polarity. Crust generated during this interval is also magnetically 'quiet'.


INDIAN OCEAN
(MERCATOR)
OCEAN-FLOOR SPREADING
20°
30°
40°
50°
60°
70°
80°
90°
100°
ARABIAN
SEA
BAY OF BENGAL
GULF OF ADEN
OWEN F.Z.
CARLSBERG RIDGE
SOMALI
BASIN
CENTRAL INDIAN OCEAN RIDGE
CHAGOS-MALDIVE-LACCADIVE RIDGE
INDRANI F.Z.
INDIRA F.Z.
MASCARENE
BASIN
MAURITIUS
BASIN
MADAGASCAR
BASIN
MOZAMBIQUE
CHANNEL
NINETYEAST
RIDGE
WHAR
BASI
BROKEN RIDGE
DIAMANTINA
SOUTH-WEST INDIAN RIDGE
AGULHAS F.Z.
CROZET
BASIN
ARGO F.Z.
YAMA F.Z.
AMSTERDAM F.Z.
ST PAUL'S F.Z.
MANU F.Z.
MITRA F.Z.
VARUNA F.Z.
SOMA F.Z.
SURYA
SOUTH-EAST BRANCH OF THE MID-INDIAN OCEAN RIDGE
MOZAMBIQUE F.Z.
PRINCE EDWARD F.Z.
MALAGASY F.Z.
M11
M10
M7
M4
M2
222
223
224
225-7
228
229
230
231
232
233
234
235
236
237
238
239
240
241
242
243-4
245
246
248
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251
252
253
254
255
212
213
214
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217
218
219
220
221
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30
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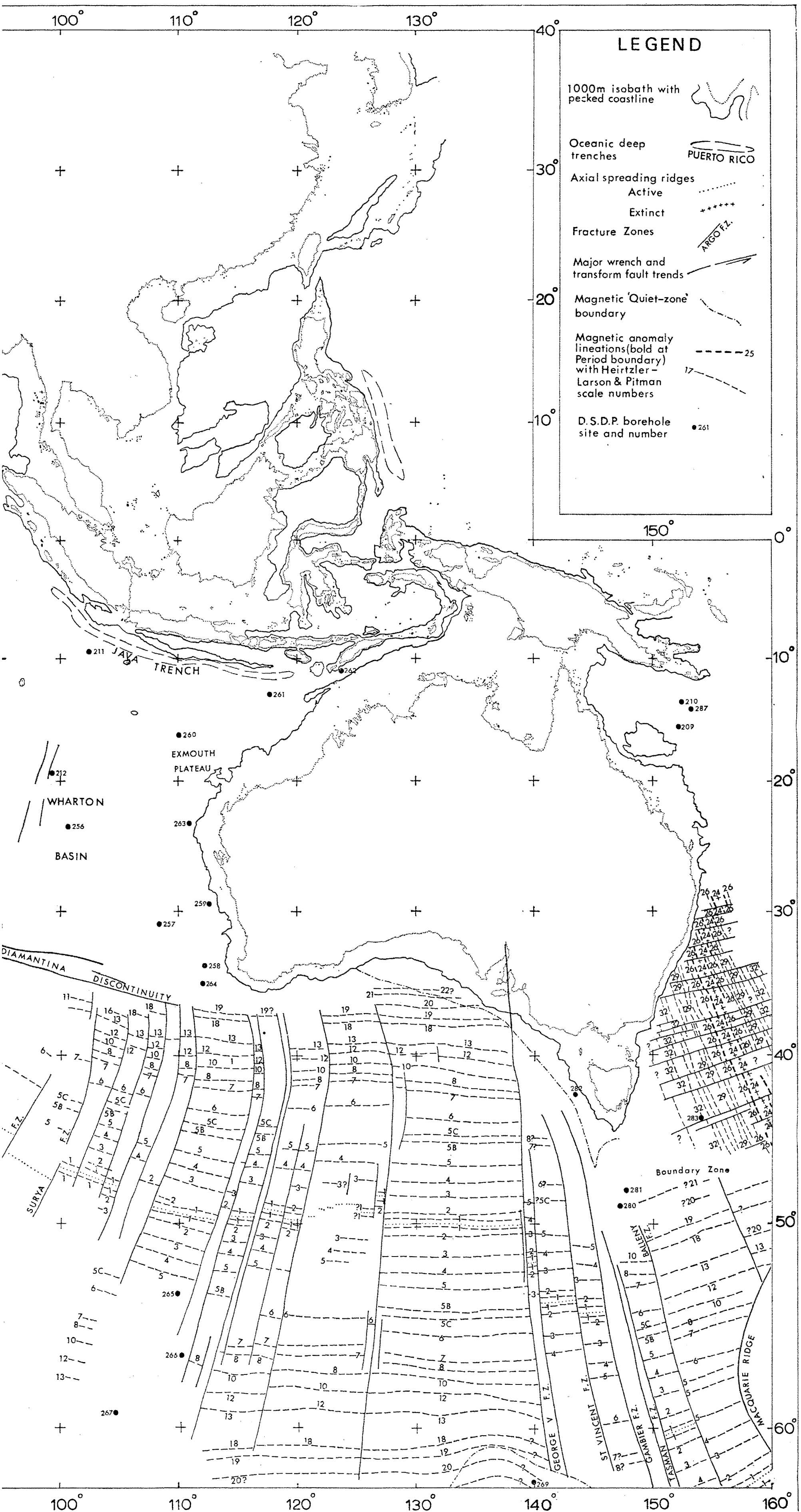
24
26
27
17
11
6
8
12
5C
5B
10
?


LEGEND
1000m isobath with pecked coastline
Oceanic deep trenches
PUERTO RICO
Axial spreading ridges
Active
Extinct
Fracture Zones
ARGO F.Z.
Major wrench and transform fault trends
Magnetic 'Quiet-zone' boundary
Magnetic anomaly lineations (bold at Period boundary) with Heirtzler – Larson & Pitman scale numbers
25
17
D.S.D.P. borehole site and number
261
100°
110°
120°
130°
140°
150°
160°
40°
30°
20°
10°
0°
50°
60°
JAVA TRENCH
EXMOUTH PLATEAU
WHARTON BASIN
DIAMANTINA DISCONTINUITY
SURYA F.Z.
Boundary Zone
BALLENY F.Z.
GEORGE V F.Z.
ST VINCENT F.Z.
GAMBIER F.Z.
TASMAN F.Z.
MACQUARIE RIDGE
211
212
256
257
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283
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287

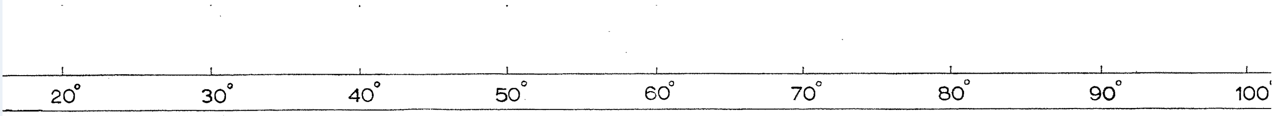
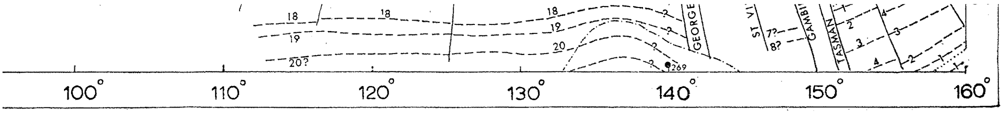


FIGURE 3. Indian Ocean (Mercator's) showing ocean floor spreading data and Deep Sea Drilling Project (D.S.D.P.
Hayes (1972), Heezen & Tharp (1965), Heirtzler *et al.* (1968), Le Pichon & Heirtzler (1968), McKenzie & Sclate
sequence is given in table 1 (p. 228) with approximate ages.

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



(D.S.D.P.) borehole sites, compiled essentially from Fisher, Sclater & McKenzie (1971), & Sclater (1971), Weissel & Hayes (1972) and JOIDES. The magnetic reversal anomaly

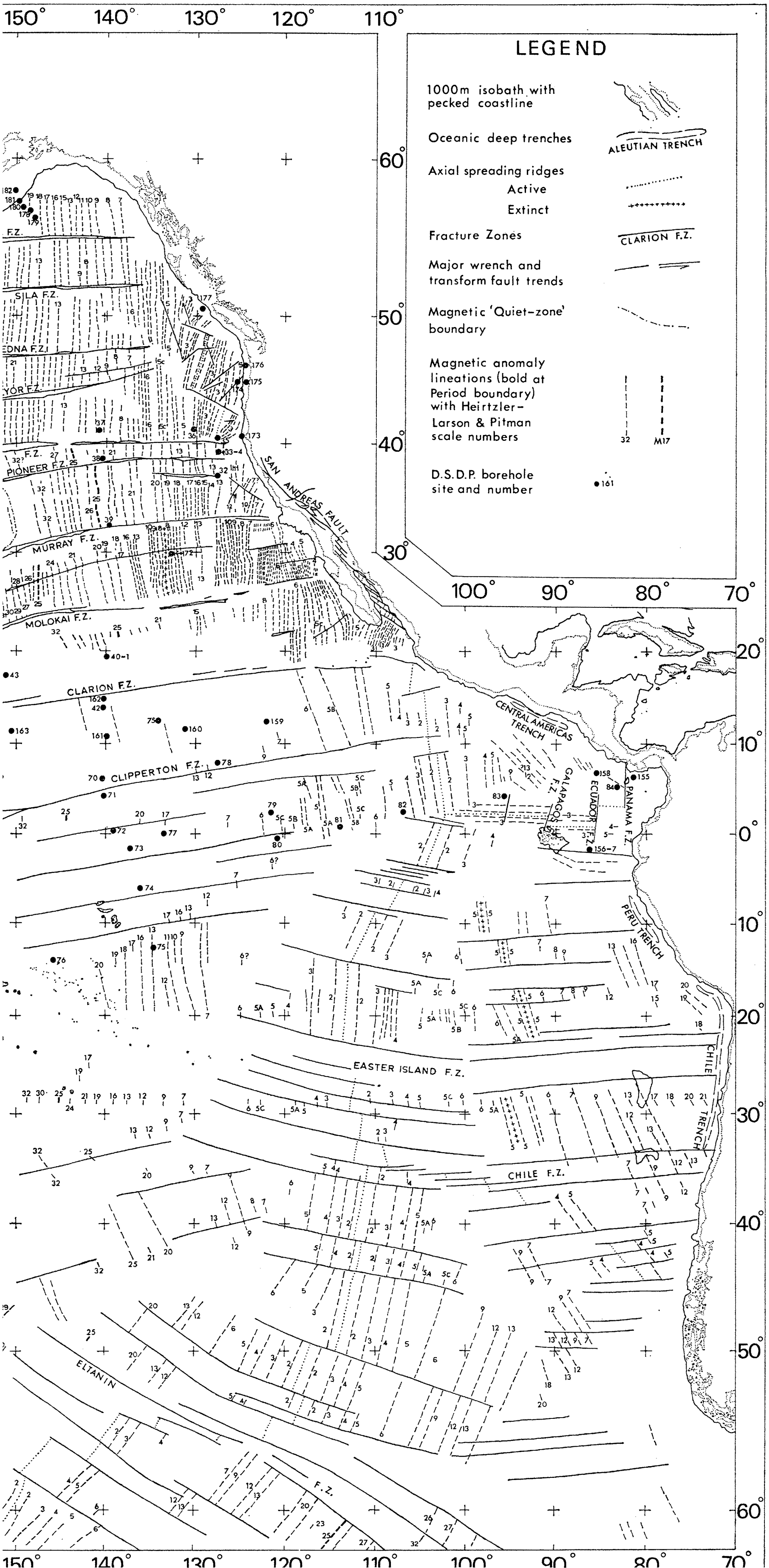
(*Facing p.* 228)

PACIFIC OCEAN

(MERCATOR)

OCEAN-FLOOR SPREADING

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



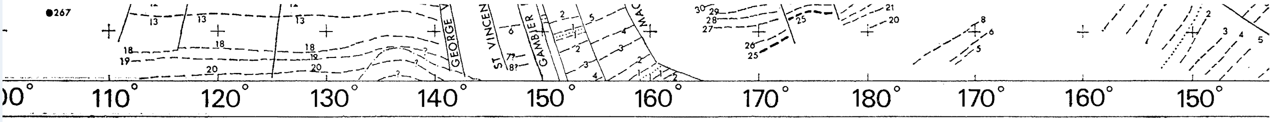
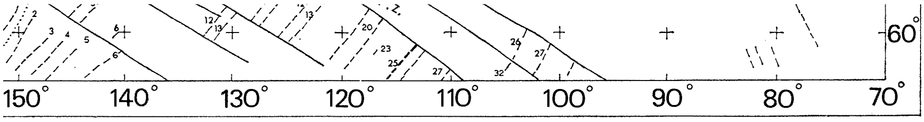


FIGURE 4. Pacific Ocean (Mercator's) showing ocean floor spreading data and Deep Sea Drilling Project (D.S.D.P.) Ben-Avraham, Bowin & Segawa (1972), Christoffel & Falconer (1972), Christoffel & Ross (1970), Hayes & Pitman (1972), Malahoff & Handschumacher (1971), Weissel & Hayes (1972), and JOIDES. The magnetic reversal anom

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



D.S.D.P.) borehole sites, compiled essentially from Atwater & Menard (1970),
Pitman (1970), Hayes & Ringis (1973), Herron (1971, 1972), Larson & Chase
sal anomaly sequence is given in table 1 (p. 228) with approximate ages.

necessary to devise a new projection. This projection, named 'trizenithal' here, is used in figures 11–18 and its construction is described in the appendix (p. 291). The positioning of the 0° prime meridian in the maps is based on the relative eastward movement of Greenwich since the early Jurassic determined from the ocean-floor spreading information and the geometry of the refit of the continents together. It has, therefore, a direct relation to the modern 0° meridian. The position of the geographic North Pole for Pangaea is again determined from the geometry of the movements of the continental fragments in this region during the Mesozoic and Cenozoic. There is, therefore, a correspondence to the modern North geographic pole, and also some correspondence to the early Mesozoic north magnetic pole. The positions of the Equator and South Pole are fixed from the above mentioned positions, and there is some palaeomagnetic and palaeoclimatic evidence to support the arrangement.

2. Estimation of the Earth's mean diameter in the Late Triassic to Middle Jurassic

The present mean radius of the Earth is 6376 km (3960 miles) giving a mean surface curvature of 1:5000000. The Earth is not a perfect sphere being slightly flattened in the region of the geographic North Pole and somewhat extended in the region of the South Pole. It has probably never been perfectly spherical, but from the analysis presented in this paper, it has not departed sufficiently from a sphere to invalidate the observations made here.

Various techniques have been described for obtaining the outlines of the continental regions from a globe in order to reconstruct Pangaea (see, for example, Carey 1958, p. 218; Creer 1965, p. 539). However, as Carey noted, no globes of reasonable size have sufficiently accurate data recorded on them. It is necessary, therefore, to produce cut-outs of the continental areas with the aid of first class maps. Most workers have used a stereographic projection, but for greater accuracy the zenithal equidistant projection, with origin body-centred on the continent concerned, has been used here. This is a tedious projection to use but it has the advantage that all meridional distances and bearings from the centre of the construction are true (Lee 1947; and for an introduction to cartographic projections see Steers 1962). Base maps of the continents out to the 1000 m isobath, here taken as the edge of the continental shelf, were constructed for a modern globe of 38 cm diameter. With these base maps as a guide, cut outs of 2 mm thick expanded polystyrene were made with a high precision hot wire cutting device.

Rubber inflatable spheres were first used to determine whether there was a point at which the various continents fitted together to reform Pangaea precisely, one which agreed with geological fit data for the late Triassic and early Jurassic and with the earliest break-up chronology indicated by the ocean floor spreading data. It was found that the best geometric fit of the polystyrene continents, that agreed with the geological matches, occurred at only one value of surface curvature, that which gives a scale diameter of 30.5 cm. At diameters below this value, Pangaea could not be reformed on a sphere without producing intracontinental dislocations. Moreover, the actual initial ocean floor spreading history would not tally with the mode of post-Middle Jurassic break-up of the configuration of this supercontinent. Above the 30.5 cm diameter value, angular misfits and wedge-shaped voids, which would represent pre-Middle Jurassic oceanic crust, became increasingly evident, and the subsequent development of ocean-basins and alpide orogenic belts becomes more difficult to reconcile with the field evidence.

From the continental geological and geometric evidence, Pangaea in the configuration that is generally accepted, can only be reconstructed at a comparatively small interval of geological time (late Triassic–Lower Jurassic) and within very narrow limits in the value of the Earth's surface curvature. The diameter of the Earth in the late Triassic–early Jurassic determined from the surface curvature is approximately 80 % of its modern mean diameter. The expansion by 20 % of the Earth's present diameter during the last 180–200 million years (Ma), coupled with the style of ocean floor spreading during this period, permits a much more straightforward kinematic evolution of the modern oceanic areas of the Earth.

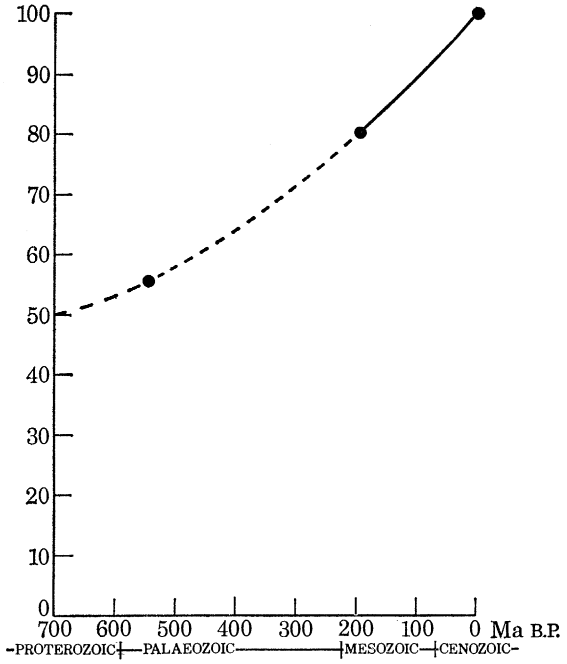


Figure 5. Exponential curve of the value of the Earth's mean diameter through time, assuming today's value, a value of 80 % of the modern diameter 180–200 Ma b.p., and a complete sialic crust at a diameter of about 55 % of the modern diameter of the Earth. The curve also assumes that the Earth has retained its shape as a sphere of rotation throughout this period.

Is this expansion the latter phase of a continuing process, and is the expansion linear or exponential? It has been argued that less dense elements and compounds in the differentiating outer layers of the primaeval Earth would migrate to the surface to form a complete sialic crust (see, for example, Hilgenberg 1933, 1966; Barnett 1962; Creer 1965; Carey 1970, 1975). The diameter at which the Earth could have possessed such an entire outer sialic crust immediately before the breakthrough of simatic crust, has been variously estimated, but the figure of 55 % given by Creer (1965) has the firmest areal data to support it. If the Earth has expanded steadily with time, its increase in diameter will be exponential. If so, the Earth's mean diameter would have been approximately half of its current value 700 Ma ago. This value together with the figure of 80 % of modern diameter at the end of the Trias and the modern diameter of the Earth, provide three points which lie on an exponential curve (figure 5).

The rate of expansion indicated by the exponential curve in figure 5 differs from the value suggested by Hoyle (1972). The curve also shows that for the last 200 Ma the difference between linear and exponential expansion is negligible.

With the surface areal constraints imposed by a globe expanding by 20% of its current (modern) diameter during the last 180–200 Ma, the development together of all the Earth's modern ocean basins during the Mesozoic and Cenozoic will occur within very close spherical geometric limits. The maps presented here show that this is indeed the case. Although no oceanic crust is known from the Pacific earlier in age than Upper Jurassic, there is spherical geometric evidence for the presence of a major ocean basin in this region by the early Mesozoic, although it was much smaller than its modern counterpart. This older crust would have been subducted during the Mesozoic, and there is ample evidence of marginal Pacific subduction zones during this period (§3(*e*), p. 275).

Briden & Smith (*in* discussion of Smith *et al.* 1973, p. 42) have reiterated the view widely held at present that palaeomagnetic observations probably give the most reliable estimate of the past size of the Earth, and that these give no indication of global expansion during the last 100 Ma at least. The remanent vector information (declination) given by modern palaeomagnetic determinative methods is largely accurate. However, there are many geological inponderables involved in the determination of the original attitudes of rock samples which make remanent inclination (dip) results, and thus the measure of original latitude, very subjective. Schouten (1971) has shown, however, that the shape of the remanent magnetic waveform obtained from traverses across ocean-floor magnetic anomaly lineations, can give an indication of the original magnetic field latitude. The significance of this in the Pacific is discussed later (§3(*e*), p. 275).

3. POSSIBLE DEVELOPMENT OF OCEANIC REGIONS

Vital clues to the original spherical geometry of the Earth in the early Mesozoic are given in particular by regions such as the Arctic, Caribbean, Mediterranean and southeast Asia and Indonesia. The current reconstructions of Pangaea which assume a globe of modern diameter are inconsistent with the geological and ocean floor spreading data. These reconstructions postulate a large 'Arctic Ocean' long before the present day Arctic Ocean basins started to develop (see, for example, Dietz & Holden 1970; Robinson 1971; Smith 1971; Smith *et al.* 1973; and figure 1 herein). Moreover, there is no geological evidence for subduction zones around the Arctic Ocean which would be required to absorb this postulated pre-early Mesozoic crust, because it is not present today.

Most reconstructions of the Caribbean and Central American region which assume a globe of modern dimensions, are contrary to the geological and ocean floor spreading evidence now available. On a constant dimensions globe, the Mediterranean region forms the apex of a triangular-shaped 'Tethys Ocean' (figure 1). This would require a subsequent history of subduction of pre-early Mesozoic crust and movement of continents contrary to the actual field evidence. Also, it fails to explain the development of the Alpine orogenic belts in the Balkans, southern Russia, Turkey and the Middle East (see, for example, Kent 1969). The Mesozoic and Cenozoic ocean floor spreading history of the eastern Indian Ocean and west Pacific, together with tectonic trends, preclude completely the wide oceanic gap between Australia and New Guinea on the one hand, and Indonesia, the Philippines and southeast Asia on the other which is obligatory in Pangaea reconstructions made on a globe of modern dimensions.

Reconstructions assuming a constant diameter Earth require that these four regions in particular must contract in area during the Mesozoic and Cenozoic. In reality, the geological and ocean floor spreading evidence shows that they have expanded their area during this time. The development suggested below for these regions and the major ocean basins, based on an Earth with a mean diameter in the late Triassic–early Jurassic of 80% of its present mean value expanding to its present dimensions, will proceed in a geometrically straightforward sequence. This sequence agrees with the constraints imposed by the geological evidence, tectonic style and ocean floor spreading data, which many published reconstructions assuming an Earth of constant dimensions fail to do.

(*a*) *Arctic Ocean* (*figures* 6*a–f*)

The physical features of the present day floor of the Arctic Ocean have been described by Dietz & Shumway (1961), Heezen & Ewing (1961), Ostenso (1963, 1973), Demenitskaya & Hunkins (1970), Vogt & Ostenso (1970), and Ostenso & Wold (1971), and are shown in figure 6*f*. Two main basins are present – the Amerasian and the Eurasian – with an oceanic crust generated essentially from the late Cretaceous to the present day. Vogt & Ostenso (1970) indicate that crust of the Amerasian Basin was largely generated by the Alpha Cordillera spreading axis from the late Cretaceous into the Eocene (about 40 Ma ago). This axis is a continuation of the extinct spreading-ridge system which extended northward from the Charlie or Gibbs fracture zone in the North Atlantic to separate Greenland from Canada (§3(*b*)(i), p. 241).

The Canada Basin forms part of the Amerasian Basin and is apparently the oldest oceanic crustal region present in the Arctic Ocean; its exact age is uncertain despite much speculation (see, for example, Ostenso 1973; Tailleur 1973). The Eurasian Basin is the product of Eocene to present day ocean-crustal generation from the Nansen Ridge which is the extension of the mid-Atlantic ridge into the Arctic (Vogt & Ostenso 1970). Crustal generation from the mid-Atlantic ridge has progressively separated Greenland and North America from Europe since the Palaeocene (§3(*b*)(i), p. 241).

Reconstructions of the evolution of the Arctic from the early Mesozoic to the present which assume a globe of constant modern dimensions (see, for example, Dietz & Holden 1970; Robinson 1971, Figures 5, 6; Smith *et al.* 1973), show major inconsistencies when the ocean floor spreading history and the circum-Arctic Ocean tectonic styles are compared with them. If Greenland and North America are rotated towards the combined European and Asian continent across the surface of a globe representing the Earth's modern dimensions, all to meet at the 1000 m isobath, there is no other geometric choice but to produce an Arctic Ocean of much greater surface area than that seen today (e.g. figure 1). This greatly extended 'Palaearctic Ocean', would have been present in the Lower to Middle Jurassic before the start of clockwise rotation of North America in response to the initial development of the southern North Atlantic (§3(*b*)(i), p. 240). The fit of the continents together, however, is not perfect. Wedge-shaped voids are demanded by the reconstruction (e.g. figure 1) and these open out northward between Baffin Island and West Greenland, and between Greenland and Ellesmere Island. This geometrically necessary oceanic crust, like that of the 'Palaearctic Ocean', would have been generated before spreading began in the southern North Atlantic in the early Upper Jurassic. All of this postulated oceanic crust, save a doubtful relic in the Canada Basin, would have to be entirely subducted during the Mesozoic, for it is absent today. The Mesozoic stratigraphic evidence and the tectonic style of the whole Arctic Region (see, for example, Atlasov *et al.* 1969; King *et al.* 1969; Plauchut 1973) positively excludes the presence of the necessary Mesozoic or Cenozoic subduction zones, which would be associated with fringing mountain chains, at the Arctic Ocean continental margins and the regions of Canada and Greenland flanking the Labrador Sea–Baffin Bay spreading region.

The field evidence indicates an expansion of area of the Arctic Ocean, essentially during the last 80 Ma, and in two separately generated basins. The geometric reconstructions of the stages of development since the early Mesozoic, assuming an Earth of constant modern dimensions, require contraction of area of the Arctic Ocean which is irreconcilable with the field evidence. From the gross structural and geometric point of view, the development of the present day boreal region depends on the clockwise rotation of North America, initially with Greenland, then away from Greenland, and then subsequently both continents together away from Eurasia, in response to the development of the North Atlantic (§3(*b*)(i), p. 241).

If Pangaea is reconstructed on a globe 80% of modern diameter, an excellent fit of the continents together is obtained in the boreal region (figure 6*a*), one which accords with the subsequent trend of block movements and the ocean floor spreading history. The anomalous wedge-shaped voids in the Labrador Sea and Baffin Bay region and between Greenland and Ellesmere Island simply do not occur as a consequence of the increase in surface curvature. The 'Palaearctic Ocean' is likewise eliminated, aided by the refit of the Verkhoyansk–Anadyr block of northeast Asia (Owen 1973) shown in figure 6*a*. The subsequent evolution of the boreal region assuming a steady increase in global diameter, stages of which are shown in figures 6*b–f*, complies with the known tectonic and spreading data from the entire region. Subduction zones are present around the present North Pacific margin, and therefore, it is not possible to obtain a complete picture of the development of the ocean floor there except that it has been overridden during the Cenozoic. Fortunately, all relative movements of North America can be accurately related in the diagrams to the spreading history of the North Atlantic in which marginal subduction zones are absent.

The initial development of the southern region of the North Atlantic from the early Upper Jurassic onward, produced a clockwise rotation and westward displacement of North America relative to Africa and Europe (§3(*b*)(i), p. 240). In the Arctic, the Alaskan region and Verkhoyansk–Anadyr block (which is similar in area to the Yano–Chukotsk geoblock of Krasny 1973, or the Verkhoyansk–Chukotsk region of Belyi 1973) acted as pivots for this movement, producing orogenic deformation in the late Jurassic and Lower Cretaceous. Extensive block, rift and tear faulting occurred in the Canadian Arctic region and in East Greenland (Vischer 1943; Haller 1969) (figures 6*a–c*). It is probable that the Canada Basin started to develop during this period by oceanic spreading thus initiating the Arctic Ocean.

The onset of late Cretaceous (82 Ma B.P. Coniacian) to mid-Eocene ocean floor spreading in the Labrador Sea to Baffin Bay area occurred in response to the continuing clockwise rotation of North America. The generation of oceanic crust from the Alpha Ridge to form the Amerasian Basin also reflects this movement, and in turn appears to have caused the Alaska region and Verkhoyansk–Anadyr block to move relatively southwestward along major wrench faults (figures 6*c*, *d*). The effect of this displacement is particularly apparent in the fracture and major dislocation of the Okhotsk–Chukotsk volcanic belt (Krasny 1973, p. 190, Figure 1; Belyi 1973) which forms the Aptian to Turonian counterpart of the adjacent present day Pacific marginal volcanic belt (figures 6*d–f*).

By the mid-Eocene (*ca.* 40 Ma ago), the development of the Amerasian Basin by ocean floor spreading had ceased (figure 6*e*). The associated fragmentation of the Canadian Arctic Islands region, and the formation of oceanic crust in the Labrador Sea–Baffin Bay region and Lancaster Sound (Keen, Johnson & Park 1972) would also have been completed. Ocean floor spreading in the developing northern North Atlantic and in the Arctic Eurasian basin now displaced the continental region of North America together with the Amerasian basin towards the North Pacific, overriding its northern margin (§3(*e*), p. 270). The Verkhoyansk–Anadyr block continued to be displaced and rotated anticlockwise by the general development of the Eurasian basin (figures 6*e*–*f*).

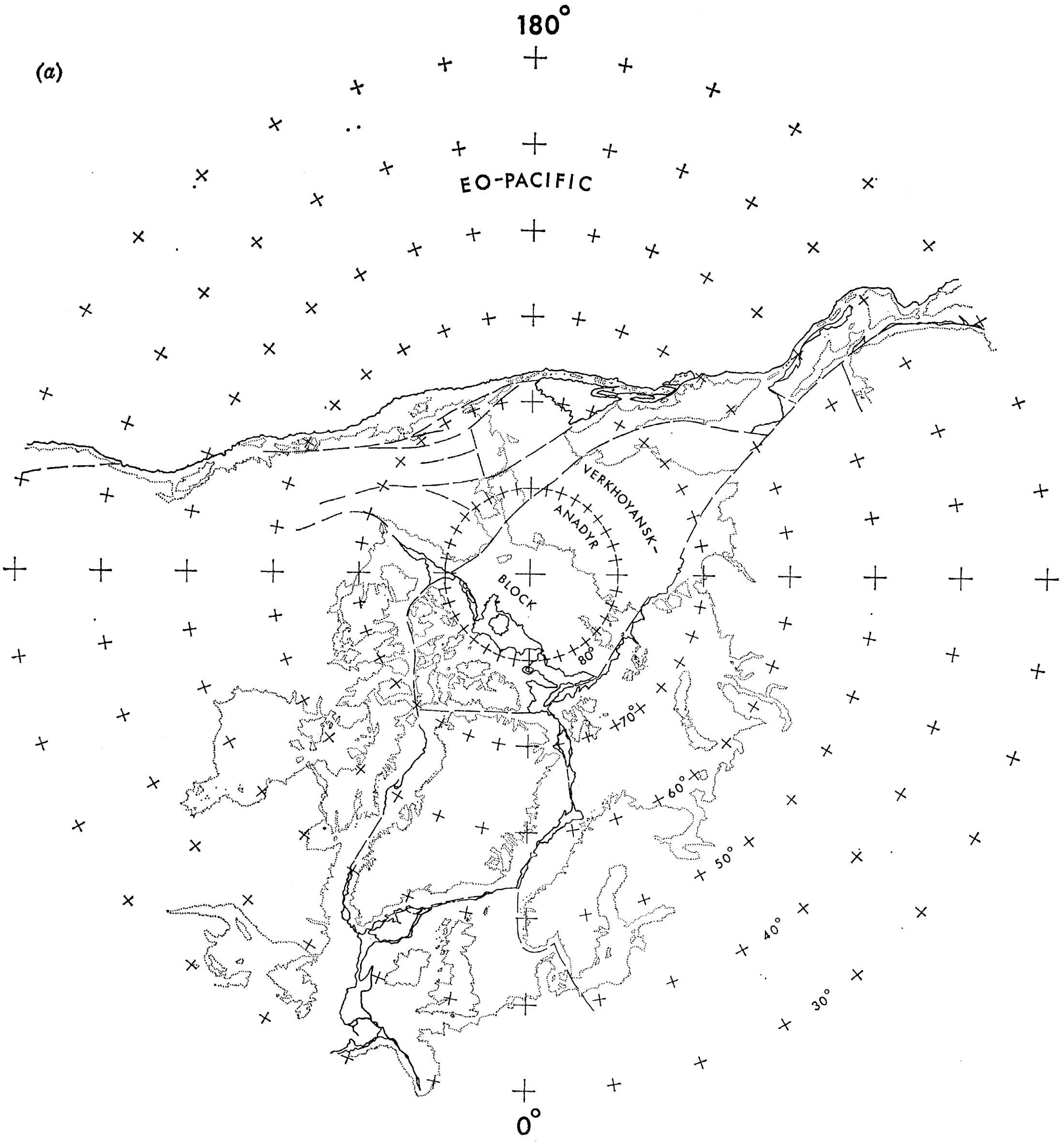


FIGURE 6. Six stages in the development of the Boreal Region during the Mesozoic and Cenozoic, projected from an expanding globe. Zenithal equidistant projection. Epicontinental seas and land areas present at each period of time are omitted except in figure 6*f*. For description see figures 2–4.

FIGURE 6*a*. Boreal region at the Pangaea stage of continental displacement 180 Ma B.P. Projection centred on the North geographic pole constructed for that time. Diameter of the Earth is 80% of modern mean value.

The reconstruction for the Oligocene (figure 6*e*) follows closely the earlier Eocene configuration suggested by Lowell (1972, p. 3092, Figure 1). The clockwise rotation of Greenland against Svalbard shown in the reconstructions would produce the Tertiary orogenic movements described by Harland (1969*a*, *b*, 1971). Continued widening of the North Atlantic and the Eurasian Basin of the Arctic would lead to the modern configuration of the boreal region (figure 6*f*).

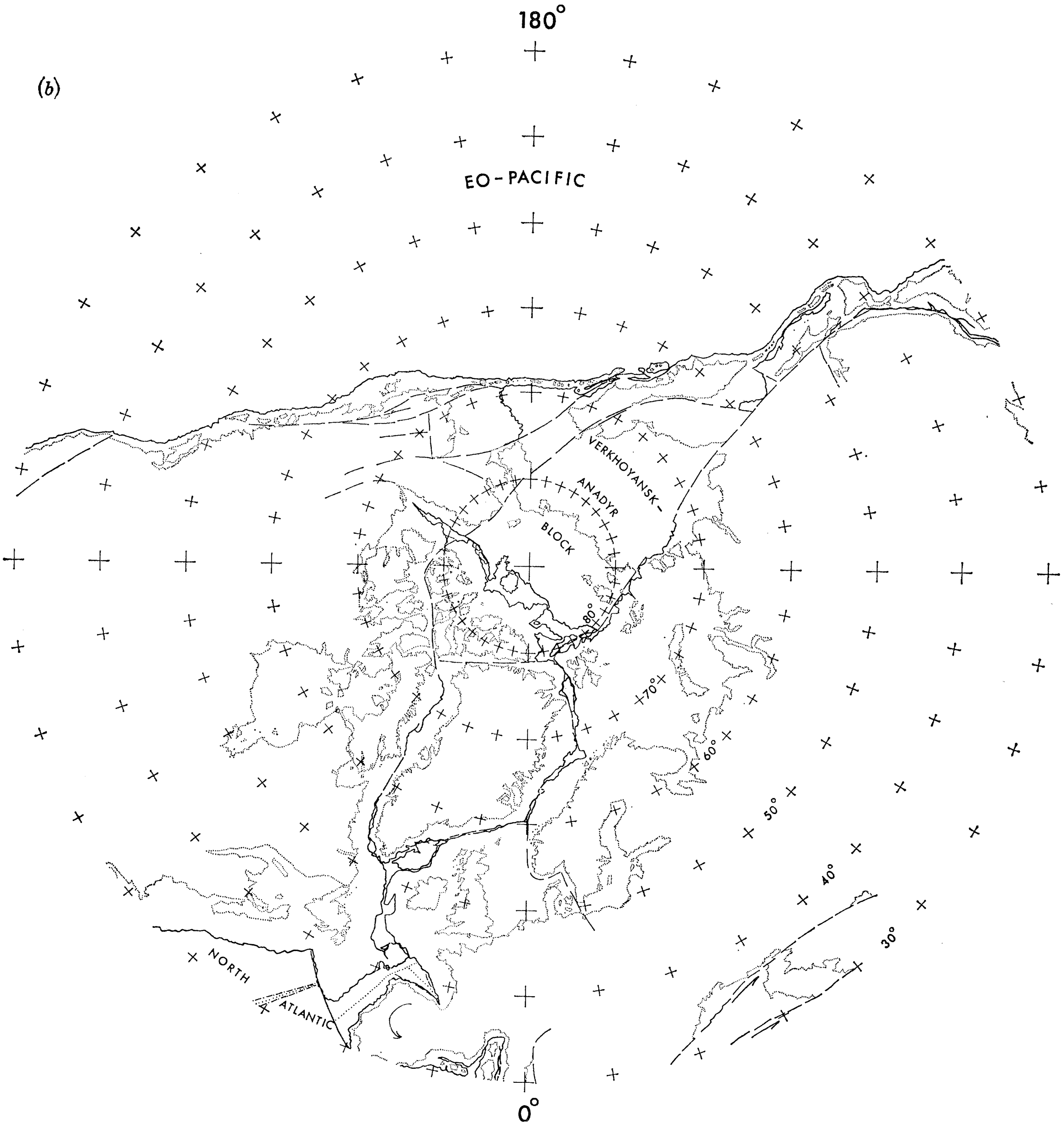


Figure 6*b*. Boreal region in the early Cretaceous (Hauterivian) 120 Ma B.P. Projection centred on the North geographic pole constructed for that time. Diameter of the Earth is approximately 87% of current mean value.

(*b*) *Atlantic Ocean*

The closely matching outlines of the continental margins of the various land masses bordering the modern Atlantic Ocean provided the germ for the continental drift theory. No major subduction zones are present to distort the outlines of continental margins, or destroy the earliest Mesozoic spreading history. Thus, the geometry of refit at the 1000 m isobath is com-

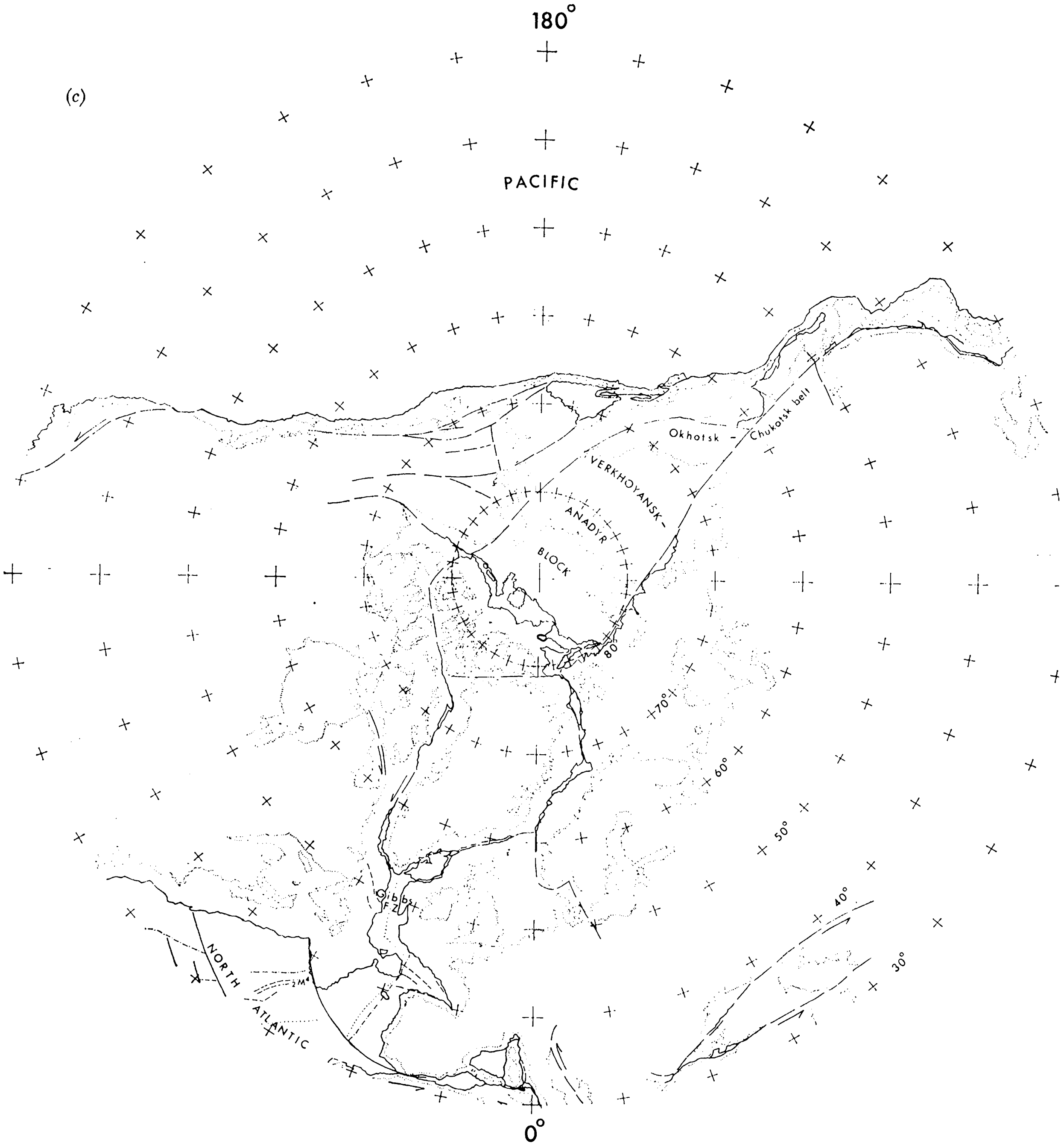


FIGURE 6*c*. Boreal region in the Upper Cretaceous (Turonian) 90 Ma B.P. Projection centred on the North geographic pole constructed for that time. Diameter of the Earth is 90% of current mean value.

paratively simple to determine even without oceanic spreading data. Two small subduction zones, the Greater Antilles line and South Sandwich Trench, provide minor but important information on the displacement history. Figure 1 herein, which assumes a globe of modern dimensions, shows that the fit of the continents together, although excellent at the contact between northwest Africa and the North American east coast embayment, progressively

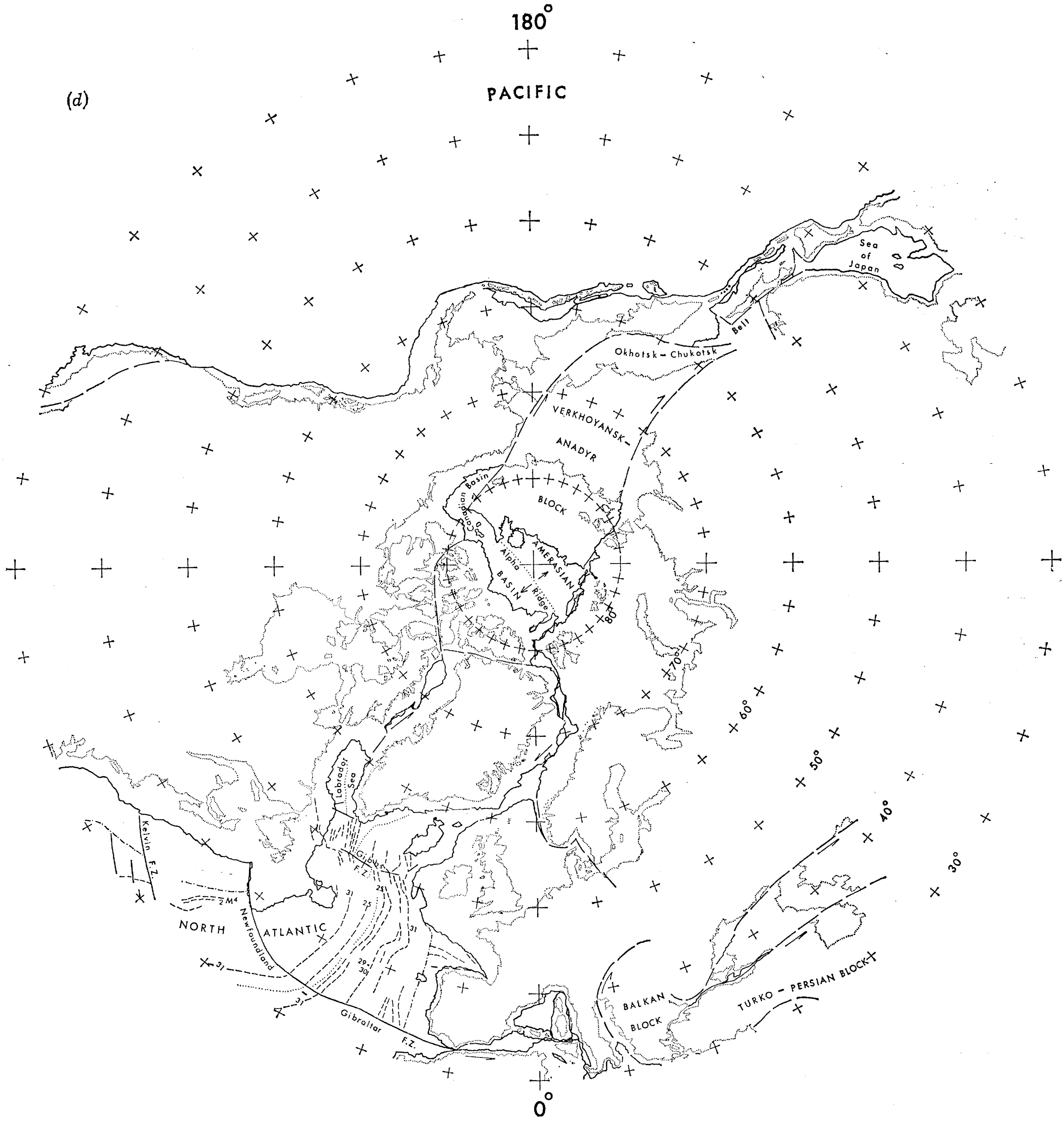


FIGURE 6*d*. Boreal region in the early Tertiary (Palaeocene) 60 Ma B.P. (anomaly 24). Projection centred on the North geographic pole constructed for that time. Diameter of the Earth is approximately 93% of current mean value.

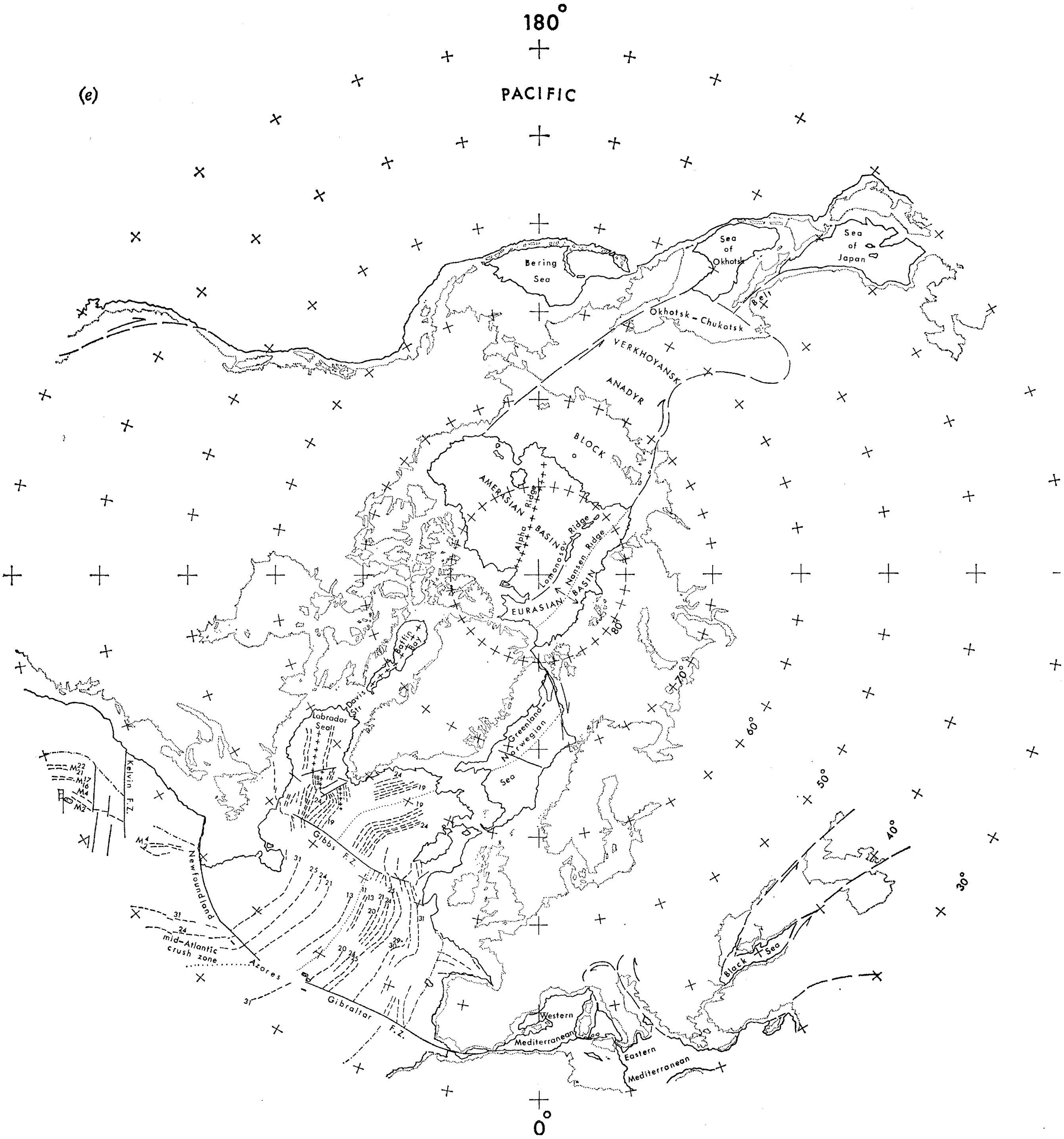


Figure 6*e*. Boreal region in the middle Tertiary (Oligocene) 30 Ma B.P. (anomaly 9). Projection centred on the North geographic pole constructed for that time. Diameter of the Earth is approximately 97% of current mean value.

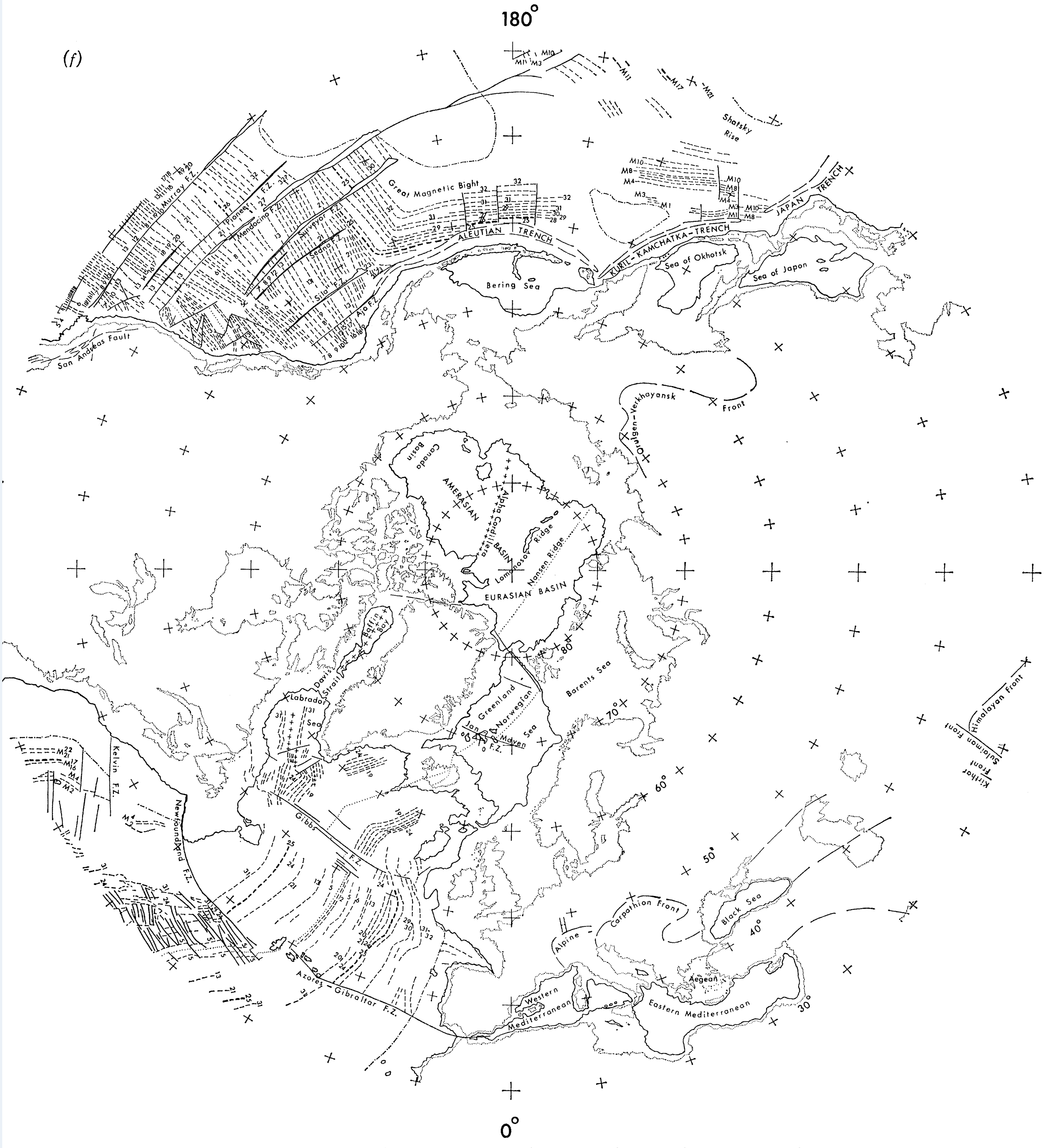


FIGURE 6*f*. Geographic and ocean floor spreading map of the modern Boreal region.

deteriorates towards the geographic poles. If the Earth's diameter is reduced by 20% of its modern value, the increased surface curvature produces an excellent fit (e.g. figure 11).

Ocean floor spreading data from the southern North Atlantic show that Pangaea in the strict sense started to fragment in the Middle to early Upper Jurassic. South America and Africa, however, did not start to separate with the formation of the South Atlantic until the Lower Cretaceous, and it was not until the late Cretaceous that the spreading histories of the North and South Atlantic became more uniform. The differential movements of North America, South America and Africa during the Mesozoic and Cenozoic caused the development of the Gulf of Mexico and Caribbean regions.

(i) *North Atlantic* (*figures* 2, 6, 7, 8, 11, 13, 15, 17)

The bulk of the ocean floor spreading data derived from the Atlantic is shown in figure 2, together with the JOIDES Deep Sea Drilling Project sites of Legs 1, 2, 4, 11, 12 and 14 (Ewing, Worzel *et al.* 1969; Peterson, Edgar *et al.* 1970; Bader, Gerard *et al.* 1970; Hollister, Ewing *et al.* 1972; Laughton, Berggren *et al.* 1972; and Hayes, Pimm *et al.* 1972). The computer fit of the continents now bordering the North Atlantic suggested by Bullard, Everett & Smith (1965) has been modified by Le Pichon & Fox (1971). The latter authors use the major marginal fracture zones in the older southern region of the North Atlantic to determine the pre-displacement fit, and their results are supported by the spreading data. Their fit is used in the maps given here. Further north, Palaeozoic tectonic trend lines have been employed as matches between Europe and North America and these provide additional parameters to check the geometric fit, and the fit indicated by the spreading data.

The oldest regions of the Atlantic Ocean crust lie off the East Coast of the United States between the Bahamas and Newfoundland fracture zones, and off the corresponding coast of West Africa between the Guinea and Azores–Gibraltar fracture zones (figure 2). Vogt, Anderson & Bracey (1971), Vogt & Johnson (1971), Larson & Pitman (1972) and Lattimore, Rona & De Wald (1974) show the known distribution of Upper Jurassic and Lower Cretaceous magnetic reversal anomaly lineations in the region off the United States East Coast. Similar, but less complete information is available from the corresponding oceanic region off the north-west African margin (Rona, Brakl & Heirtzler 1970; Klerkx & Paepe 1971; Robb 1971; Lattimore *et al.* 1974). This information, supplemented by Deep Sea Drilling Project borings, indicates that the southern North Atlantic started to develop by ocean floor spreading at the end of the Middle Jurassic following rift faulting that began in the Trias or even earlier (see Ballard & Uchupi 1972, for the Gulf of Maine). The earliest oceanic sediments known are of Callovian age.

During the Upper Jurassic, the combined South American and African continent, and the North American continent, had rotated sufficiently away from each other in response to the continued ocean floor spreading in the early Atlantic, to permit a narrow crustal wedge to open northward. This wedge extended from the Newfoundland–Gibraltar fracture zone to the area near the Porcupine Bank adjacent to the continental margin of Ireland (figures 6*b*, 8*b*). The Iberian Peninsula began to rotate anticlockwise perhaps as early as the Jurassic–Cretaceous boundary (136 Ma B.P.) in response to the eastward drag of Africa relative to the southern margin of Europe (§3(*c*), p. 251). Major rift faulting occurred along the western margin of Europe and in the North Sea in response to the tension produced by these continental movements (see, for example, Wood & Woodland 1969; Blundell, Davey & Graves 1971) and the corresponding margin of North America (see, for example, Auzende, Olivet & Bonnin 1970; Kraft, Sheridan & Maisano 1971; McIver 1972; A. C. Grant 1972). This tensional faulting between North America–Greenland and Europe is evident as far north as East Greenland (Vischer 1943; Haller 1969) and perhaps even further north, about the time of the Jurassic–Cretaceous boundary. Rift valley formation at the common margin of South America and Africa occurred also at the same time (§3(*b*) (iii), p. 247).

Spreading of the North Atlantic continued in the same manner during the Lower and early Upper Cretaceous. The wedge of oceanic crust mentioned above extended northward to about the latitude of the Gibbs fracture zone (figure 6*c*). During the early Upper Albian, there occurred a short period of major block faulting widespread throughout the western hemisphere at least. This could be correlated with the start of complete ocean floor spreading between South America and Africa in particular.

The evolution of the North Atlantic north of the Gibbs fracture zone up to Iceland, and including the Labrador Sea, has been described principally by Le Pichon, Hyndman & Pautot (1971), Hyndman (1973), Laughton (1971), and Vogt & Avery (1974). Figure 1 shows that the fit of North America, Greenland and Europe on a globe of modern dimensions becomes more imperfect northwards towards the Arctic, and the narrow spherical triangular voids would presumably consist of ancient simatic crust. This crust would have to be subducted during the Mesozoic or Cenozoic because it is absent today. The necessary subduction zones do not exist, however, and the ocean floor spreading pattern actually present demands the reconstructions given in figures 6*c*–*f*.

This spreading pattern indicates that as North America continued to rotate clockwise in response to the widening of the North Atlantic further south, a split developed between Greenland and Canada extending northward into the Arctic (figures 6*c*–*e*). The Labrador Sea and Baffin Bay began to develop by spreading from the resulting axis about 82 Ma B.P. (Upper Cretaceous, Coniacian) and spreading continued to about 47 Ma B.P. (Eocene) (Laughton 1971; Keen, Johnson & Park 1972; Keen, Barrett, Manchester & Ross 1972). Further north along this axis in the Arctic, spreading continued to about 40 Ma B.P. (Eocene) (§3(*a*), p. 233). The rotation of North America also caused a spreading axis to develop about 60 Ma ago (Palaeocene) along the much earlier rift valley system at the common margin of Greenland and Europe. Spreading from this axis has produced the Denmark Strait and Iceland, and the Norwegian and Greenland Seas. By the Eocene, this axis had extended northward into the Arctic (the Nansen Ridge) and began the generation of the Eurasian basin (see, for example, Vogt & Ostenso 1970; Johnson, Vogt & Avery 1971; Laughton 1971; Pitman & Talwani 1972; Johnson & Vogt 1973).

The clockwise rotation of North America during the Cenozoic before anomaly 5 (Miocene) has produced the marked crush zone west of the mid-Atlantic ridge, and south of the Newfoundland–Azores–Gibraltar fracture zone shown in figures 6*e*, *f* and 7*e*.

The North Atlantic oceanic crust, therefore, approximates in shape to a spherical triangle, its base marked by the Bahamas–St Pauls fracture zone. The apex of the triangle moved progressively northward as the ocean widened, aided by the decrease in surface curvature as the Earth expanded (figures 11, 13, 15, 17). First Africa split from North America in the Jurassic and early Cretaceous, then North America split from Greenland in the Upper Cretaceous and early Tertiary. Finally, Greenland split away from Europe in the early Tertiary as the apex of the triangle penetrated into the Arctic.

(ii) *Caribbean* (*figures* 2, 7 *a–e*)

Assuming a modern diameter globe, various attempts have been made to reassemble the individual cratons of the Central American region into a pangaean configuration, and then to follow their subsequent dispersal to current positions (see, for example, Carey 1958; Dietz & Holden 1970; Freeland & Dietz 1971; Smith *et al.* 1973). The original surface area available for these refits depends geometrically on how South America is fitted against Africa.

There are essentially two ways of fitting these continents together which considerably affect this original area. The first of these is to fit the corresponding continental margins of North Brazil and Guinea according to the geological matches (see, for example, Choubert 1969; Burke, Dessauvageie & Whiteman 1971; Choudhuri & Milner 1971; Asmus & Ponte 1973). This gives the smallest area for the reconstruction of middle America, and was advocated by Bullard *et al.* (1965, Figure 8). Either this fit, or the modification of it proposed by Le Pichon & Fox (1971, p. 6299, Figure 3), is used in most attempts at reconstructing the subsequent development of this region. However, it produces a narrow triangular void widening southward between the eastern continental margin of South America and the western margin of Africa south of the Niger Delta region, although the pre-Triassic geological matches indicate direct connection (see, for example, Maack 1969; Asmus & Ponte 1973).

The second method is to fit the eastern margin of South America against the western margin of Africa south of the Niger Delta (see, for example, Vogt *et al.* 1971, p. 4819, Figure 15). This produces a narrow triangular void between the Guinea and North Brazilian margins which widens westward producing a significantly greater area for the refit of Florida and Central America. However, such an arrangement produces major dislocations between the transform and wrench-fault traces off the North American east coast and northwest African margins matched by Le Pichon & Fox (1971), and the subsequent ocean floor spreading patterns.

This looseness of fit can be controlled geometrically by altering the amount of the Earth's surface curvature. If accurately made cut-outs of South America and Africa are fitted against each other on a flat surface, the V-shaped gaps subtended from the Niger Delta region become well marked at this minimum value of curvature. These gaps become progressively narrower as surface curvature is increased and disappear altogether when the diameter of the globe is reduced to 80% of current value.

The inconsistencies between the geometric requirements of the constant dimension reconstructions and the ocean floor spreading and continental geological data can now be examined. Ball & Harrison (1969) and Le Pichon & Fox (1971, p. 6301) show that the ocean floor spreading data places severe constraints on the original size and early continental displacement geometry of the middle American region (see also Uchupi *et al.* 1971 and figures 7*b*, *c* herein). Until the Albian, South America was displaced eastward relative to North America while it was still attached to Africa (figures 7*b* and *c*, 8*b*). Although the axis from which the South Atlantic has been generated caused the clockwise rotation of South America away from Africa from the Valanginian onward, spreading did not extend northward to the Niger Delta region until the Albian, and complete separation did not occur at the common north Brazilian–Guinea margin until the Turonian (§3(*b*)(iii), p. 249). South America was thus held at the north Brazilian margin by Africa until the Turonian.

Despite the clockwise rotation of South America, it is still necessary on constant dimensions reconstructions (such as Le Pichon & Fox 1971, p. 6305, Figure 6*c*) to elongate south eastward the Gulf of Mexico–Caribbean region to an extent that, from the Turonian onward, major northward oceanic and continental excursion is required for the region to reach its modern size and configuration. The ocean floor spreading data from the Atlantic east of the Lesser Antilles island arc (Peter, Lattimore, De Wald & Merrill 1973) indicate that this northward migration would have to occur between the Turonian and the Campanian (Upper Cretaceous, anomaly 30; table 1), but there is no evidence of the necessary subduction. Moreover, it was partly during this period that the southern Caribbean, flanked by the growing Lesser Antilles arc, developed by northwest to southeast extension. Again, as in the Arctic, the constant-dimensions hypothesis demands contraction of oceanic area by subduction while the spreading data indicate an increase of area and no subduction.

The history of deformation and cratonic movement proposed for the Central American region by some authors also produces inconsistencies when a constant dimension globe is assumed. The reconstructions of the pangaean Central American region and its subsequent displacement to a modern configuration given by Freeland & Dietz (1971) and Smith *et al.* (1973), require that the Yucatan and Honduras–Nicaragua cratons rotate *clockwise* against the eastward and southeastward movement of South America relative to North America. The Mesozoic and Cenozoic tectonic structures do not appear to support the hypothesis (e.g. Mattson 1972). Indeed, a fairly accurate cartographic reconstruction shows that these cratons will not fit into the available space formed by the Gulf of Mexico. Smith *et al.* (1973, Figures 6, 7, 14*b* and 15*b*) and Malfait & Dinkelman (1972), for example, indicate the necessity in the Mesozoic to dislocate completely the Central American region from South America. This has to be done in such a manner that the subsequent northward movement of South America and the Caribbean towards North America would produce tectonic styles entirely different from those actually present today.

The reconstructions given here in figures 7*a–e* accord with the relative directional movements of the North American, South American and African continents to each other, indicated by Ball & Harrison (1969) and Le Pichon & Fox (1971), which caused the development of the Gulf of Mexico and the Caribbean. The addition of an expansion factor for the Earth since the late Triassic–Lower Jurassic in figures 7, however, yields a much better kinematic sequence of development for the region. Excessive oceanic crustal subduction at the Greater Antilles line during the Cretaceous and Cenozoic, and crustal consumption in the Atlantic east of the Lesser Antilles arc, are not required. The Central American sialic link between North and South America is not broken in these reconstructions. Thus, the major tectonic problems which have to be overcome if this link was forged only in the late Cretaceous and Cenozoic, do not arise.

Wilhelm & Ewing (1972) suggest that the simatic crust of the Gulf of Mexico could be of late Palaeozoic age and have originated with the Carboniferous Ouachita orogeny. A small area o oceanic crust has to be constructed here (figure 7*a*) even when the Earth's mean diameter is reduced by 20%, but this need only have been present in the late Triassic–Lower Jurassic. What circumstantial evidence exists from the circum-Gulf region suggests that it was partially in being as an oceanic spreading area before the Middle to Upper Jurassic evaporite sequences were accumulated. Kirkland & Gerhard (1971) describe a Middle or Upper Jurassic palynomorph assemblage from the Calcite caprock of the Challenger Knoll. The underlying Sigsbee Salt, therefore, represents an earlier phase of evaporite accumulation.

Matches of late Palaeozoic structural trends and stratigraphic units suggest that the Nicaragua–Honduras craton was alongside the Mexican Pacific coast in the late Trias–Lower

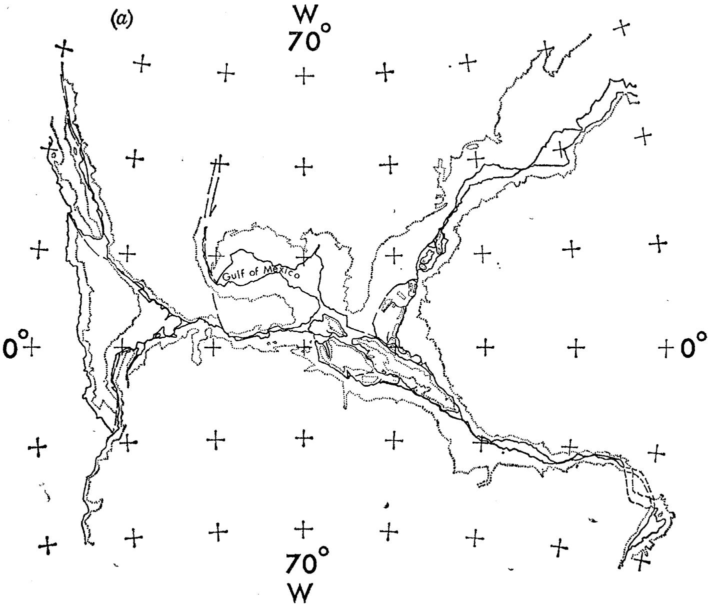


Figure 7. Five stages in the development of the Central American, Gulf of Mexico and Caribbean region during the Mesozoic and Cenozoic projected from an expanding globe. Zenithal equidistant projection. Epicontinental seas and land areas present at each period of time are omitted except in figure 7*e*. Description as in figures 2–4.

Figure 7*a*. American 'Mediterranean' in the Lower Jurassic before the start of ocean floor spreading in the southern North Atlantic; 180 Ma B.P. Projection pole is latitude 0°, longitude 70° W constructed for that time. Diameter of the Earth is 80 % of current mean value.

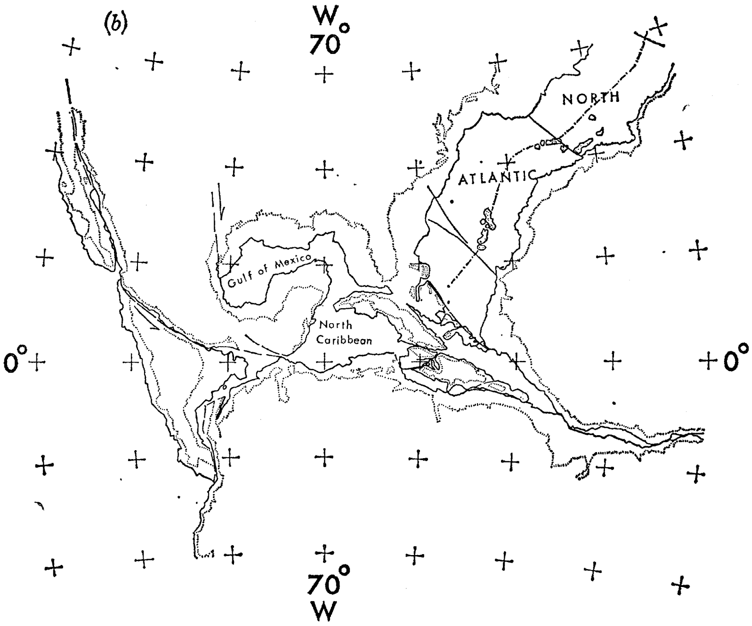


Figure 7*b*. American 'Mediterranean' at the Upper Jurassic (Oxfordian) 'Quiet Zone' boundary, 150 Ma B.P. Projection pole is latitude 0°, longitude 70° W constructed for that time. Diameter of the Earth is approximately 83 % of current mean value.

Jurassic (compare Goddard *et al.* 1965; King *et al.* 1969). The subsequent kinematic sequence in figures 7*b*–*e* is similar to that of Pinet (1972). Southeastward extension of the North American Western Cordilleran region from the early Upper Jurassic, in response to the inception of the North Atlantic, would produce wrench fault movements between the Yucatan and Nicaragua–Honduras cratons as South America, still fully attached to Africa moved differentially to North America (figure 7*b*).

The enlarging oceanic crust of the Gulf of Mexico was separated from the early Northern Caribbean by the Yucatan and Cuba cratons which would act as a partial barrier, allowing the accumulation of evaporites in the Gulf of Mexico (Ewing, Worzel *et al.* 1969; Worzel, Bryant *et al.* 1973). The relative eastward movement of the Nicaragua–Honduras craton would produce the late Jurassic folding and tectogenesis indicated by Arden (1969) in the northern Caribbean region (see also Pinet 1972; Mattson 1974*a*, *b*). Continued southeastward extension of the Central American and Caribbean region, and to a limited extent the Gulf of Mexico during the early Cretaceous is indicated in figure 7*c*.

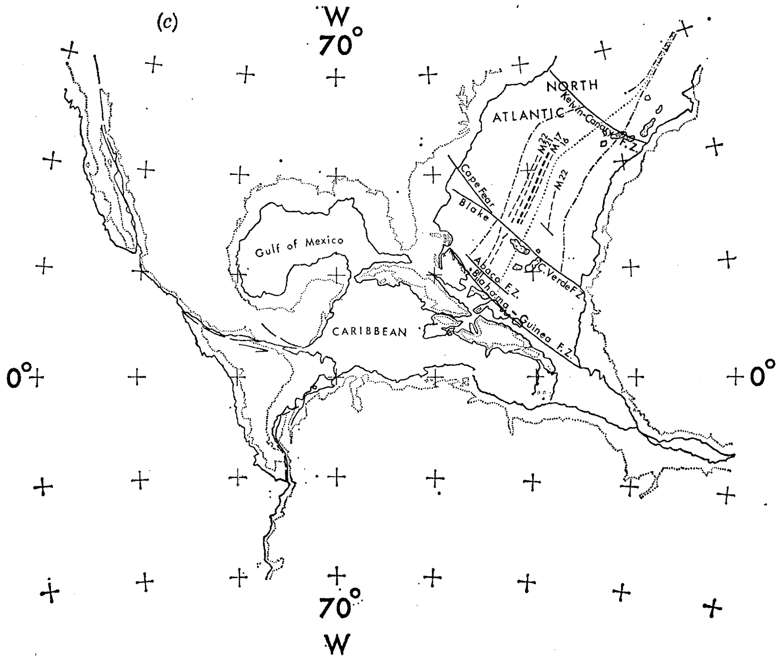


FIGURE 7*c*. American 'Mediterranean' in the Early Cretaceous (Hauterivian) 120 Ma B.P. Projection pole is latitude 0°, longitude 70° W constructed for that time. Diameter of the Earth is approximately 87% of current mean value.

Throughout the remainder of the Lower Cretaceous, and to a lesser extent in the early Upper Cretaceous, South America rotated markedly clockwise away from Africa in response to spreading in the South Atlantic, the confines of the Guinea margin being cleared by the Turonian. Maximum extension of Central America would have occurred, therefore, in the period immediately before this complete separation of South America from Africa. Clockwise rotation of South America has continued from the Turonian onward in response to the greater rate of oceanic crustal spreading apparent in the Southern Hemisphere during the Cenozoic (§3(*e*), p. 271). This rotation of South America has had a marked effect on the Central American, Gulf of Mexico and Caribbean regions. The relative movement of the northwestern region

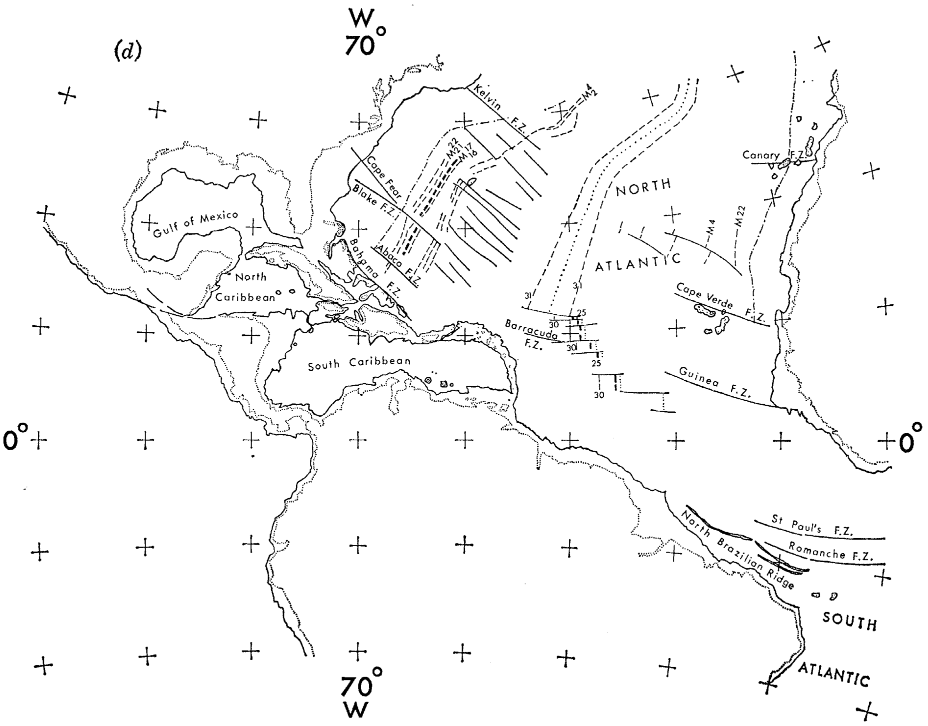


FIGURE 7*d*. American 'Mediterranean' in the early Tertiary (Palaeocene) 60 Ma B.P. (anomaly 24). Projection pole is latitude 0°, longitude 70° W constructed for that time. Diameter of the Earth is approximately 93% of current mean value.

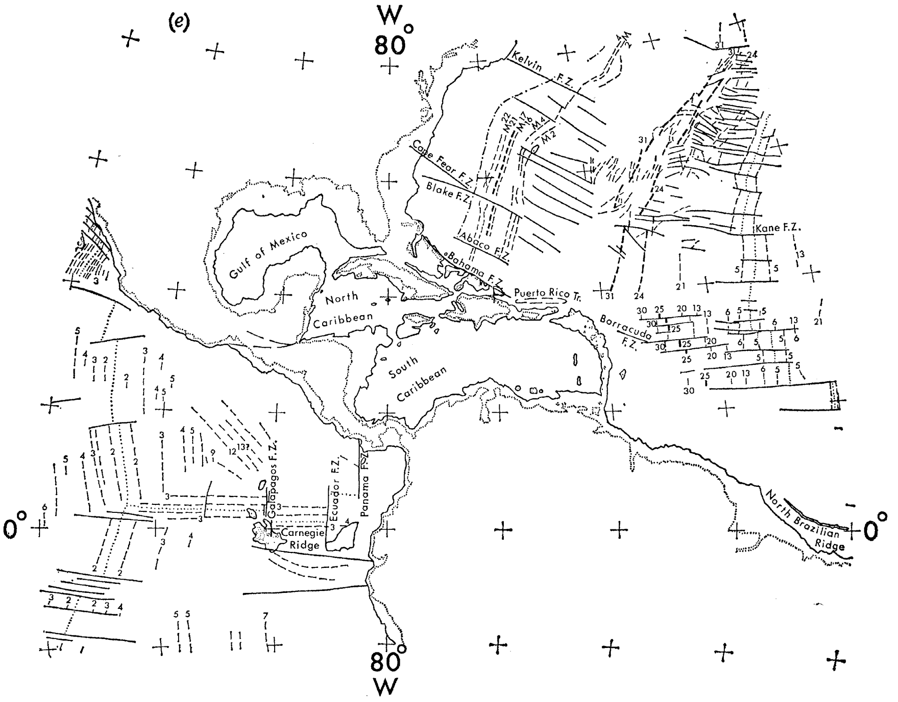


FIGURE 7*e*. Geographic and ocean floor spreading map of the modern American 'Mediterranean'. Projection pole is latitude 0°, longitude 80° W.

of South America changed in the Upper Cretaceous to become northwestward relative to the East Pacific ocean crust and the Pacific side of Central America, but effectively northeastward relative to the Caribbean. Huffman (1972) indicates a differential lateral movement of the Santa Lucia craton of some 150 miles on the Pacific side of the San Andreas fault since the Miocene, and that this movement trend has continued since within the Upper Cretaceous.

By the Palaeocene (figure 7*d*), the formerly oceanic crust of the Panama Isthmus would start to buckle, and south to north compression of the Colombian Basin would occur (see, for example, Arden 1969; Krause 1971). These compressional movements are complemented by tensional structures along the southern margin of the Venezuelan Basin of the Southern Caribbean (Ball *et al.* 1971) as a consequence of the clockwise rotation of South America. The effect of this rotation on the tectonic evolution of the Greater Antilles arc has been demonstrated by Malfait & Dinkelman (1972) and Mattson (1974*a*, *b*). The northward differential movements of the Nicaragua–Honduras craton against Yucatan would produce the marked halikinesis in the Gulf of Mexico evaporite sequences.

From the above, it is apparent that the middle American region has developed within very close geometric limits throughout its history. The various constraints are satisfied only if the reconstructions are made on a globe expanding from 80 % of its present diameter in the late Trias–Lower Jurassic to its present size.

(iii) *South Atlantic* (*figures* 2, 7, 8, 10, 11, 13, 15, 17)

The geological matches between the undeformed West African and eastern South American margins before their Lower Cretaceous separation are particularly clear. They have been described for example by Du Toit (1937), Maack (1969), Choubert (1969), Burke *et al.* (1971), Choudhuri & Milner (1971), Le Pichon & Hayes (1971), and Asmus & Ponte among others *in* Nairn & Stehli (1973). The ocean floor spreading data is shown in figure 2 together with the borehole sites of Deep Sea Drilling Project Leg 3 (Maxwell, Von Heerzen *et al.* 1970). Larson & Ladd (1973) have discussed the age of the earliest magnetic anomalies (Lower Cretaceous) in the Cape Basin off South Africa and in the corresponding Argentine Basin. However, little is known of the detailed pre-Coniacian spreading history of the South Atlantic.

The magnetic anomaly pattern in the Cape Basin off South Africa, reinterpreted by Larson & Ladd (1973), indicates that ocean floor spreading commenced to form the South Atlantic in the Valanginian following rift faulting at the Jurassic–Cretaceous boundary in this general region (see, for example, Dingle & Klinger 1971; Dingle 1972; Leyden, Ewing & Simpson 1971). Upper Jurassic sediments are preserved in the resulting grabens. This period of faulting produced a major rift valley system which extended northward along the then common margin of South America and Africa up to the Guinea coast (e.g. Furon 1960; Maack 1969; Machens 1970; Asmus & Ponte 1973). Thick accumulations of evaporites were formed in the resulting isolated basins and volcanic activity was evident, much like the late Tertiary to present day East African Rift Valley system and the Dead Sea graben.

However, as Jeffrey's (e.g. 1962) has pointed out, when the South American and African continental margins are placed together in reconstructions assuming an Earth of modern dimensions, a narrow spherical triangular void is produced widening southward (see figure 1). This void would have to consist of ancient pre-Lower Cretaceous oceanic crust. But, as in the northern North Atlantic, there is no evidence of marginal subduction zones at the South African or Argentine continental margins where this ancient crust could be subducted, for it is absent today. This wedge can be eliminated by rotating South America slightly anticlockwise. However, this would create a spherical triangular gap between the Guinea Coast and North Brazil destroying the geological continuity, and produce an unacceptably large area for the Caribbean in terms of its ocean floor spreading history (§3(*b*)(ii), p. 242).

The reconstructions shown in figures 7*a*–*e*, 8*a*–*e* and 10*a*–*e* given here, which assume an increase of the Earth's diameter of 20% of its modern mean value since the late Triassic–early Jurassic, permit the stratigraphic and tectonic matches at the continental margins of South America and Africa to fit correctly together without any anomalous gaps between them. At the same time, the increased surface curvature of the Earth at the time of Pangaea allows the fit of the tectonic and stratigraphic matches across the Guinea Coast–North Brazilian margin prior to the Upper Cretaceous. The subsequent development of the middle American region and adjacent Atlantic also will proceed in accordance with the field evidence (§3(*b*)(ii).

In order to obtain a picture of the development of the South Atlantic it is necessary to consider the position of Antarctica in Pangaea together with its subsequent movement. Its early Mesozoic position relative to the other fragments of Gondwanaland has been much debated. The reconstruction given here (figures 8*a*, 9*a*, 10*a*, 11 and 12) is based on: (i) the best geometric fit obtainable at the 1000 m isobath on a globe with a mean diameter 80% of its current value; (ii) the trend line patterns of the early Mesozoic Ellsworth Orogen of West Antarctica, the Cape Orogen of South Africa, and the Sierra Orogen of South America; (iii) the Tertiary to present day ocean floor spreading pattern between Antarctica and Australia; and (iv) the late Cretaceous and Tertiary ocean floor spreading pattern between West Antarctica and New Zealand. The reconstruction is similar to that of Craddock (in Craddock *et al.* 1969–70, sheets 21 and 23) and Smith & Hallam (1970), but differs from that of Elliott (1972) for example, who by rotating Antarctica anticlockwise brings Australia and India into direct contact, an arrangement which runs contrary to the ocean floor spreading information from the Wharton Basin (§3(*d*), p. 258).

Assuming an expanding Earth, the South Atlantic appears to have developed in the following manner which accords with the field evidence available at this time. At the end of the Middle Jurassic, Africa and South America together began to move eastward relative to Laurasia, as part of a unified Gondwanaland, in response to spreading in the early North Atlantic. By the Jurassic–Cretaceous boundary, increasing tension, perhaps due partly to the change in surface curvature, caused extensive faulting and rift valley formation, thus demarcating the various fragments of Gondwanaland. A wedge of ocean floor spreading had started to develop off the western Australian margin by this time (§3(*d*), p. 258) and as a result Antarctica would have started to move clockwise relative to South America and Africa.

By the Hauterivian (anomaly M7) this clockwise rotation of Antarctica would have caused West Antarctica, attached to South America at the Antarctic Peninsula region, to move differentially to East Antarctica along the Transantarctic Mountain front (compare Hayes & Ringis 1973). The movement of Antarctica shown in figures 10*a*–*c* would tend to straighten the southern extremity of South America, thus opening a wedge of ocean floor spreading between the Argentine and South Africa terminated northward by the older portion of the Walvis Ridge. The dating of the earliest part of the magnetic anomaly sequences in the Cape and Argentine Basins given by Larson & Ladd (1973) coincides with an Upper Valanginian marine transgression onto the continental margin of the southern portion of South Africa and southern Argentina (Reyment & Tait 1972, p. 87).

The distribution of magnetic 'quiet zones' in the South Atlantic plotted by Mascle & Phillips (1972, Figure 5), and shown in figure 2 herein, indicates a marked clockwise rotation of South America relative to Africa up to the Turonian. This rotation agrees with the reconstructions of Le Pichon & Hayes (1971), although not their chronology, and is reflected in the pattern of progressive marine transgression northward to the Gulf of Guinea, where in Nigeria the earliest open sea conditions occurred in the Upper Albian. However, until the Cenomanian at least, the Guinea coast was in direct contact with the northeast margin of Brazil at the line of a major tear fault. This view is supported by the structure and age of the North Brazilian Ridge described by Hayes & Ewing (1970) which they estimate to be about 100 million years old (Albian–Cenomanian boundary). N. K. Grant (1972) provides some evidence that the Cretaceous sediments of the Benue Trough in Nigeria are underlain by a Cretaceous simatic basement. This sequence and structure would result from the tensional splitting and associated vulcanism produced by the rotation of South America on the Gulf of Guinea region.

A better fit of the magnetic 'quiet zones' than that given by Mascle & Phillips (1972, Figure 6) is shown in the Turonian reconstruction given here (figure 10*c*). The differences are partly due to the correcting of the Mercator's cartographic projection necessary because of the rotation of South America and the corresponding oceanic region towards Africa. From the Cenomanian onward, the northeastern margin of Brazil moved away obliquely from the Guinea Coast margin in response to the continuing clockwise rotation of South America, the trace being marked by the St Pauls, Romanche and Chain fracture zones. It appears to have cleared the Guinea Coast by the late Turonian (figures 8*c*, 10*d*).

In the southern South Atlantic, the development of the Weddell Sea and the straightening of the Antarctic Peninsula shown in figures 10*c*, *d* would follow from the clockwise rotation of South America and Antarctica in response to spreading during the Cretaceous. Continued clockwise rotation of Antarctica as a whole relative to Africa and India would cause ocean floor spreading to start to form the Indian Ocean west of the older region of the Ninetyeast Ridge, and an early Upper Cretaceous change in spreading direction seen in the Wharton Basin (§3(*d*), p. 259). Thus, the rift valley system which formed at the common margin of southeast Africa and Queen Maud Land at the Jurassic–Cretaceous boundary, soon became a major wrench and transform fault zone. A narrow oceanic wedge probably existed between southeast Africa and Queen Maud Land in the Upper Cretaceous, but appears to have remained narrow until the latter part of the Cretaceous and early Tertiary.

The Scotia Ridge system and the South Sandwich Trench provide further evidence for the direction and nature of the movement of South America and Antarctica relative to Africa. The Ridge consists of a northern and a southern portion separated by the Scotia Sea which is a region of essentially Eocene to Recent ocean floor (Barker 1970, 1972*a*, *b*; Griffiths & Barker 1972). Subtraction of the area of the Scotia Sea and the sequence of magnetic anomaly lineations in the South Atlantic back to the Palaeocene (anomaly 24), produces the configuration shown in figure 10*d*. The position of the Sea is now marked by a transform fault which trends ENE. towards the Mozambique fracture zone. Figure 10*c* indicates that this fault existed from Turonian times at least and probably began to form in the early Lower Cretaceous. When figures 10*d* and *e* are compared it is apparent that the Tertiary to Recent spreading to form the Scotia Sea would interact with the continued spreading in the South Atlantic. This has produced the South Sandwich Trench subduction zone and the island arc directly west of it. The chronology of ocean floor spreading south of 55° S latitude is at present little known, but the geometric constraints imposed on the development of the South Atlantic by the spreading patterns in the Indian Ocean and southern Pacific are complied with in the reconstructions presented here.

From the late Cretaceous onward, the separate nature of the development of the North and South Atlantic seen hitherto tends to disappear. However, the Tertiary development of the Mediterranean region indicates that Africa has continued to move eastward relative to the southern margin of Eurasia until the Pliocene at least (figures 8*d*, *e*). The ocean floor spreading pattern and the results obtained from the Deep Sea Drilling Project, indicate that the South Atlantic, like the other oceanic regions of the Southern Hemisphere, has grown in area much faster than the North Atlantic. The significance of this major increase of oceanic crust in the Southern Hemisphere during the late Mesozoic and Cenozoic is discussed below (§3(*f*), p. 271).

(*c*) *Mediterranean* (*figures* 2, 8*a–e*)

Global expansion at the rate envisaged here explains better the development of the Mediterranean regions. Reconstructions of Pangaea made on a globe of modern dimensions (e.g. figure 1) show the Mediterranean region at the western apex of a triangular oceanic area, the Tethyan Ocean, which widens eastward towards the Pacific (see, for example, Carey 1955, 1958; Dietz & Holden 1970; Robinson 1971; Smith *et al.* 1973; Dewey, Pitman, Ryan & Bonnin 1973). There is indeed no other geometric choice but to produce such a spherical triangular divergence between eastern Europe and Asia on the one hand, and northeast Africa, Arabia, India and Australasia on the other.

The subsequent history of this region during the Mesozoic and Cenozoic would be, therefore, the progressive elimination of the 'Tethyan Ocean' by the subduction, or thrusting, of its pre-late Triassic simatic crust. In the Mediterranean region, some authors have suggested that this was achieved by the anticlockwise rotation of the joint African–Arabian continent associated with an eastward movement of it relative to the southern margin of Europe (Smith *et al.* 1973; Dewey *et al.* 1973). This differential movement would cause the rotation of the Iberian Peninsula, Corsica and Sardinia, and Italy to their present positions. However, although this explanation seems plausible for the western Mediterranean, it does not explain the geological history of the Balkans, eastern Mediterranean regions and further east, as Kent has pointed out (1969). Indeed, the evidence for a former large Tethyan Ocean between Gondwanaland and Laurasia is non-existent. The 'Ocean' is only a *geometric artefact* which has to be constructed when a globe of constant modern dimensions is postulated for the Mesozoic and Cenozoic.

Clues to the development of the Mediterranean region are provided by the rotational history of the Iberian Peninsula, the oceanic crust of the Western and Eastern Mediterranean basins and the now fragmented Alpide orogenic belt extending from northwest Africa to Iran and beyond. The essentially Mesozoic southeastward displacement and anticlockwise rotation of the Iberian Peninsula occurred in response to the eastward movement of Africa relative to Europe produced by the post-Middle Jurassic inception and development of the North Atlantic (see, for example, Choukroune, Le Pichon, Seguret & Sibuet 1973). Stauffer & Tarling (1971) indicate from palaeomagnetic data an anticlockwise rotation of Iberia from the Kimmeridgian Stage (Upper Jurassic) to the Palaeocene (early Tertiary) (see also Van der Voo & Zijderveld 1971). The magnetic anomaly lineations in the Bay of Biscay indicate pre-Santonian (Upper Cretaceous, anomaly 32) rotation, but have not provided a detailed chronology (Matthews & Williams 1968; Williams & McKenzie 1971; Williams 1971). The deep sea drillings into the bed of the central part of the Bay of Biscay penetrated to Palaeocene sediments but not to oceanic crust (e.g. Laughton & Berggren 1971). The orogenic history of the Pyrenees (see, for example, Choukroune *et al.* 1973; Mattauer & Henry 1974), the alpide belt in Morocco, Algeria and Tunisia (e.g. Choubert & Faure-Muret 1974; Caire 1974) and the Betic range (see, for example, Rondeel & Simon 1974), reflect the differential movements of Africa, Iberia and southern Europe.

These movements produced also the Alpine deformation of southern Europe and the development of the oceanic crust of the western and eastern Mediterranean basins seen today. However, very little is known of the detailed history of the development of the western Mediterranean basin before the Miocene; the Deep Sea Drilling Project and other borings give a very incomplete picture (Ryan, Hsü *et al.* 1973; Heezen, Gray, Segre & Zarudski 1971). What is known of the magnetic anomaly patterns of the western Mediterranean oceanic crust suggests that the spreading pattern is complex (Vogt, Higgs & Johnson 1971; Storetvedt 1973; Auzende, Olivet & Bonnin 1974). The palaeomagnetic vectors given by Van der Voo & Zijderveld (1971) support Mesozoic and Cenozoic anticlockwise rotations of Iberia, Sardinia, Corsica and the southern Alps of the order required in figures 8*a–e* here.

The development of the eastern Mediterranean basin is slightly better documented. Most workers agree that it is the product of an essentially Mesozoic phase of ocean floor spreading. The deep structure of the basin has been determined on seismic grounds (see, for example, Caputo, Panza & Postpischl 1970; Comninakis & Papazachos 1972; McKenzie 1970) and to this can be added the results of Leg 13 of the Deep Sea Drilling Project (Ryan, Hsü *et al.* 1973). Comninakis & Papazachos indicate that the eastern Mediterranean ridge is not now a spreading axis, but rather that the underthrusting of the 'African plate' beneath the Aegean arc detectable today begins at the ridge which might now be a submarine fold structure. These authors indicate in effect that the 'African plate' is still moving relatively eastward to Europe.

If one assumes that the Iberian Peninsula was dragged eastward and started to rotate in an anticlockwise direction from the end of the Jurassic, in response to the eastward movement of North Africa, it is possible to construct on a globe 80 % of the Earth's modern diameter expanding to its present size, a straightforward series of movements which ends with the configuration of the Modern Mediterranean (figures 8*a–e*). Moreover, the relation between the development of the Mediterranean region and that of the surrounding regions is wholly compatible in these reconstructions. The eastward displacement of the Morocco–Algeria–Tunisia–Sicily block rotated the Iberian Peninsula and pushed Italy and to a certain extent the Balkans eastward, rotating Italy anticlockwise and the Balkans clockwise. At the same time, the northeast margin of the African–Arabian continent pushed eastward and northeastward into the southern flank of Laurasia producing the Alpine chains and wrench fault systems in Turkey, the Caucasus and Iran. The reconstruction of Pangaea given in figure 8*a* on a globe of 80 % of modern diameter makes it unnecessary to postulate oceanic crust between Gondwanaland and Laurasia. This in no way precludes the existence of a Tethys epicontinental sea which was extensive at this time. The original positions of the Balearic Islands, Sardinia and Corsica are somewhat different in figure 8*a* from most previous arrangements, but agree with the computer fit of Westphal, Bardon, Bossert & Hamzeh (1973).

In the development of the Mediterranean region, therefore, the important feature was not the primarily north–south closure of the Tethyan Ocean accompanied by some eastward movement of the joint African–Arabian continent, as required by the constant dimensions hypothesis. Instead, the major factor was the differential movement of the joint African–Arabian continent eastward relative to Laurasia, gouging into and pushing eastward before it, along major wrench faults, fragments of the southern margin of Laurasia from the Iberian Peninsula and North Africa to the Tibetan plateau region. This was accompanied by an important but comparatively minor anticlockwise rotation of Africa and Arabia.

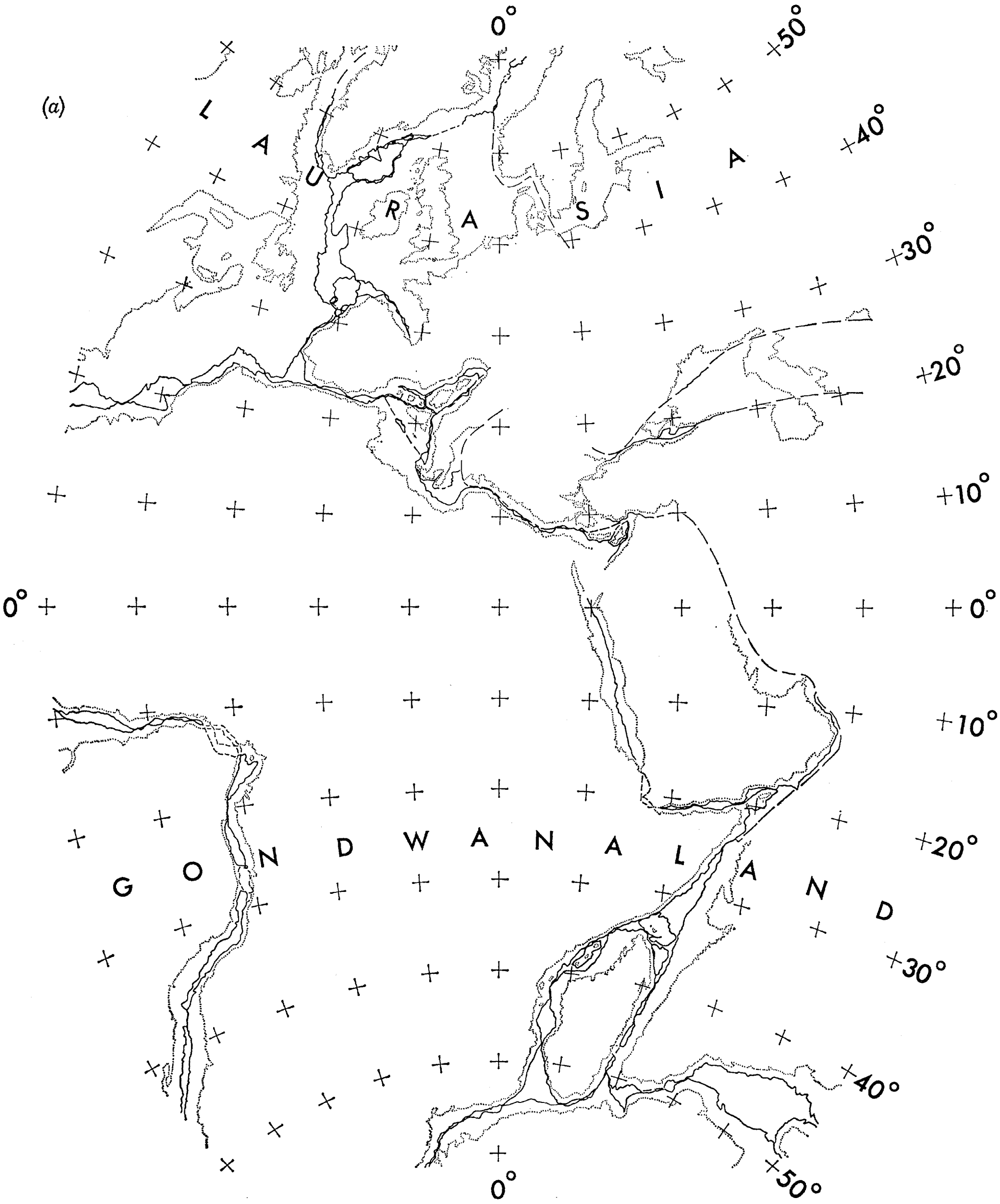


Figure 8. Five stages in the development of the eastern North and South Atlantic, Mediterranean, Middle East and western Indian Ocean, and surrounding regions during the Mesozoic and Cenozoic on an expanding globe. Zenithal Equidistant projection. Epicontinental seas and land areas present at each period of time are omitted except in figure 8*e*. Legend as in figures 2–4. These reconstructions are continued eastward in figures 9*a*–*f*.

Figure 8*a*. Pangaea stage of continental displacement 180 Ma B.P. Projection pole is 0° latitude and longitude constructed for that time. Diameter of the Earth is 80% of modern mean value.

The anticlockwise rotation of Italy and the resulting production of the Alps suggested here does not require as great a northward displacement of Italy as is required by Hsü & Schlanger (1971) and implied by Hsü (1971) for the post-Middle Cretaceous to Recent development of this region assuming a constant dimensions globe. Indeed, there is apparently nothing fundamental in the reconstructions given here in figures 8*b*–*e* which contradicts the development of the Alps and Appenines as described by Bernoulli, Laubscher, Trümpy & Wenk (1974), Oxburgh (1974), and Sestini (1974). The movements between Corsica and the northern Appenines suggested here agree with the hypothesis proposed for the formation of the northern Tyrrhenian Sea by Boccaletti, Elter & Guazzone (1971). The eastward drag of Italy led also

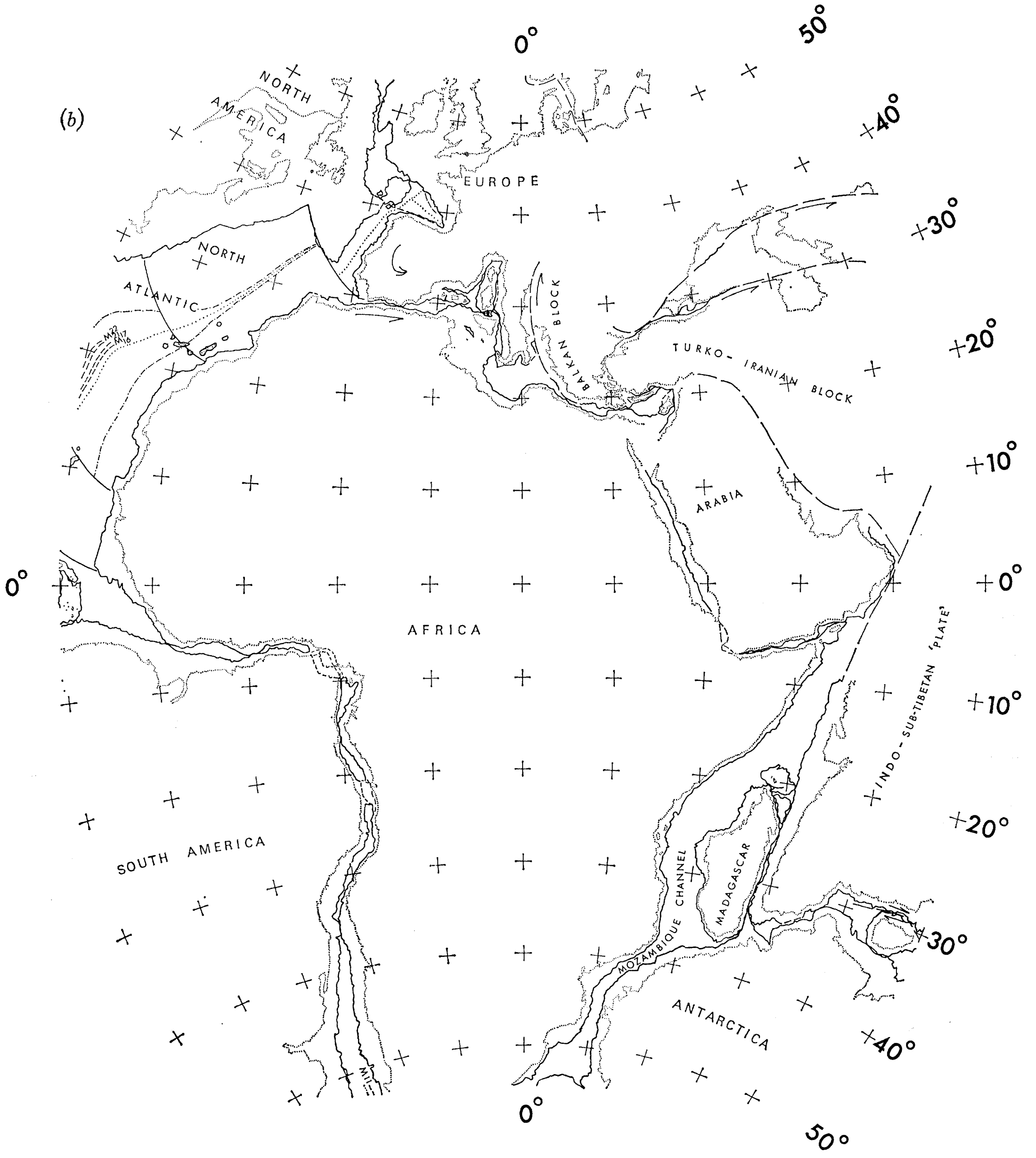


FIGURE 8*b*. Early Cretaceous (Hauterivian) 120 Ma B.P. Projection pole is 0° latitude and longitude constructed for that time. Diameter of the Earth is approximately 87% of current mean value.

in the late Cenozoic to the development of the Rhine graben and associated volcanic activity in Germany and France.

It is, however, in the eastern Mediterranean that the reconstructions given here help to eliminate altogether the problems of trying to close the 'Tethyan Ocean', which accompany all constant dimensions reconstructions. The kinematics suggested here, allow ocean floor spreading to occur in the eastern Mediterranean during the Mesozoic, and north and north-eastward thrusting from the late-Cretaceous onward, particularly during the Tertiary, in accordance with the field evidence. There is no fundamental geometric problem involved for example in the thrusting of the Troodos Massif in Cyprus (Gass 1968). The reconstructions given here also suggest a straightforward developmental history of the Black Sea region; the

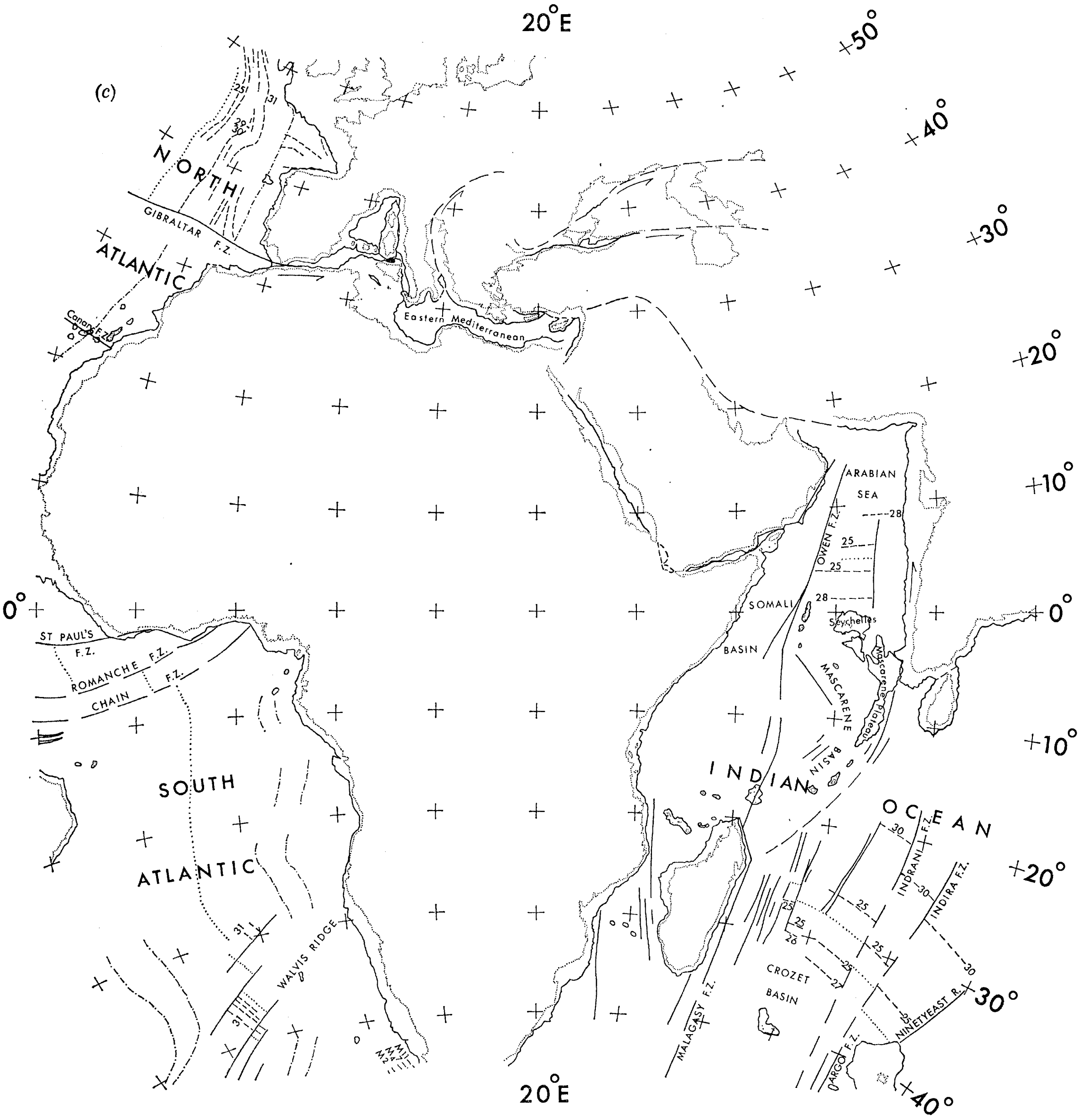


FIGURE 8*c*. Early Tertiary (Palaeocene) 60 Ma B.P. (anomaly 24). Projection pole is latitude 0°, longitude 20° E constructed for that time. Diameter of the Earth is approximately 93% of current mean value.

orogenic belts of the Balkans (e.g. Birkenmajer 1974), Turkey (e.g. Ilhan 1974) and the Caucasus; the platform tectonics of the southern margin of the Russian platform north of the Black Sea (e.g. Vereschagin & Ronov 1968); together with the evident fragmentation of the alpide belts and development of the Aegean Sea during the late Cenozoic; all in response to the lateral movements of what are here termed the Balkan and Turko–Iranian blocks and Black Sea–Caspian wedge. These movements occurred in response to the relatively eastward displacement of the joint African–Arabian continent against the southern margin of Laurasia.

The debate occasioned by the constant dimensions hypothesis on whether the Tethyan Ocean lay north of Turkey or between North and South Turkey does not arise (Hsü 1971; Smith 1971; Smith *et al.* 1973; Dewey *et al.* 1973). The reconstructions in figure 8 would accord with

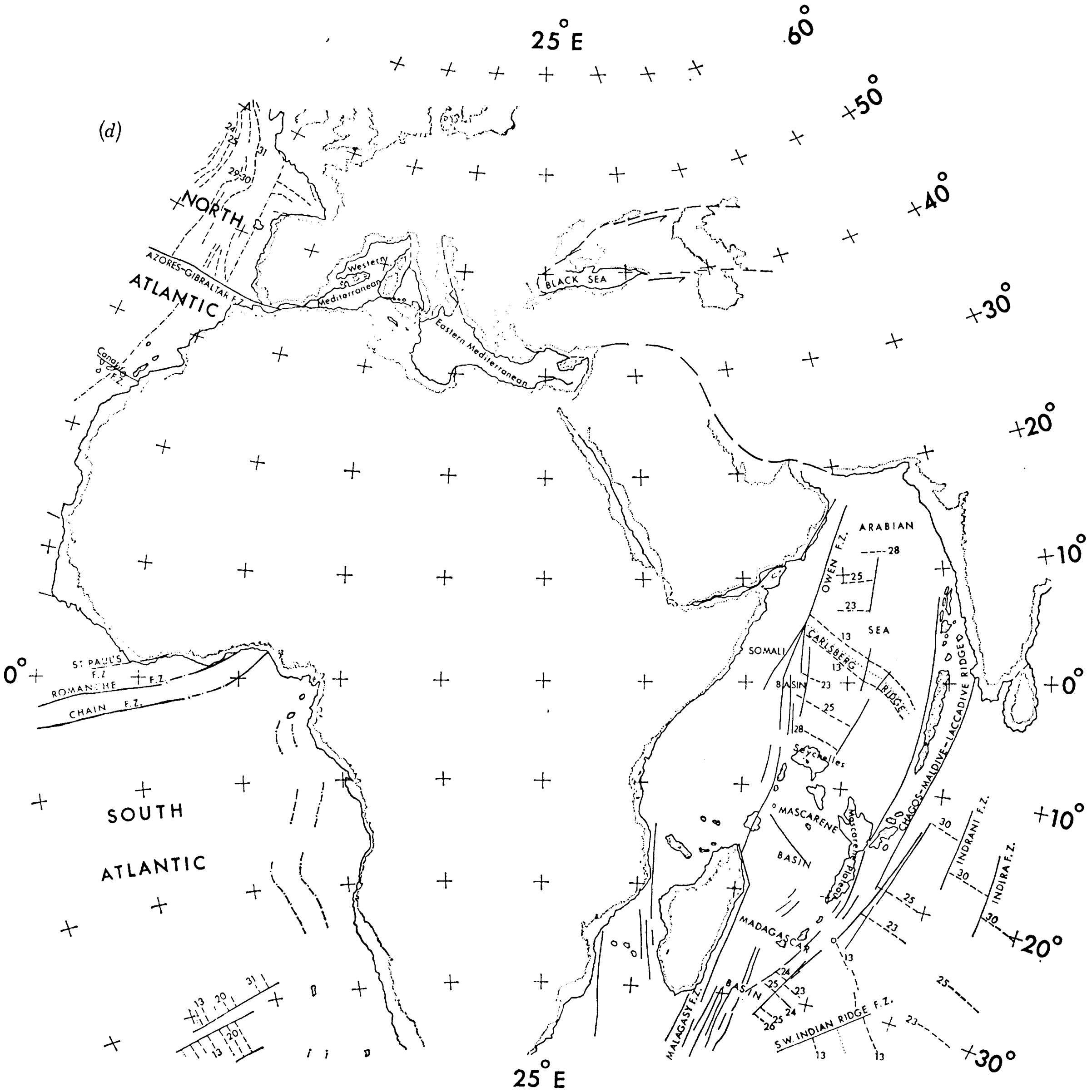


FIGURE 8*d*. Middle Tertiary (Oligocene) 30 Ma B.P. (anomaly 9). Projection pole is latitude 0°, longitude 25° E constructed for that time. Diameter of the Earth is approximately 97% of current mean value.

Brinkmann's results in Anatolia (1972) and similar results in Iran (§3(*d*), p. 268) which suggest the absence of any major area of oceanic crust to the north.

These reconstructions do not deny the presence from time to time of local subduction zones, or the major thrusting of simatic crust. Indeed, the movements envisaged here provide frictional forces at tectonic sutures which could produce the outflooding of volcanic lava on a grand scale.

(*d*) *Indian Ocean, southeast Asia and Indonesia* (*figures* 3, 8, 9 and 10)

The development of the Indian Ocean by the break-up of Gondwanaland is very important to the argument for global expansion. Before 1968, the growth of its oceanic crust had been

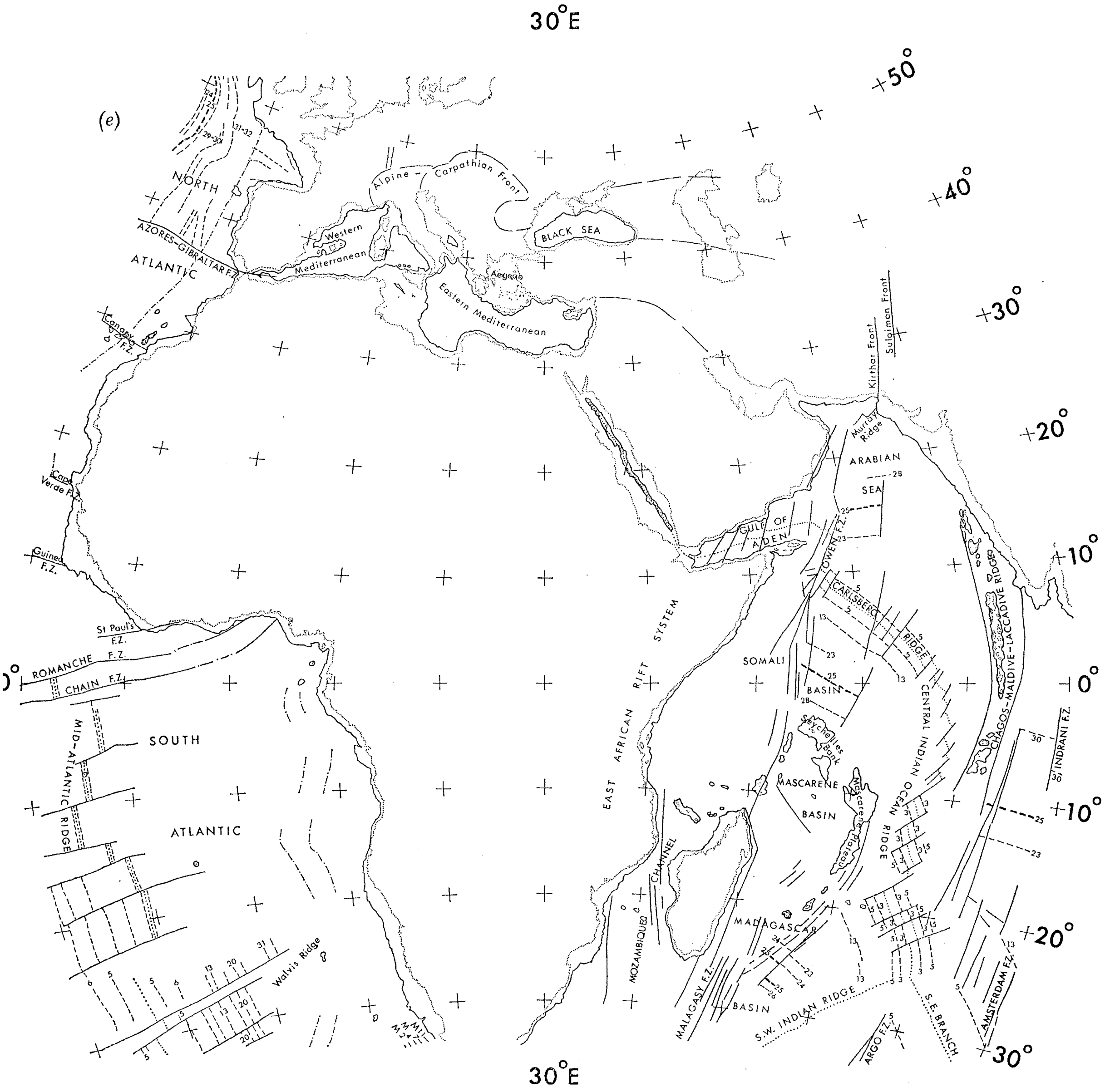


FIGURE 8*e*. Geographic and ocean floor spreading map of the Modern Mediterranean region, eastern North and South Atlantic and western Indian Ocean. Projection pole is latitude 0°, longitude 30° E.

postulated essentially from the various geometric fits of the continents together to reform Gondwanaland and their possible dispersal to current positions. The ocean floor spreading and tectonic information now available, shown in figures 3, 8*e*, 9*f* and 10*e*, is sufficient to determine the manner in which Gondwanaland started to fragment together with the broad development of the Indian Ocean from the late Jurassic to the present day. To the ocean floor spreading information summarized in the maps must be added the preliminary results of the Deep Sea Drilling Project Legs 22–28 given by Von der Borch, Sclater *et al.* (1972), Whitmarsh, Weser *et al.* (1972), Ross, Whitmarsh *et al.* (1972), Fisher, Bunce *et al.* (1972), Simpson, Schlich *et al.* (1972), Luyendyk, Davies *et al.* (1973), Veevers, Heirtzler *et al.* (1973), and Hayes, Frakes *et al.* (1973), respectively.

It is apparent in the text-figures given here that there are three main spreading regions within the Indian Ocean crust. The first of these consists of two areas which contain the oldest known oceanic crust in the Indian Ocean; of late Jurassic and early Cretaceous age. They are (i) in the eastern half of the Wharton Basin region which is bounded by the western Australian margin, the Diamentina discontinuity–Broken Ridge system, the Ninetyeast Ridge and the Java Trench; and (ii) the region between the Owen fracture zone and the East African coast.

The second main region consists of oceanic crust generated throughout the Upper Cretaceous and early Tertiary until anomaly 23, from approximately west-to-east trending axes. This phase of simatic crustal generation caused the development of the western region of the Wharton Basin and the major expansion of the area of the Indian Ocean west of the Ninetyeast Ridge transform fault. Excluding the Wharton Basin, the region has been fragmented into four parts by the third phase of crustal generation which started in the Eocene and continues today. The first fragment is the triangular-shaped Arabian Sea bordered by the Arabian continental margin, the western Indian continental margin, the northern end of the Maldive–Laccadive ridge and by the active Gulf of Aden–Carlsberg Ridge spreading region. The second fragment is the Bay of Bengal flanked by the eastern Indian continental margin, the Central Indian Ocean and southeast Indian Ocean ridge active spreading zone, and the Andaman–Nicobar–Ninetyeast Ridge system. The third fragment, which is itself broken up into smaller structural areas, occupies the region east of the Owen–Malagasy Coast fracture zone bordered by the active spreading zone of the Carlsberg–Central Indian Ocean and southwest Indian Ocean ridges. The fourth fragment consists of the Kerguelen–Gaussberg Ridge and the Kerguelen and Indian–Atlantic–Antarctic basins, bordered by the still active southwest and southeast Indian Ocean Ridge zones to the north and the continental margin of Antarctica to the south.

The third main region consists of simatic crust generated from the Eocene to the present day from two mid-oceanic ridges. The main ridge, represented by the southeast Indian Ocean, Central Indian Ocean and Carlsberg Ridge systems, started to generate simatic ocean floor between Australia and Antarctica in the early Eocene. This generating ridge split its way northward during the Palaeogene to penetrate between the African and Arabian continental regions within the Miocene. A triple junction in the Central Indian Ocean Ridge provides a link with the southwest Indian Ocean Ridge, a much narrower spreading zone which joins with the mid-Atlantic ridge. The magnetic anomaly lineation pattern of this third region is, to all intents and purposes, parallel to the generating ridge concerned as one would expect.

There have been essentially two different methods of reconstructing Gondwanaland. The first of these, advocated by Carey (1958), Veevers (1971), Veevers, Jones & Talent (1971), Tarling (1971) brings the western margin of Australia directly into contact with the eastern or northeastern margin of India. The development of the Wharton Basin region would be in response to the lateral separation of these two continents, and would show magnetic anomaly lineation patterns running parallel to the continental margins probably generated from the Ninetyeast Ridge axis.

The other method of reconstructing Gondwanaland employs the fit of Australia to Antarctica described by Sproll & Dietz (1969) which has subsequently been confirmed by the pattern of Eocene to Recent ocean floor spreading which has separated these two continents. This fit has been used by Smith & Hallam (1970) and Craddock (1969–70) among others and is similar to that of Du Toit (1937) and King (1958) for example among earlier workers. This arrangement produces an oceanic gap termed the 'Sinus Australis' between the western margin of Australia and India which Dietz & Holden (1971) suggested should have a crust of pre-Mesozoic age. This reconstruction of Gondwanaland is used in figure 1 herein.

The above mentioned reconstructions assume an Earth of modern dimensions at the time of Pangaea. Such reconstructions demand the presence of a wide divergence between Gondwanaland and Laurasia called the Tethyan Ocean. Carey (1958, p. 280, Figure 39*d*) demonstrated the geometric necessity of separating Australia and New Guinea as part of Gondwanaland from the bulk of southeast Asia which formed part of Laurasia. He also demonstrated some of the geological contradictions produced by such an arrangement. The reconstructions of Dietz & Holden (1970, 1971), and Smith *et al.* (1973) for example, show this wide oceanic separation in the maps for the Permian through to the Jurassic. In their Cretaceous reconstruction, Smith *et al.* (1973, Figure 7) show Indonesia and New Guinea as having converged from their original late Palaeozoic wide separation. On the other hand, Ridd (1970, 1971) and Audley-Charles, Carter & Milsom (1972) on tectonic grounds indicate that Indo-China and Indonesia once formed part of Gondwanaland, and they suggest that much of Indonesia would occupy the 'Sinus Australis' gap between Australia and India. Audley-Charles *et al.* transfer the Tethyan Ocean north of this continental 'Sinus Australis' and the Australasian region of Gondwanaland. Their Mesozoic position of Indonesia does not appear to be invalidated by the *Upper Palaeozoic* palaeomagnetic results from Malaya, contrary to the assertion of McElhinny, Haile & Crawford (1974).

The site of the 'Sinus Australis' is the present day Wharton Basin region. Drillings made during Legs 22, 26 and 27 of the Deep Sea Drilling Project program, together with data from magnetic anomaly lineations, indicate that the Wharton Basin is essentially an area of Cretaceous ocean floor spreading truncated on its northern side by the Java Trench subduction zone. The Ninetyeast Ridge and Broken Ridge–Diamentina 'fracture zone' are discontinuities demarcating the Wharton Basin oceanic plate from adjacent regions of oceanic floor. These results, which are summarized below, affect profoundly the postulated history of the early development of the Indian Ocean and the concept of a 'Tethyan Ocean' to the north of it.

The positions of the drilling sites in the Indian Ocean are shown in figure 3. In the Wharton Basin, the oldest sediments detected so far are of Tithonian (uppermost Jurassic) or Berriasian (lowest Cretaceous) age resting upon basalt at site 261 situated in the Argo Abyssal Plain (Veevers, Heirtzler *et al.* 1973). Sites 259 and 260 show 'Neocomian' Lower Cretaceous sediments resting upon basalt. All of these sites then indicate a major Lower Cretaceous hiatus in sedimentation until the Albian, and with site 263 (where the boring penetrated only to Albian sediments), flank the continental slope of Western Australia. The corresponding hole, site 258, of Leg 26 (Luyendyk, Davies *et al.* 1973) did not reach simatic crust, but also penetrated to Albian sediments. Site 257 shows Albian sediments resting directly upon basalt, while site 256 shows a thin development of Lower Cretaceous sediment above the basalt.

To the north of site 256, site 212 of Leg 22 (Von der Borch, Sclater *et al.* 1972) shows possible Lower Cretaceous sediments above the basalt, but further north still at site 211, Upper Cretaceous (Campanian) sediments rest on extrusive rocks. To the west of site 211 at site 213, still within the Wharton Basin, upper Palaeocene sediments rest upon pillow basalts. This particular site is important because it is situated upon the west–east trending magnetic anomaly lineation identified by Sclater as 25–26 on the Heirtzler scale (table 1, p. 228). This anomaly is one of a sequence reported to become older towards the south. Sites 214, 253 and 254 show the extent of the discontinuity at the Ninetyeast Ridge where ?Palaeocene, Middle Eocene and perhaps Palaeogene sediments rest respectively upon basalt. The extent of the discontinuity marked by Broken Ridge and the Diamentina 'fracture zone' is apparent from the borehole data of the Wharton Basin and the Cenozoic spreading pattern generated by the South East Indian Ocean Ridge which has separated Antarctica from Australia.

The ocean floor spreading evidence gleaned so far places marked geometric constraints upon the developmental history of the Indian Ocean. The borehole and magnetic anomaly data summarized above, imperfect although it is, indicates that the Wharton Basin developed initially as an oceanic wedge which opened in the late Jurassic–early Cretaceous between Australia and whatever continental region lay to the west of it. Certainly from the late Albian onward, this sialic region to the west started to move northward relative to Antarctica and Australia while these two continents were still joined together. The western margin of the developing Wharton Basin was marked by what is now the Ninetyeast Ridge discontinuity, a major wrench and transform fault trace. There should also be a discontinuity running roughly parallel to the west Australian margin within the Wharton Basin which would mark the margin of the initial wedge of ocean floor spreading. There is evidence of a lineation extending southwestward from the Exmouth Plateau which might mark such a discontinuity (figures 3 and 9*f*). The Broken Ridge–Diamentina 'fracture zone' to the south marks the former southern margin of the Basin where it abutted against Antarctica. The development of spreading between Australia and Antarctica from the Eocene onward to the present day has caused the displacement northward of the Wharton Basin and Australia against Indonesia with the resulting development of the Java Trench.

All the proposed reconstructions of the Indian Ocean which assume a globe of constant modern dimensions since the early Mesozoic produce major inconsistencies between the requirements of the geometry of the reconstructions and the field evidence. The concept that Australia fitted directly against India, mentioned above, is not supported by the ocean floor spreading evidence from the Wharton Basin, although it is clear that Australia rotated away from a continental region to the west of it during the late Jurassic–early Cretaceous. On the other hand, the fit of Australia to Antarctica which is supported by the subsequent ocean floor spreading pattern between these two continents produces a 'Sinus Australis' gap between Australia and India which, according to the constant dimensions reconstructions should consist of pre-Triassic oceanic crust. This crust would have to be eliminated by subduction for it is absent today. There is, however, no evidence at the western Australian continental margin or at any of the ridge systems bounding the modern Wharton Basin of the necessary subduction zones. There is strong evidence that the site of the 'Sinus Australis' was filled by part of

Indonesia, but there is no evidence of the former occurrence of a Tethyan Ocean to the north of it, or indeed along the site of the alpide chains from Iran eastward.

McKenzie & Sclater (1971) give reconstructions of the Indian Ocean back into the late Cretaceous based on the spreading information then available, and using rigidly the 'theory' of plate tectonics. They conclude (1971, p. 513) that their results indicate no appreciable expansion of the Earth since the late Cretaceous. They admit, however, that it was not clear to them how the geographical relations shown in their 75 Ma B.P. reconstruction (1971, Figure 45) had been achieved, and that it was difficult to understand how the reconstruction of Gondwanaland given by Smith & Hallam (1970) could have evolved to their late Cretaceous configuration. This could not be achieved without reduction of area and thus subduction of

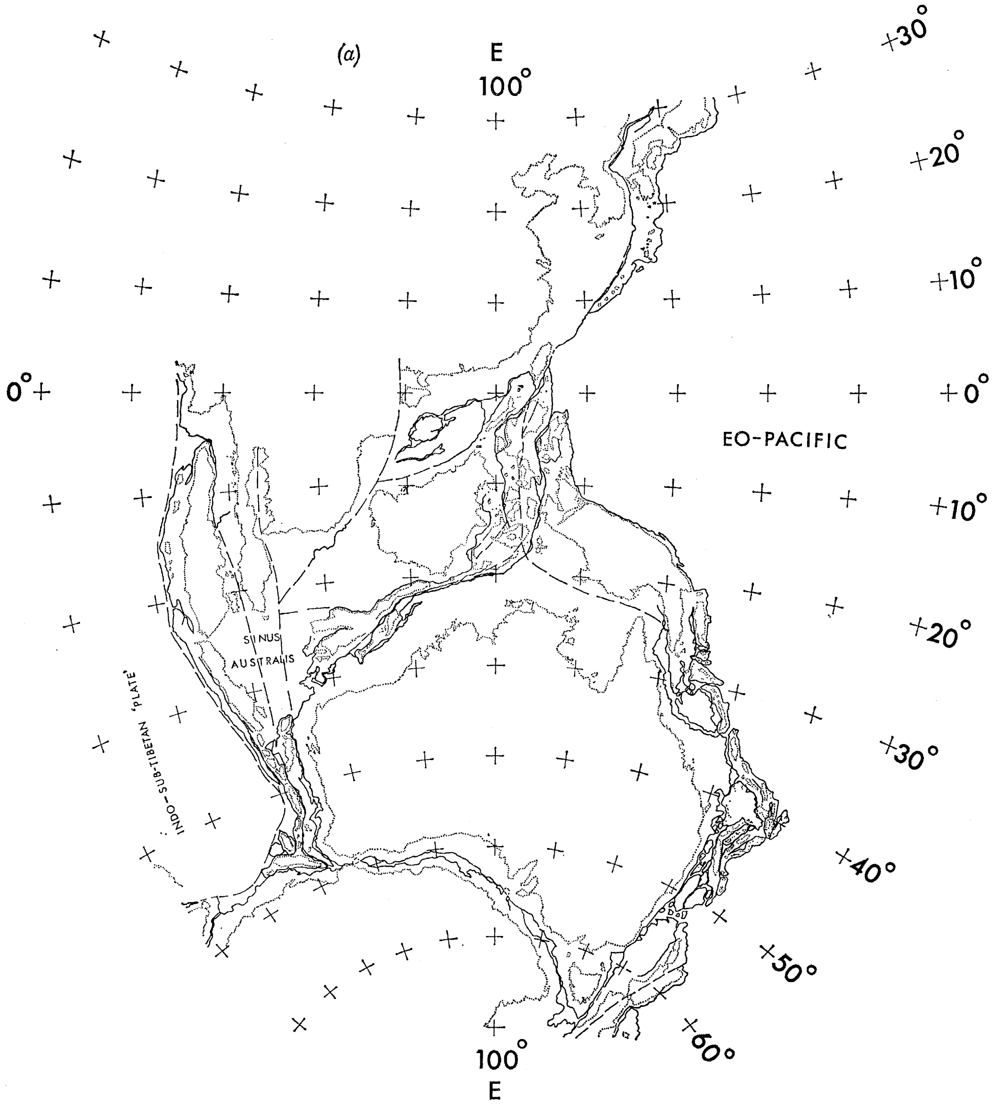


FIGURE 9. Six stages in the development of southeast Asia and Australasia during the Mesozoic and Cenozoic projected from an expanding globe. Zenithal Equidistant projection. Epicontinental seas and land areas present at each period of time are omitted except in figure 9*f*. Description as in figures 2–4.

FIGURE 9*a*. Southeast Asia and Australasia at the Pangaea Stage of continental displacement 180 Ma B.P. Projection pole is latitude 0°, longitude 100° E constructed for that time. Diameter of the Earth is 80% of modern mean value.

previously generated ocean floor. This is true even when important magnetic anomaly evidence from the Madagascar and Crozet Basins, excluded from their late Cretaceous to early Tertiary reconstructions, is used in conjunction with borings completed since the publication of their paper. The ocean floor spreading evidence indicates that the Mascarene Basin was formed, not between Madagascar and India as shown in their late Cretaceous reconstruction (1971, Figure 45), but to the northeast of Madagascar as India was displaced northward during the late Cretaceous spreading phase (figures 8*b*–*e*).

If one reduces the diameter of the Earth to 80 % of its present day value in the late Triassic–early Jurassic, and thus increase the value of surface curvature, the 'Tethyan Ocean' is eliminated and it becomes possible to produce a straightforward kinematic sequence of reconstructions from a Gondwanaland configuration similar to that of Smith & Hallam (1970, p. 140, Figure 1) to that of the modern Indian Ocean (figures 8*a*–*e*, 9*a*–*f*, 10*a*–*e*). These

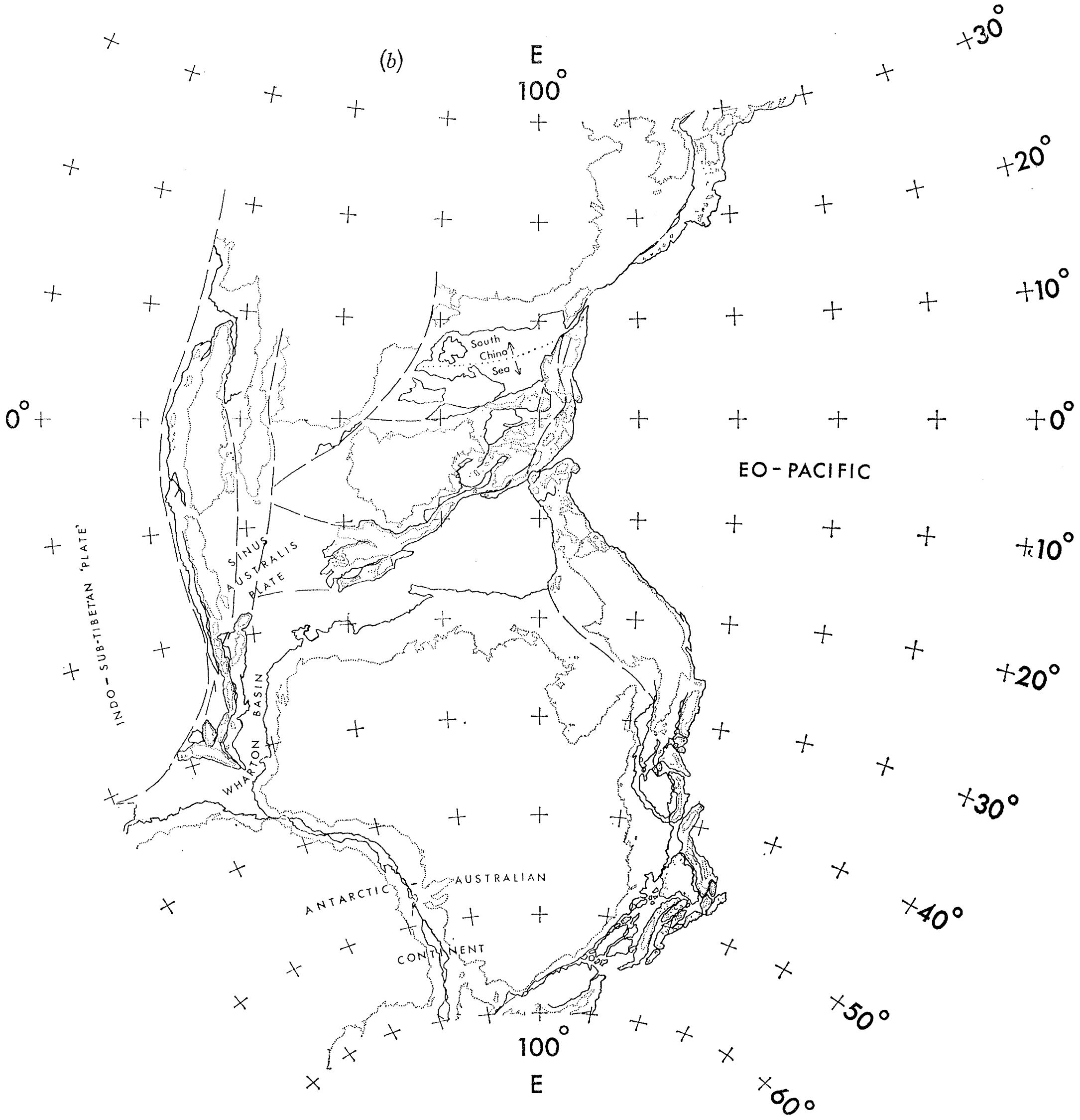


Figure 9*b*. Southeast Asia and Australasia in the early Cretaceous (Hauterivian) 120 Ma B.P. Projection pole is latitude 0°, longitude 100° E constructed for that time. Diameter of the Earth is approximately 87 % of current mean value.

reconstructions agree with the ocean floor spreading data now available from the Indian Ocean and the geological data from the continental regions surrounding it. The reconstructions given in figures 9*a–f* are not invalidated by the greatly simplified movements shown in Indonesia, where islands such as Borneo, Java, Sulawesi, etc., are shown for clarity with more or less their modern outline, only major wrench faults being taken into account.

The reconstruction of Gondwanaland given here in figures 8*a* and 10*a* shows Madagascar fitted against the East African margin of Kenya and Tanzania. However, authors such as Carey (1958), Maack (1969), Flores (1970), Tarling (1971), Green (1972) and Sowerbutts (1972), place Madagascar off the continental margin of South East Africa and Mozambique. This arrangement would require modifications to be made to the fit of Antarctica with Australia

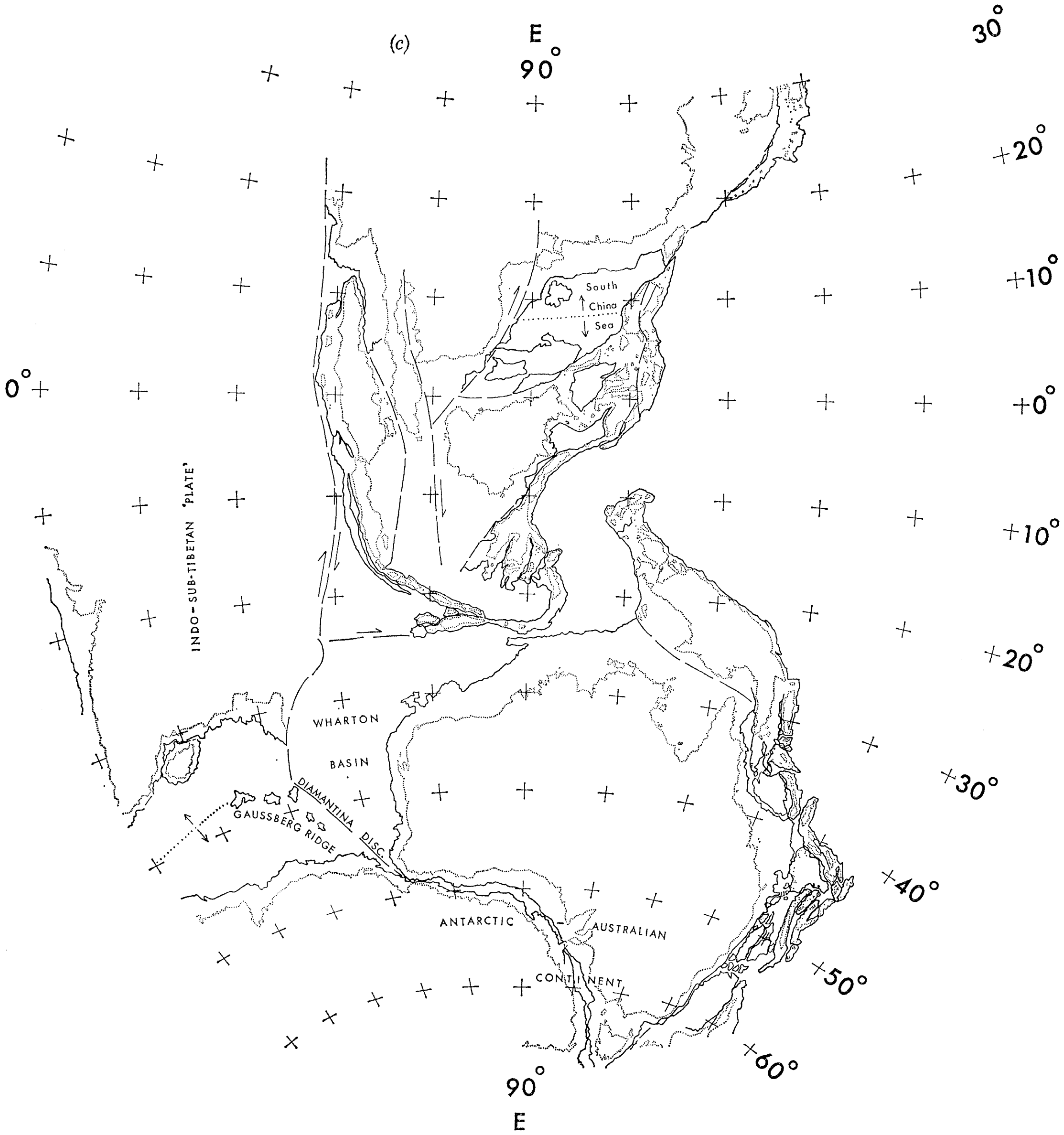


FIGURE 9*c*. India, southeast Asia and Australasia in the mid-Upper Cretaceous (Turonian) 90 Ma B.P. Projection pole is latitude 0°, longitude 90° E constructed for that time. Diameter of the Earth is 90% of current mean value.

and India similar to those proposed by Carey (1958), Veevers (1971), Veevers *et al.* (1971) and Tarling (1971), among others, which apparently do not comply with the subsequent ocean floor spreading history outlined above and in figures 9*b–f*. Similarly, the spreading data from the region of the Indian Ocean between Madagascar and the southwest Indian Ocean Ridge would appear to preclude the northeast movement of Madagascar relative to Africa. The Triassic to Upper Jurassic palaeogeography also favours the northerly position of Madagascar (compare Arkell 1956). But, its exact position in Gondwanaland can only be determined when deep drilling of the oceanic regions surrounding the island and the dating of the oceanic crust have been carried out.

In the reconstructions of Pangaea given here (figures 8*a*, 9*a*) no Tethyan Ocean (a geometric artefact) is present, and the northern margin of Gondwanaland is in direct contact with

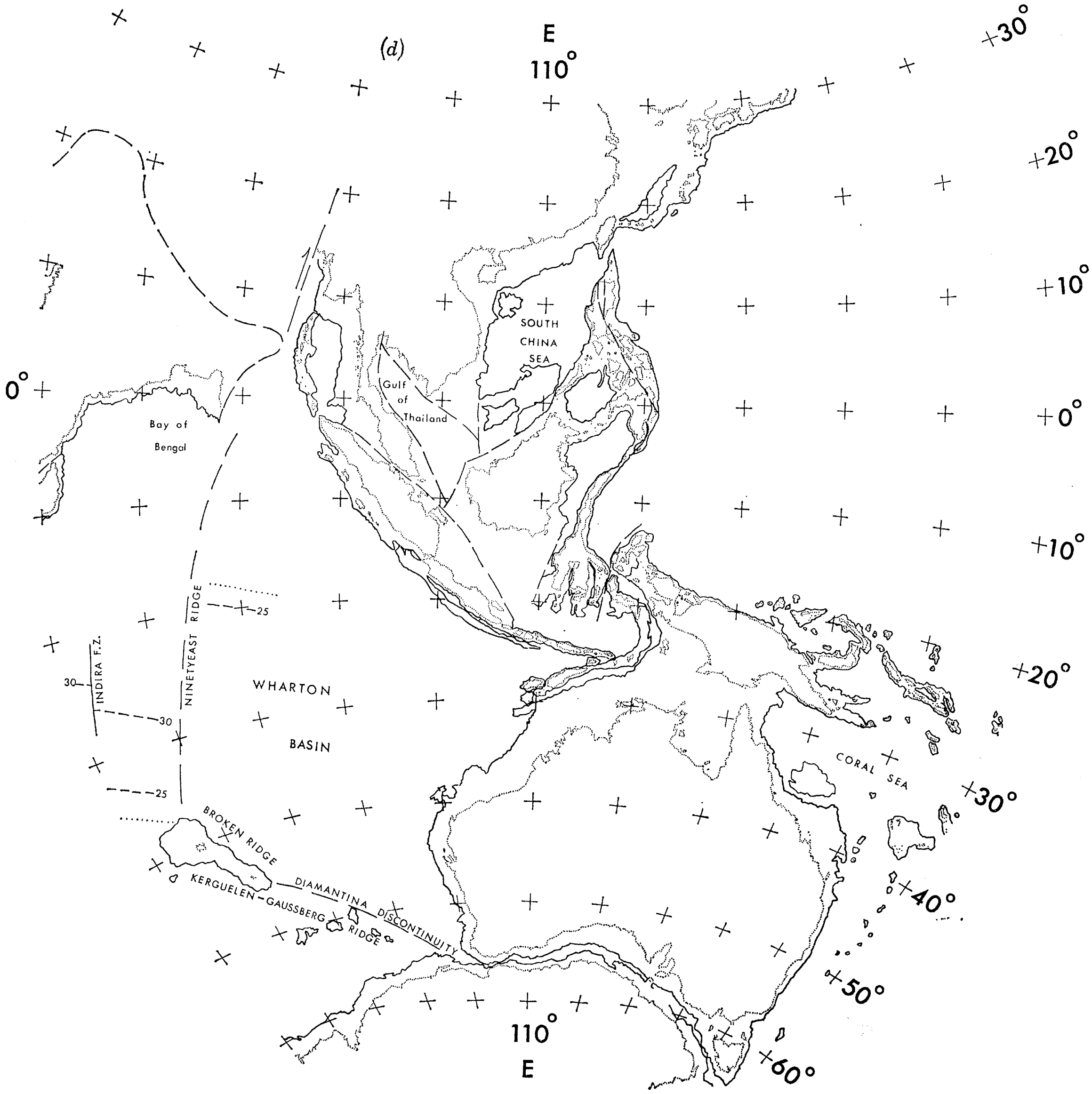


FIGURE 9*d*. India, southeast Asia and Australasia in the early Tertiary (Palaeocene) 60 Ma B.P. (anomaly 24). Projection pole is latitude 0°, longitude 110° E constructed for that time. Diameter of the Earth is approximately 93 % of current mean value.

the southern margin of Laurasia. The initiation of ocean floor spreading during the Jurassic in the southern North Atlantic, caused a counter-clockwise rotation of Africa and South America away from North America. This movement led to the initial break-up of Gondwanaland, because, with Laurasia in direct contact to the north, the supercontinent could not rotate as a whole. Thus major tension, and in consequence rift faulting, occurred at the common margin of eastern Africa, Antarctica, Madagascar and India. From the early Cretaceous history of the southern South Atlantic discussed above (§3(*b*)(iii), p. 248), the combined Antarctic and Australian continents started to rotate clockwise in response to the movement of the combined South American and African continents. This produced tension at the common western Australian and Indonesian margin followed by the development of a wedge of ocean floor spreading to form the eastern portion of the Wharton Basin during the late Jurassic and Lower Cretaceous.

Probably from the Upper Albian onward, the spreading direction changed in the Wharton Basin in response to the development of the South Atlantic and continued clockwise rotation of Antarctica with Australia attached (§3(*b*)(iii), p. 248). North to south ocean floor generation now commenced to form the major area of the Wharton Basin, and the generating axis was soon to penetrate westward between India and Antarctica thus producing the second crustal region of the Indian Ocean during the Upper Cretaceous and Palaeocene (figures 9*c*, 10*c*).

The precise chronology of the displacement of Madagascar is not determinable at present, although it must have reached its current position by about the late Turonian according to the distribution of Upper Cretaceous magnetic anomalies. Besairie & Collignon (1971) have shown that the major outpouring of plateau basalts occurred in the Middle Turonian. Aerial magnetic traverses across the Mozambique Channel given by Green (1972) are significantly 'quiet' which suggests the long late Lower Cretaceous to Coniacian period of normal polarity. These contrast sharply with the well marked north–south trending anomalies shown by him in tracks 540, 545 and 523 south of the Island. Although undated, these anomalies trend in the right direction to mark the Lower Cretaceous and early Upper Cretaceous displacement of the Queen Maud Land margin of Antarctica away from South East Africa indicated in figures 10*b* and *c*. They appear to preclude, however, the north-easterly migration of Madagascar away from the southeast African continental margin during the Mesozoic favoured by Green. However, in reality Madagascar has probably remained stationary during the late Jurassic–Early Cretaceous, and that it is Africa which has rotated relatively anticlockwise to it, Madagascar appearing to move southward initially along the line of a tear fault (figures 8*a*, *b*). Some generation of oceanic crust would be associated with this movement, but the lack of volcanic rocks or volcanogenic sediments in the post-Upper Jurassic Mesozoic sequences of the East African countries (e.g. Kent 1972) may not be an obstacle to the reconstruction given here in figures 8*a*, *b*, 10*a*–*c*.

There is, unfortunately, little ocean floor spreading information yet published from the bulk of the second main region of the Indian Ocean until the Campanian–Maestrichtian boundary (about anomaly 31, 72 Ma B.P.). During this long 28–30 million years of normal polarity, the Indian Ocean evolved from a configuration similar to that of figures 8*b*, 9*b*, 10*b*, 13 and 14 to that indicated by the dykes of anomaly 30 on the Palaeocene maps (figures 8*c*, 9*d* and 10*d*). However, areal expansion during this period can be determined by the movement of Antarctica (and thus Australia), indicated by the development of the South Atlantic, and the constraints put upon the pre-Campanian spreading pattern by the style of the late-Cretaceous to Palaeocene crustal generation shown in the distribution of the dykes of anomalies 31–23. The Turonian construction given in figures 9*c* and 10*c* comply with these constraints, and if the spreading rate was reasonably constant, the series of reconstructions from those of the Hauterivian to those of the Palaeocene would be kinematically straightforward. In figure 8*c* (Palaeocene), the magnetic lineations of the Crozet Basin, which were considered anomalous by McKenzie & Sclater, are used in the construction. By so doing, the development of the Mascarene and Mauritius Basins accords with the Deep Sea Drilling Project borehole evidence from this region of the Indian Ocean.

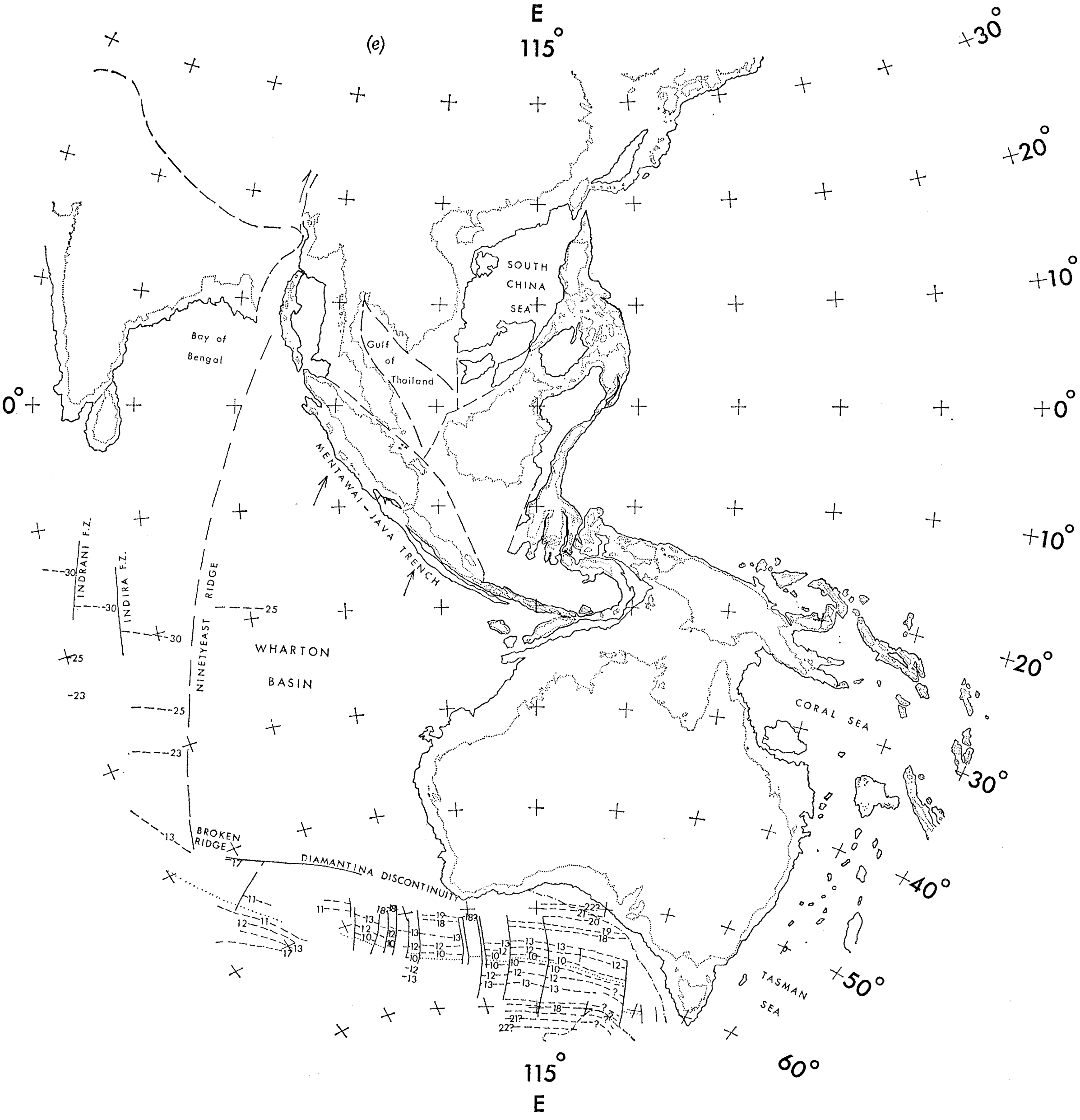


FIGURE 9*e*. India, southeast Asia and Australasia in the middle Tertiary (Oligocene) 30 Ma B.P. (anomaly 9). Projection pole is latitude 0°, longitude 115° E constructed for that time. Diameter of the Earth is approximately 97% of current mean value.

The development of the Arabian Sea and eastern Somali Basin follows logically as India is displaced northward along the more southerly portion of the Chagos–Maldive–Laccadive Ridge and Ninetyeast transform faults (Dietz & Holden 1971). The west–east trending axis east of the Ninetyeast Ridge transform was displaced markedly northward during the development of the western region of the Wharton Basin. The displacement movements which produced the series of predominantly west to east trending anomalies of the second main phase of development of the Indian Ocean, stopped abruptly in the late Palaeocene after the generation of anomaly 23 dykes. The northward movement of India during the accumulation of the Deccan Traps from the late Cretaceous into the Eocene is also indicated by the palaeomagnetic vector determinations of Hasnain & Qureshy (1971) and Wensink & Klootwijk (1971).

The Eocene to Recent development of the Indian Ocean depends on the growth of a new ocean floor spreading area from two axes. The principal axis penetrated westward from the South Pacific between Antarctica and Australia in the late Palaeocene–early Eocene. It then extended northwestward towards the Gulf of Aden reaching the Red Sea by the Miocene (see, for example, Hutchinson & Engels 1972; Lowell & Genik 1972; Tazieff, Varet, Barberi & Giglia 1972). Initially, this spreading axis was offset by the transform fault which marked the northward movement of the western margin of India (figure 8*c*). This fault was then built up into a major ridge feature, the Chagos–Maldive–Laccadive ridge (figure 8*d*), by vulcanism during the Lower Tertiary as indicated by borings at sites 219, 220 and 288 of the Deep Sea Drilling Project (Whitmarsh, Weser *et al.* 1972; Fisher, Bunce *et al.* 1972). Later still, the southeast Indian Ocean Ridge and the Carlsberg Ridge were joined into a single spreading axis by the development of the central Indian Ocean Ridge close to the line of this earlier transform fault (figure 8*e*).

The commencement of the insertion of a spherical triangular region of new ocean crust into the older Indian Ocean floor of the second main spreading region, produced tension, then lateral displacement, between South Africa and Antarctica along the line of what is here termed the southwest Indian Ocean Ridge fracture zone (figure 8*d*). Continued widening of the main spreading zone and associated tension eventually produced a triple junction at the intersection of the southwest Indian Ocean Ridge fracture zone and the southern extremity of the central Indian Ocean Ridge generating axis. Spreading from the resulting southwest Indian Ocean Ridge generating axis continues today (figure 8*e*) and its relation with the spreading axis of the South Atlantic is shown in figure 10*e*.

The development of ocean floor spreading in the Gulf of Aden as the generating axis split its way northwestward by the Miocene (Whitmarsh, Weser *et al.* 1972; Ross, Whitmarsh *et al.* 1972), caused the anticlockwise rotation of Arabia and its separation from the African continent (compare figures 8*d–e*). The tension produced by spreading in this region led to the development of yet another triple junction in the region of the Afar depression. Because of the anticlockwise rotation of Arabia, the active spreading axis would favour the rift valley branch which has now developed into the Red Sea. Although vulcanism has been extensive in the southern–East African Rift Valley system-branch from this triple junction since the Miocene, actual spreading, as opposed to extension, has not occurred.

At the same time, with the generation of the Tertiary to Recent crust from the Carlsberg Ridge, there occurred a complementary southward displacement of the oceanic region east of the Owen fracture zone, comprising the southeast Somali Basin, Seychelles and Mascarene Ridge and Basin with the Mauritius Basin, from the position shown in figure 8*c* to that of figure 8*d* to reach its modern position (figure 8*e*). These movements are reflected in the fracture zone pattern of the central Indian Ocean Ridge shown in figure 8*e*.

From the Eocene to the present day, Australasia with the Wharton Basin has been displaced northward as ocean floor spreading separated Australia from Antarctica (figures 9*e–f*). Because of the mode of crustal areal expansion, demonstrated by the increased generation of oceanic crust to form the 'Southern Ocean' during the Cenozoic (figures 10*d* and *e*), Australasia and the Wharton Basin have been displaced northward by approximately half the width of the oceanic crust between Australia and Antarctica, and not by the whole width. For that reason, only the northern part of the Wharton Basin has been subducted at the Mentawai–Java Trench subduction zone. Southeast Asia and Indonesia have been deformed further, and displaced northward to their present position with the development of the Philippine Trench and marginal subduction zones flanking northern New Guinea. The structure and history of

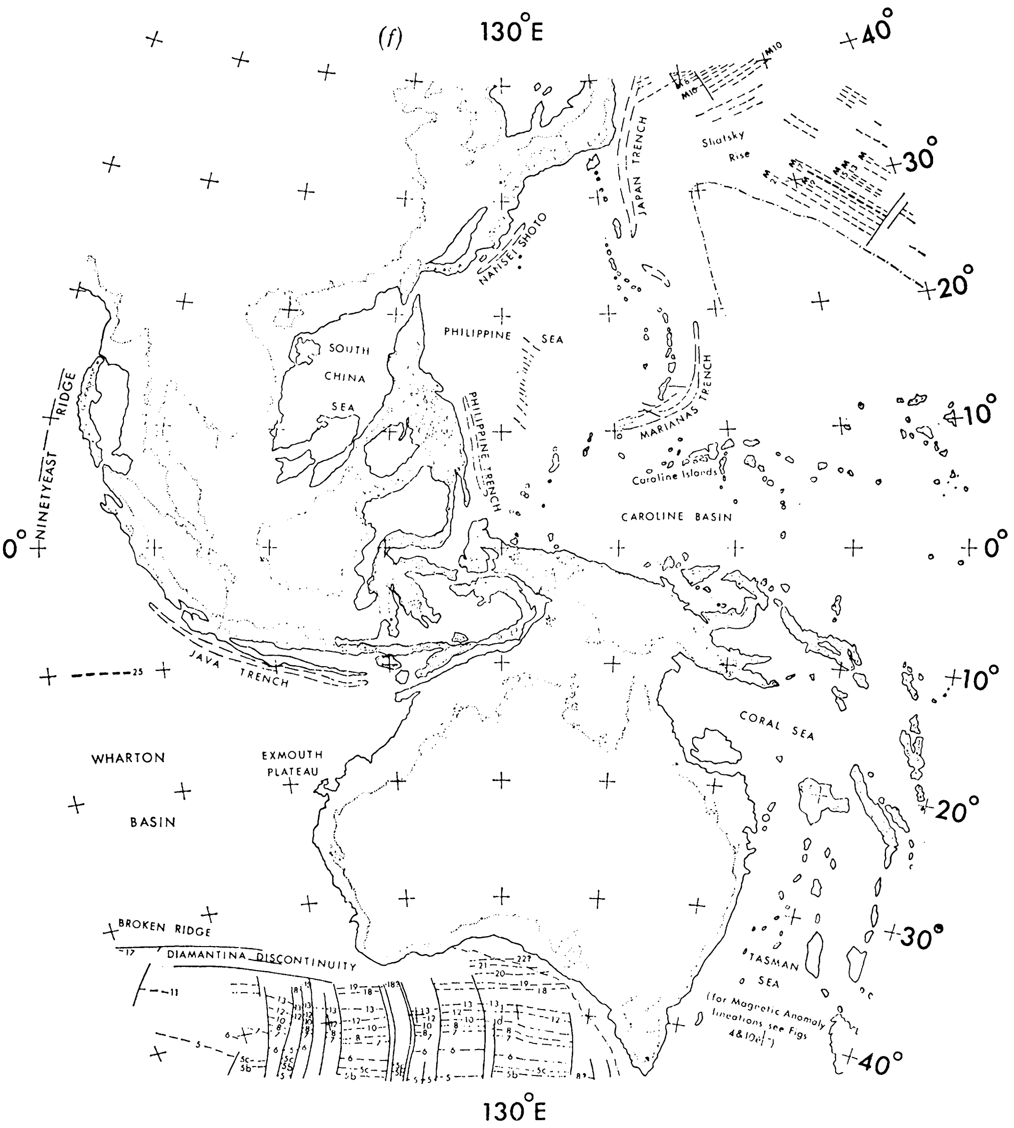


FIGURE 9*f*. Geographic and ocean floor spreading map of southeast Asia and Australasia as seen today. Projection pole is latitude 0°, longitude 130° E.

development of the South China Sea appears to support the kinematics advocated here (see, for example, Parke, Emery, Szymakiewicz & Reynolds 1971).

The deformation of the southern margin of Laurasia, with the building of the Alpine–Himalayan mountain chains from Iran to southeast Asia, is intimately connected with the displacement of India and Arabia by the growth of oceanic crust in the Indian Ocean. The effect of the relatively eastward displacement of the combined African–Arabian continent on the structural development of southern Europe and the Middle East has been discussed above (§3(*c*), p. 254). This movement is also responsible for much of the deformation in the Zagros mountain belt in southern Iran, where Falcon (1974, p. 206) favours the concept of the north-easterly movement of Arabia in conjunction with north–south faulting in the basement. The reconstructions of continental displacement in this region given here agrees with Falcon's view. In the late Upper Cretaceous–Lower Tertiary, major deformation produced a proto-Zagros belt which can be correlated with the development of the Gulf of Oman and Arabian Sea as India continued to migrate northward (figure 8*c*). The main phase of deformation of the Zagros mountain belt occurred in the Miocene and Pliocene, and can be correlated with the displacement and rotation of Arabia away from Africa by spreading in the Gulf of Aden and Red Sea (figures 8*d*–*e*).

The effect of the northward displacement of India on the tectonic evolution of the Alpine–Himalayan orogenic belts becomes more important in Afghanistan and eastward to the major north–south structural discontinuity marked by the Ornach-Nal, Chaman and Kirthar–Sulaiman wrench fault systems. This discontinuity and the equivalent discontinuity separating the Himalayan and Indo-Burman ranges mark the west and east boundaries of the Indian continent as it was displaced northward into the southern margin of Asia.

There is an extensive bibliography on the geology of the Himalayan and associated regions. The detailed reviews of Gansser (1964) and the Hunting Survey Corporation (1961) have been supplemented more recently by the study of the structural trends from space satellite photographs (Abdel Gawad 1971), together with review descriptions of the various regions given by Auden (1974, Afghanistan), Desio (1974, Karakorum), Gansser (1974, Himalaya) and Brunnschweiler (1974, Burma). In the outline reconstructions given here, the terminology is based on Abdel Gawad (1971) for the major lines of discontinuity.

Figures 8 and 9 show that India travelled a total distance of just over 1600 km (1000 miles) from its Pangaea position northward to its current position. This is a little over one third the distance required by the Dietz & Holden (1970) and like reconstructions (e.g. figure 1) made on a globe of constant modern dimensions. By subtracting the amount of movement northward along the structural discontinuity termed the Kirthar–Sulaiman front in figure 8*e*, the Indian continent south of the Himalayan front can be placed in a position corresponding to that of anomaly 28 (Maestrichtian) in the Indian Ocean. The time range from the late Cretaceous to the present day, and the northward movement of India coupled with anticlockwise rotation indicated by the ocean floor spreading pattern during this period, accords with the principal deformation of the Himalayas and associated ranges. The renewed displacement of India by the development of the Carlsberg, Central Indian Ocean and southeast Indian Ocean Ridge spreading zones would indeed have produced the paroxysmal Miocene–Pliocene intensification of orogeny seen in the Himalayas.

If a Tethyan Ocean with a simatic floor ever existed, it would occupy only the narrow region extending north of India shown in the Pangaea reconstructions (figures 9*a* and 11) and there termed the 'Indo-SubTibetan plate'. This hypothetical 'ocean' would contract in a north–south direction as India was displaced northward away from Antarctica during the Cretaceous until the Maestrichtian (anomaly 28). India would then come into contact with the southern edge of Laurasia and the main phase of the Himalayan orogeny would start. From the reconstructions given here, the north–south dimensions of the 'Ocean' would have been approximately 960 km (600 miles).

However, in both the Himalayas and the Tibetan Plateau north of them, there occurs a sialic crust of twice the average thickness of the continents. The area and the outline of this region of double thickness suggests that it corresponds to the tectonically foreshortened and granitized Indo-SubTibetan plate which was, therefore, originally a continental region. The northward migration and foreshortening of this *sialic* 'plate' would occur at least through the Upper Cretaceous to the Maestrichtian, and probably to a limited extent from the late Jurassic onward (cf. Vereschagin & Ronov 1968) in response to the differential rotations between Laurasia and Gondwanaland caused by the spreading in the southern North Atlantic. This movement of the Indo-SubTibetan plate would tend to push East Asia aside producing the Mesozoic fold belts of that region, and would explain the Jurassic and Cretaceous sediment sequences and patterns seen in Afghanistan (Auden 1974), the Karakorum (Desio 1974) and the Indo-Burman ranges (Brunnschweiler 1974).

There is, therefore, no need to infer the presence of Tethyan oceanic crust north of India, nor to use ophiolite belts as evidence of its former existence. The presence of ophiolite belts, marking the outpouring of lavas derived from the sima on a grand scale, is hardly surprising in regions of major tectonic disruption involving the entire sialic crust such as occurs in the Alpine–Himalayan orogenic belts.

(*e*) *Pacific Ocean* (*figures* 4, 6, 7, 9, 10, 12, 14, 16, 18)

The Pacific Ocean occupies nearly half the surface area of the modern Earth, and can be divided arbitrarily into North and South regions at the Equator. The continental margins of the North Pacific (figure 4) are of two distinct types. The eastern margin is marked by a subduction zone, directly adjacent to North America, in which ocean floor is thrust down beneath the cordilleran fold belt. The northern margin is marked by the Aleutian Trench subduction zone, flanked by the Aleutian Island arc. On the north side of the arc lies the marginal basin of the Bering Sea. Marginal oceanic basins are characteristic of the western Pacific margin and separate the various West Pacific island arcs, such as the Japanese Islands, from the Asian continent to the west. Here, the principal subduction zones lie to the east of the Island arcs and are again marked by deep trenches such as the Marianas Trench (figures 4 and 6*f*).

The South Pacific extends from the Equator to the Antarctic continental margin. On the eastern side, the Peru–Chile Trench marks a subduction zone immediately adjacent to South America in which oceanic crust is thrust down beneath the Andean cordillera. This trench, however, extends only to about 35° S latitude (figure 10*e*). Further south, and along the southern margin of the Pacific adjacent to Antarctica, there are no active subduction zones present although they existed during the Mesozoic. The western boundary of the South Pacific, like that of the North Pacific, has marginal oceanic basins, such as the Coral and Tasman Seas which separate the Australian continental margin from the island arcs including New Zealand. Here also, the active subduction zones, marked by the Tonga and Kermadec trenches which flank the island arcs, do not extend south of about 35° S latitude (figure 10*e*).

Further south there is a wide oceanic connection with the Indian Ocean between New Zealand, Australia and Antarctica, and a much narrower gap, Drake Passage, between Tierra del Fuego and Grahamland, which leads into the Scotia Sea of the South Atlantic. The oceanic crust of both connecting regions was generated essentially during the Cenozoic.

Detailed mapping of the magnetic anomaly and fracture zone patterns of the Pacific crust is far from complete. The information published so far is summarized in figures 4, 6*f* and 10*e*. To this can be added the preliminary results of Legs 5–9, 16–20, 28, 29 of the Deep Sea Drilling Project. There is, however, sufficient information to test the geometric requirements of reconstructions of this ocean from the late Jurassic onward, which assume a globe of constant modern dimensions.

In all reconstructions of Pangaea made on such a constant dimensions globe (see, for example, Carey 1958; Dietz & Holden 1970; Robinson 1971; Smith *et al.* 1973; and figure 1 herein), the area of the Pacific Ocean is increased essentially by the sum of the areas of the Atlantic and Indian Oceans, less that of the 'Tethyan' and 'Palaearctic' oceans. This is a geometric requirement for the late Triassic to Middle Jurassic before the start of ocean floor spreading in the North Atlantic. This early Mesozoic Pacific would possess a crust generated during the Triassic and Palaeozoic at least. The Mesozoic and Cenozoic history would, therefore, be one of east–west and north–south contraction of the oceanic area to the size of the modern Pacific Ocean, the subduction of all pre-Mesozoic crust together with any generated up to about the Kimmeridgian Stage of the Upper Jurassic (the earliest crust that has survived), and the subduction of a substantial quantity of oceanic crust generated from the Kimmeridgian to the Tertiary. Superficially, this burden of subduction would not appear to present any problem because of the presence of subduction zones throughout the Mesozoic and Cenozoic at or near the margins of the Pacific. However, there are in fact major problems in the development of the ocean during the Mesozoic and Cenozoic if the constant dimensions hypothesis is adhered to. One finds that the Pacific has grown in area, particularly in the late Cretaceous and Cenozoic, whereas the constant dimensions hypothesis requires contraction of area. This is particularly apparent in the South Pacific (figures 10*a*–*e*).

In the North Pacific, the eastern oceanic margins have been progressively overridden by the North American continent as it has been displaced westward and rotated since the early Upper Jurassic commencement of ocean floor spreading in the southern North Atlantic (see, for example, Coney 1971). The apparent migration, relatively eastward, of the North Pacific spreading axis has proceeded so far that it has been largely overridden and dislocated by the North American Pacific margin (Larson & Chase 1972, Figure 14, and figures 4 and 6*f* herein). The southwestward movement of the Alaska–Bering Sea–Aleutian Arc to truncate the spreading pattern in the region of the Great Magnetic Bight in the northern North Pacific, and to bury the spreading axis, has been described by Jones (1971). This movement can be correlated with the displacement of the Arctic sialic regions by the essentially Tertiary ocean floor spreading in the two basins of the Arctic Ocean (§3(*a*), p. 234). Uyeda & Ben Avraham (1972) have suggested that marginal ocean basins such as the Bering Sea might be formed by the overriding of the spreading axis by the edge of a continent. This would cause the splitting-off of the orogenic margin to form an island arc system, such as the Aleutian Islands, backed by the development of a marginal basin, like the Bering Sea, in response to continued spreading. An earlier stage still might be represented by Baja California which is separating from the American margin in response to the Gulf of California spreading region (figure 4).

The reconstructions given in figures 6, 12, 14, 16 and 18 show the North Pacific as not much smaller during the Mesozoic and Cenozoic than today. The relative movements mentioned above could apply, therefore, either to an expanding or to a constant dimensions Earth. However, even here some significant results emerge when one studies the development of the late Jurassic–early Lower Cretaceous spreading regions in the western North Pacific and their displacement with the rest of the Pacific Ocean floor during the late Mesozoic and Cenozoic.

Larson & Chase (1972) and Larson & Pitman (1972) have described the late Jurassic and Lower Cretaceous spreading regions of the Japanese, Hawaiian and Phoenix plates (figure 4). Larson & Chase produce a series of reconstructions for the ocean floor spreading history of the Pacific at about 120, 100 and 80 Ma B.P. They assume an Earth of constant modern diameter during this period, although perhaps not without question. By comparing the shape of the magnetic wave forms of the Phoenix plate with those generated artificially for given latitudes of the Earth's current magnetic field, they conclude that the Phoenix plate was generated by ocean floor spreading some 40° south of its current latitude. They infer, therefore, that the Pacific Ocean floor is being displaced northward and northwestward to be subducted at the North American–Aleutian–Kurile–Japan–Marianas trench system in response to spreading in the South Pacific. This view is supported by other workers using different criteria (see, for example, Winterer 1973). In the North Pacific subduction has indeed occurred, due to the displacement of the older Pacific spreading region by the major generation of oceanic crust from the Upper Cretaceous to the present day particularly in the South Pacific (figures 4 and 10*e*).

The Japanese, Hawaiian and Phoenix plates were generated during the Upper Jurassic and Lower Cretaceous. Together, they imply a north–south elongation of the Pacific region during the period when a constant dimensions Earth would require the Pacific to undergo north-to-south shortening in response to the contraction of the Tethyan Ocean and convergence of Laurasia and Gondwanaland. It is unlikely that active north–south elongation of the Pacific spreading region should occur simultaneously at the same latitudes as north–south contraction of the Tethyan Ocean. Moreover, this assumes that no crustal expression of the ancient simatic floor of the Tethyan Ocean ever extended into the Pacific, which is also unlikely, for there is no evidence of a former north to south running transform fault separating these two areas of oceanic crust during the Mesozoic. The break-up of Pangaea suggested by Smith *et al.* (1973), requires that any such eastward extension of this ancient Tethyan crust into the Pacific would have to be subducted in the actual region of north–south elongation. The requirements of the constant dimensions hypothesis are already becoming impossible to meet, but if one also considers that the subsequent northward displacement of the Japanese, Hawaiian and Phoenix plates to reach their current positions required by the hypothesis would be *across* any Pacific extension of a Tethyan subduction zone, the problems become insuperable.

In addition, the ocean floor spreading south of 30° S latitude in the Pacific during the late Cretaceous and Cenozoic, indicates that major east–west expansion and north–south extension of area occurred during this period which is not compensated for by subduction. This expansion of oceanic crustal area coincided with similar west–east expansion and north–south extension in the South Atlantic and Indian Ocean (figures 10*c*, *d*, *e*). Together, this indicates a greater rate of expansion of the globe as a whole in the Earth's southern hemisphere during the Upper Cretaceous and Cenozoic (compare figures 6 and 10).

(*a*)

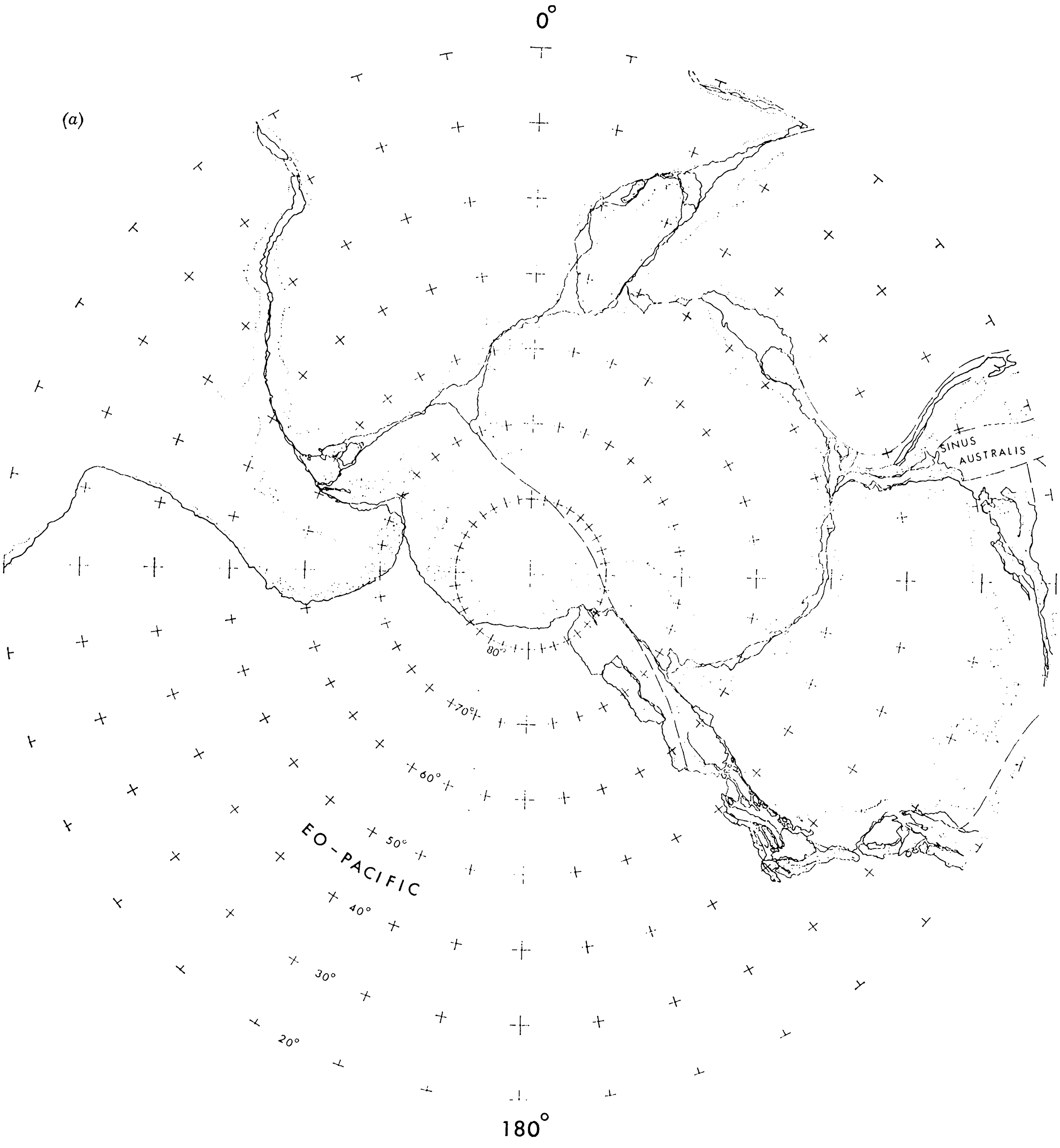


FIGURE 10. Five stages in the development of the 'Southern Ocean' and the break-up of Gondwanaland during the Mesozoic and Cenozoic, projected from an expanding globe. Zenithal Equidistant projection. Epicontinental seas and land areas present at each period of time are omitted except in figure 10*e*. Legend as in figures 2–4.

FIGURE 10*a*. The southern hemisphere north to 20° S latitude at the Pangaea stage of continental displacement 180 Ma B.P. Projection centred on the South geographic pole constructed for that time. Diameter of the Earth is 80% of current mean value.

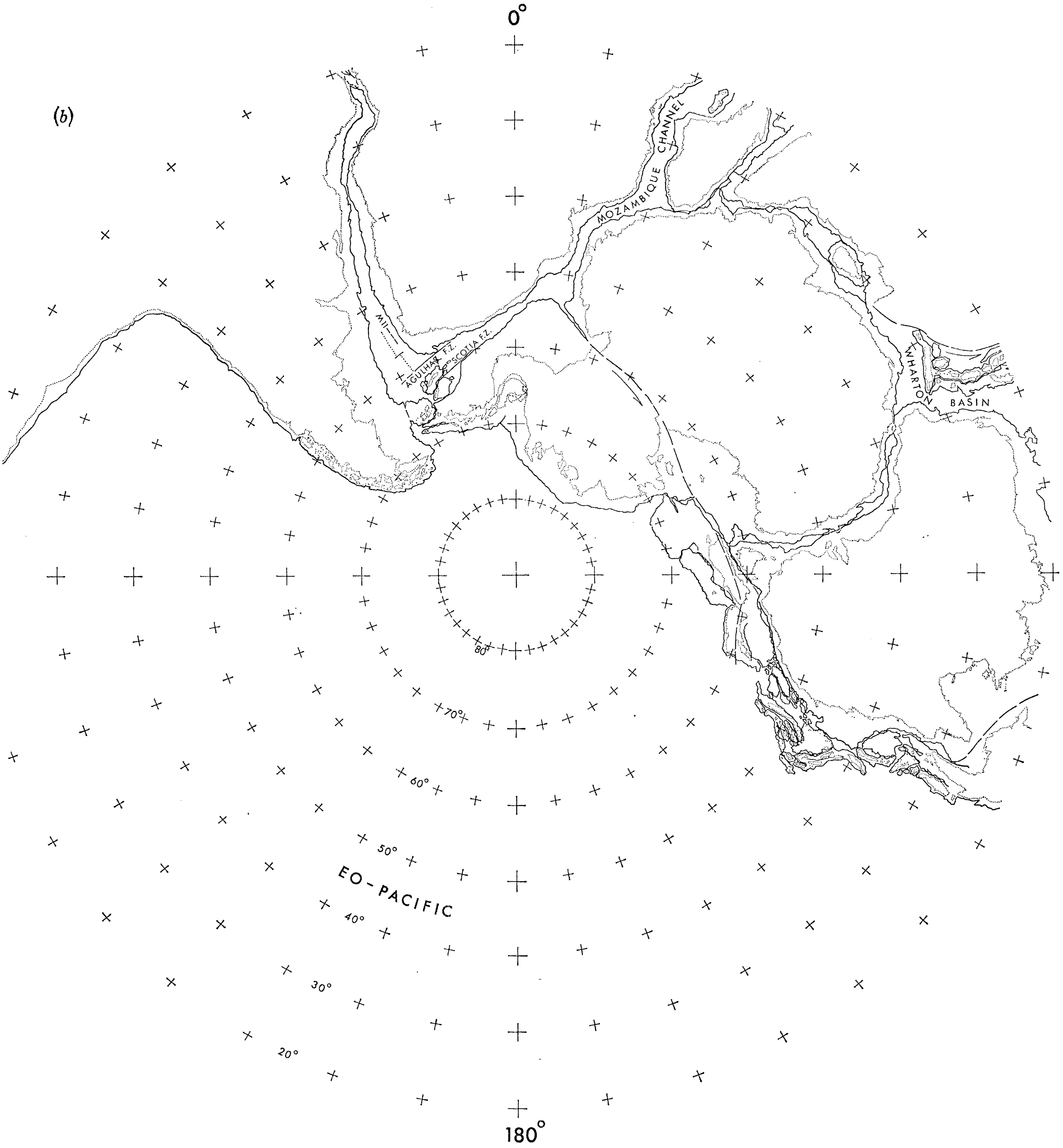


Figure 10*b*. The southern hemisphere north to 20° S latitude in the Lower Cretaceous (Hauterivian) 120 Ma B.P. Projection centred on the South geographic pole constructed for that time. Diameter of the Earth is approximately 87 % of current mean value.

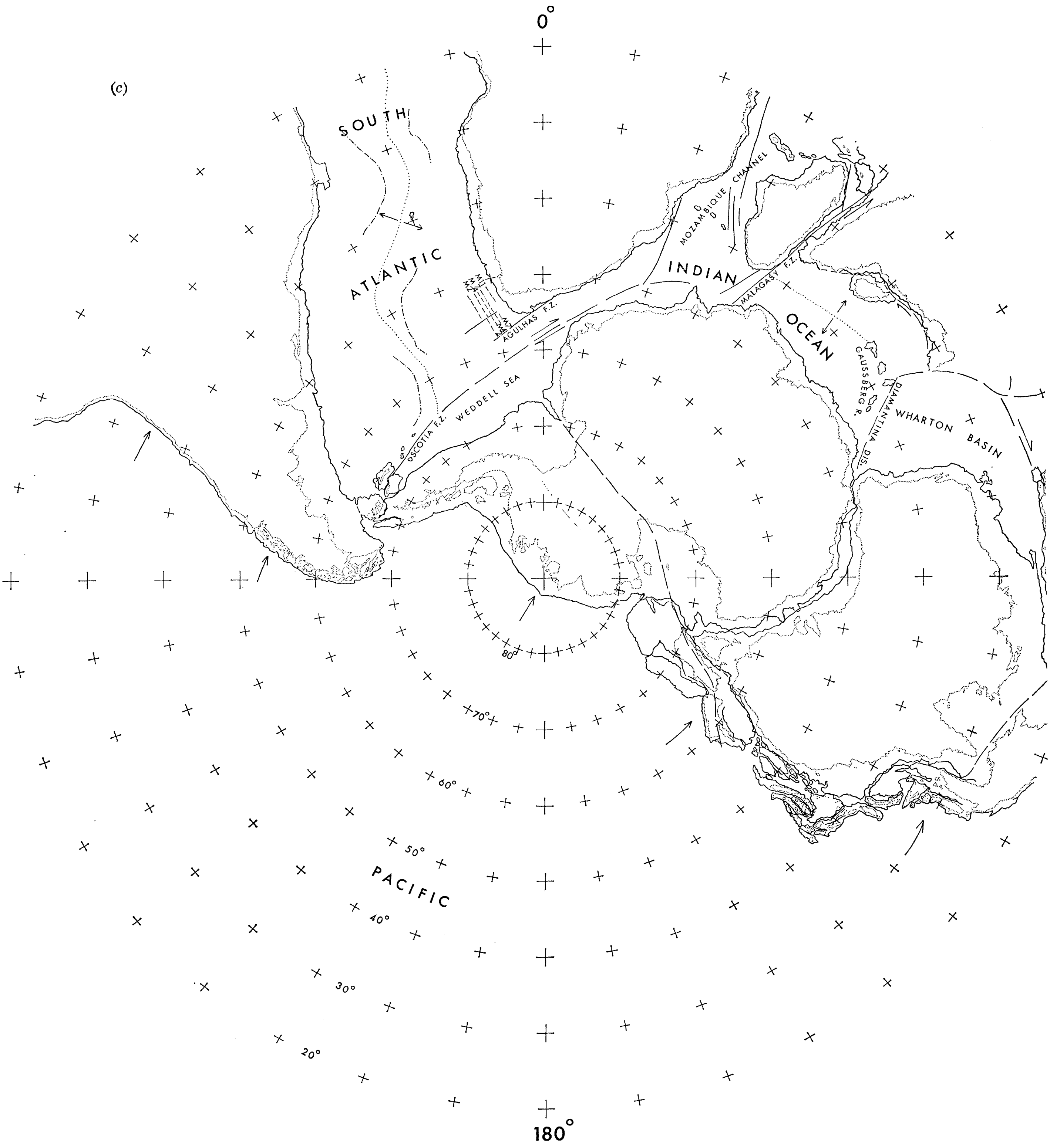


FIGURE 10c. The southern hemisphere north to 20° S latitude in the middle Upper Cretaceous (Turonian) 90 Ma B.P. Projection centred on the South geographic pole constructed for that time. Diameter of the Earth is 90% of current mean value.

Re-examination of the known ocean floor spreading patterns of the Pacific Ocean in terms of the global expansion advocated here permits certain observations (figures 10*a*–*e*). Expansion of the Earth particularly in the southern hemisphere during the late Cretaceous and Cenozoic, but with the insertion of new crust elsewhere to retain its shape as a sphere of rotation, would involve a southward shift of both the geographic and magnetic equators. If the Phoenix Plate is relocated according to the magnetic inclination determined by Larson & Chase (1972) on a globe 86% of modern diameter, as represented in figure 14, the east trending spreading axis from which the Phoenix plate was generated coincides approximately with the position required for a spreading axis which would express the north–south extension of the Central American region between the Middle Jurassic and the Coniacian (Upper Cretaceous) (figures 7*a*–*e*, §3(*b*)(ii), p. 245). The North Pacific ocean floor has, therefore, migrated northward since the formation of the Phoenix, Hawaiian and Japanese plates. However, upon this actual displacement has to be superimposed the effect of a southward migration of the magnetic equator as well as the geographic equator in response to the expansion of the Earth. This indicates that an apparent northward migration of previously generated simatic crust has to be taken into account when comparisons are made of the remanent inclination of the dykes with the field inclination at the present day.

The development of the continental marginal subduction zones flanked by cordilleran fold belts is intimately connected with the ocean floor spreading history of the Pacific. There is evidence for the presence of continental marginal fold belts, which might have flanked earlier Pacific subduction zones, from well within the Palaeozoic (see, for example, Wheeler *et al.* 1974; Rutland & Walter 1974; Biq 1974; Matsumoto & Kimura 1974; Rutland 1974). The cordilleran fold belt of South and North America has remained more or less intact to the present day, although the north–south elongation of the Pacific and the consequent development of Central America has broken a formerly continuous system. The marginal fold belt flanking the western Pacific margin has been fragmented, however, essentially by the southward displacement of the northeast Asia during the late Cretaceous and Tertiary (figures 6*c*–*f*), and by the southward displacement of the combined Australian–Antarctic continent from the late Jurassic to the early Tertiary (figures 9*a*–*d*). Further fragmentation occurred with the subsequent northward displacement of Australasia and southward displacement of Antarctica during the Cenozoic (figures 9*d*–*f*). Today, this western Pacific marginal fold belt is represented by the Antarctandes of West Antarctica, New Zealand and New Guinea and the sialic fragments between them, the Philippines, Japanese Islands, Anadyr and Kamchatka. Most of this fragmented marginal fold belt has become decoupled from the relatively undeformed Australian and Asiatic continental margins seen today, by the development of marginal oceanic basins such as the Japanese, Philippine, South China, Coral and Tasman Seas (see, for example, Ben Avraham, Bowin & Segawa 1972; Parke *et al.* 1971; Burns, Andrews *et al.* 1973; Hayes & Ringis 1973).

The ocean floor spreading data from the South Pacific shows the presence of two distinct spreading patterns (figures 4 and 10*e*). An earlier spreading region which extends south to about 50° S latitude started to form before the Upper Cretaceous anomaly 32 dykes were generated, but ceased after the generation of the dykes of anomaly 5 (late Miocene). A substantial portion of the eastern part of this region has been subducted at the South American margin which cuts obliquely across the pattern. There is also evidence of a possible subduction zone at the former Pacific cordilleran margin of Australia, now represented by island arc fragments such as New Zealand (see Grindley 1974), which has a history extending back to within the Palaeozoic. This older spreading region probably represents, therefore, the crustal output from an old axis which has been active since at least the beginning of the Mesozoic. A spreading axis has subsequently developed along the same axial trend from a triple junction close to the Chile fracture zone (figure 10*e*).

Like the Upper Cretaceous to Recent spreading region in the North Pacific, the older spreading region of the South Pacific is also partially overridden. The displacement westward and clockwise rotation of South America in response to the development of the South Atlantic is reflected in the southeast Pacific by the oblique truncation of the magnetic anomaly pattern at its margin (figures 4 and 10*e*). South America did not start its displacement until some 30 Ma after the North American continent had begun to be displaced westward by the inception of spreading in the North Atlantic. Whereas North America has partly overridden the generating axis, South America has not yet reached this older axis. If the generating axis in the North Pacific and South Pacific once formed a continuous system, it seems that once it had developed, it remained more or less fixed in position within the asthenosphere, generating new oceanic crust throughout its long history. If this suggestion proves to be correct, it has important implications for the Carnegie Ridge system in the east Central Pacific which runs east–west from northern South America. This ridge is a spreading axis analogous in direction and position to that of the late Jurassic–early Cretaceous Phoenix axis.

This older spreading region in the South Pacific is cut by a spherical triangular spreading region described by Herron (1971, 1972) and Christoffel & Falconer (1972), which started to form in the southern South Pacific in the late Cretaceous from a generating axis between New Zealand and Antarctica (figures 4 and 10*e*). This generating axis penetrated northward during the Tertiary to reach the Carnegie Ridge in the Neogene, and it clearly cuts through the older pattern north of 50° S latitude. The base of this spherical triangle is marked by the Macquarie Ridge, the transform fault which indicates the displacement path of New Zealand away from Antarctica and Australia. Since this ridge also forms the base of the spherical triangular region of Eocene to present day spreading in the Indian Ocean (§3(*d*), p. 266), the spherical figure produced approximates to a lune, however much cut by transform faults it might be. This lune of essentially Cenozoic oceanic crust has developed where no subduction zones have been active to compensate for its insertion into the older crust of the southern hemisphere.

With expansion at the rate envisaged here, the development of the western Pacific marginal basins becomes clear. The southward migration of the combined Antarctic–Australian continent would soon lead to tension at the orogenic margin. A spreading axis developed between New Zealand and Antarctica during the Upper Cretaceous as a consequence of this tension (Christoffel & Ross 1970; Christoffel & Falconer 1972). The western end of this axis penetrated northward in the late Cretaceous to split New Zealand and the other fragments of the former Australian marginal cordilleran fold belt away from the Australian hinterland to form the Tasman Sea by the Palaeocene (Hayes & Ringis 1973), and part of the Coral Sea (figure 10*d*). The generating axis changed direction as tension caused Australia to split away from Antarctica from the Eocene onward. Spreading continued in the Coral Sea and the North and South Fiji Basins during the Cenozoic (Burns, Andrews *et al.* 1973; Sclater, Hawkins, Mammericks & Chase 1972; Milsom 1970), and this has probably in turn contributed to the development of the Tonga–Kermadec Trench as a subduction zone from its apparent former rôle of a major wrench fault (figure 10*d*). The displacement of the orogenic fragments away from the continents

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
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(d)

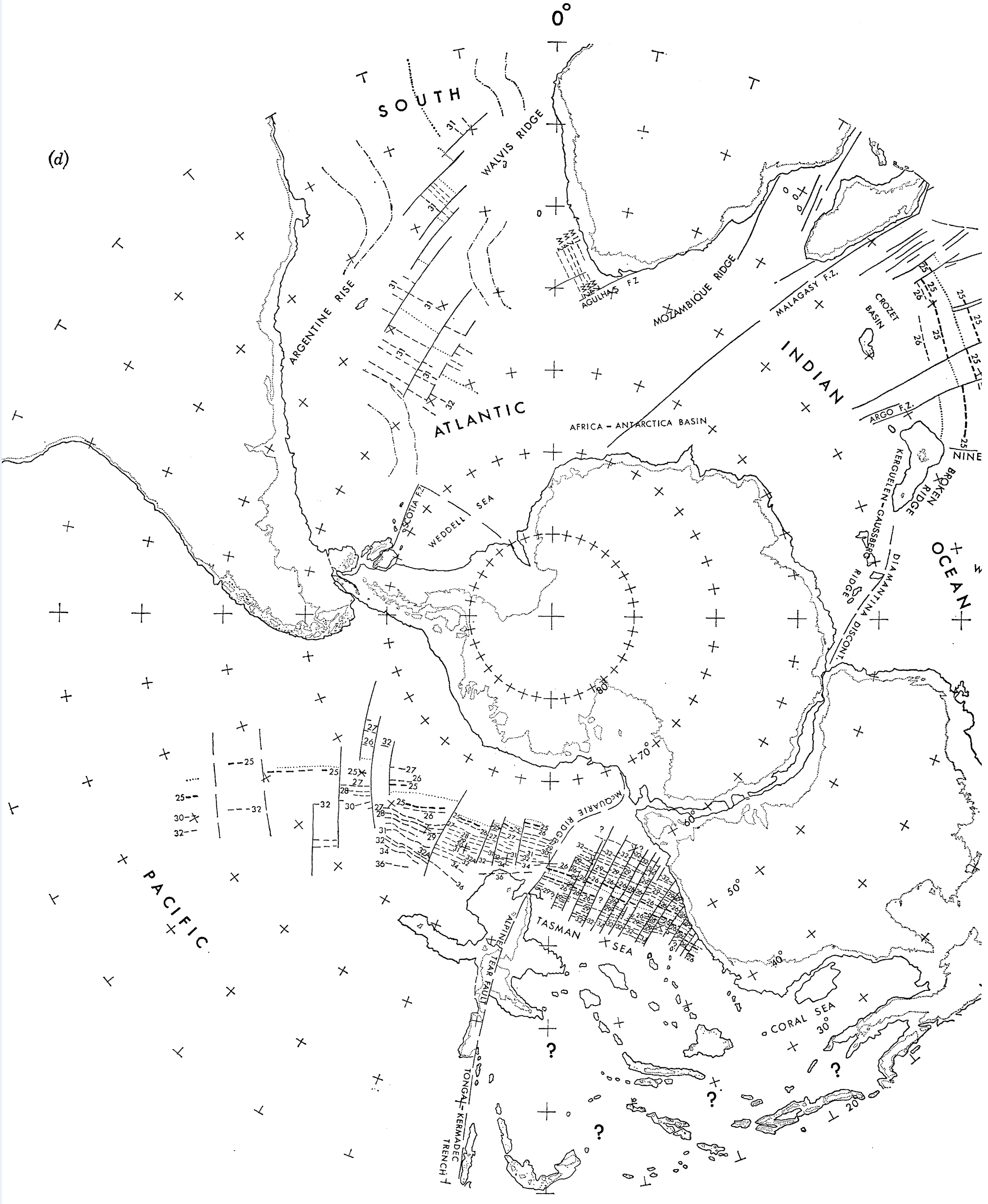

FIGURE 10*d*. The southern hemisphere north to 20° S latitude in the early Tertiary (Palaeocene) 60 Ma B. Projection centred on the South geographic pole constructed for that time. Diameter of the Earth is approximately 93% of current mean value.

(*Facing p.* 276)

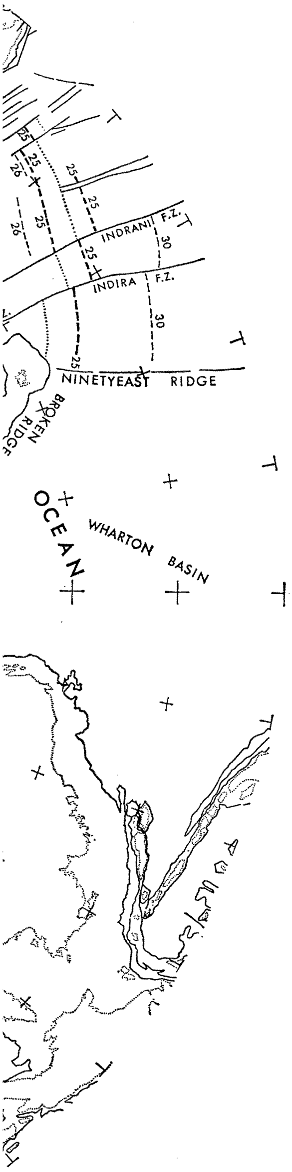

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FIGURE 10*e*. Geographic and ocean floor spreading map of the modern southern hemisphe north to 20° S latitude.

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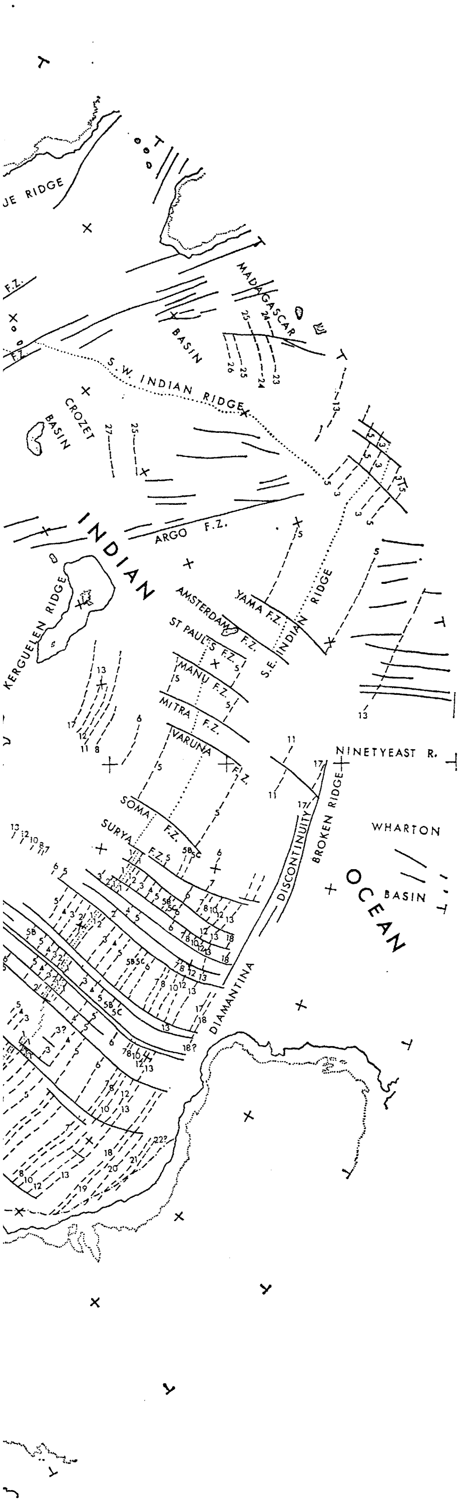

hemisphere

they originally bordered would produce marginal basins twice the width of actual migration when generation of new oceanic crust occurs symmetrically each side of the generating axis.

The southward movement of the combined Australian–Antarctic continent during the Upper Cretaceous and early Tertiary is also responsible for the development of the South China and Philippine Seas during this period. These marginal basins have formed in response to the tensional decoupling of the former Asian orogenic margin (figures 9*c–f*), and are analogous to the Tasman Sea. The origin of the Seas of Japan and Okhotsk is probably due, however, to the southward displacement of northeast Siberia in response to tectonic movements and, later, ocean floor spreading in the Arctic region (figures 6*c–f*).

From the early Eocene onward, Australasia was displaced northward relative to Antarctica (figures 9*d–f*, 10*e*), but the actual distance Australia was displaced northward is approximately half that of the total width of the spreading zone now separating these two continents. Figures 10 shows that Antarctica has formed a continental cap over the southern geographic pole and has been progressively displaced southward by ocean floor spreading that developed around it and has continued to the present day to form the 'Southern Ocean'. The northward movement of Australasia on Indonesia, the Philippines and associated marginal basins is shown in figures 9*e–f*. It has led to the development of the Philippine Trench, and the bordering trench systems off New Guinea (see, for example, Milsom 1974).

4. SUMMARY AND CONCLUSIONS

A case for global expansion at least during the last 200 Ma has been presented here. The spherical geometry given by: (i) continental geological matches, (ii) ocean floor spreading patterns and the chronological sequence of the development of spreading regions, and (iii) the subduction and orogenic history, indicates that the Earth has increased its diameter by 20% of its current mean value since the late Triassic–Lower Jurassic. In the early Mesozoic, Pangaea formed essentially an unbroken sialic region which occupied a little over half the Earth's surface area. The remaining area consisted of older Pacific oceanic crust, which had probably started to form in the early Palaeozoic, and by the Mesozoic was fringed by subduction zones flanked by cordilleran fold-belts at the continental margins. The four stages shown in figures 11–18 summarize the sequence of movements which have led to the development of the Earth's modern oceanic regions since the late Triassic–early Jurassic, and provide outline maps for palaeobiogeographical analyses.

The picture of the development and movement of the Earth's crust during the last 180–200 Ma which the writer has attempted to present here, permits a brief reflection on a possible mechanism which would permit both its expansion through time and the growth of the crust it now has. If one could stand away in space from a much scaled-down Earth, and could prod it sharply with one's finger, it would pass easily through the thin 'solid' crust into the inner viscous and differentiating layers penetrating into the core which is probably in a plasma state. The finger concerned would sustain a severe burn! The Earth's crust is seismically highly mobile, even within the minute scale of our own lifetime, let alone the 200 Ma examined in this paper. A planetary body with the structure of the Earth, no matter what its original mass might have been, would be volumetrically susceptible to any changes there might be in the value of G through time. The physics advocated by Hoyle (e.g. 1972) would help to explain expansion of the Earth at the rate indicated by the development of the oceanic crust seen today.

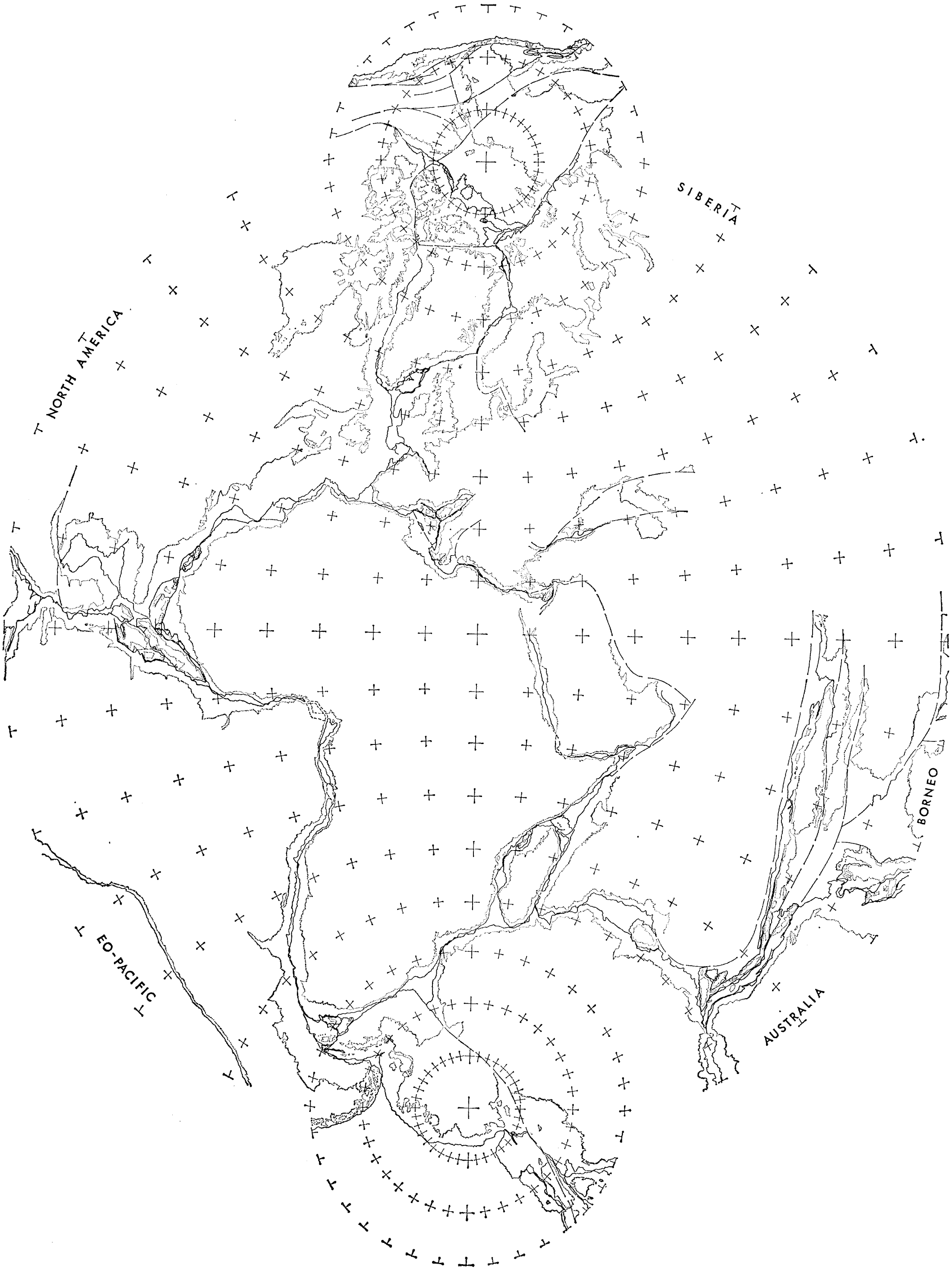

Figure 11. Outline base map of the Pangaean Hemisphere 180 Ma B.P. Trizenithal projection centred on North and South geographic poles and the intersection of 0° latitude and longitude constructed for that time. Diameter of the Earth is 80% of current mean value. Positions of sialic continents are shown represented by their modern 1000 m isobath and coast line for ease of recognition. More detailed maps of individual regions are given in figures 6*a*, 7*a*, 8*a*, 9*a* and 10*a*.

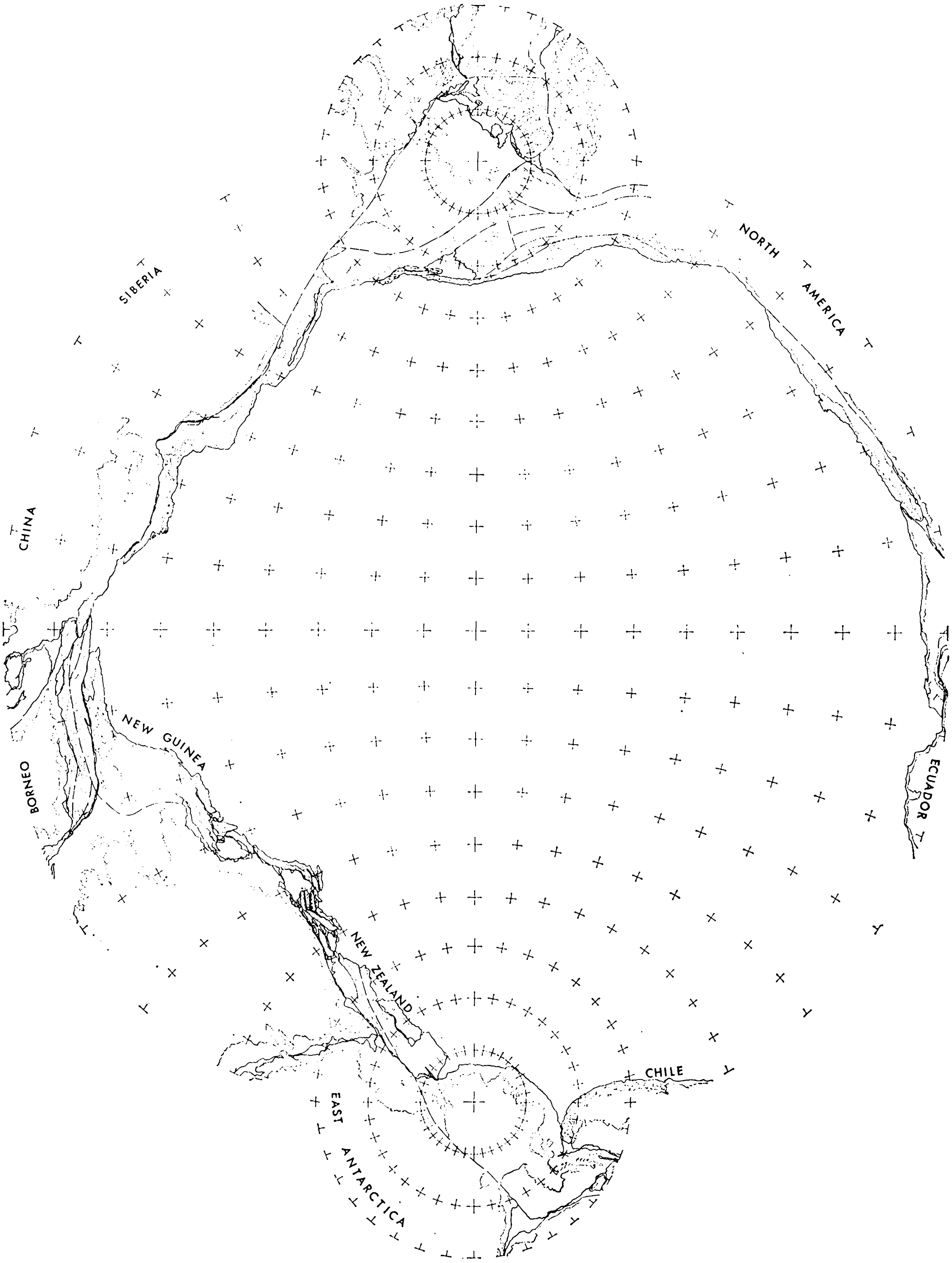

Figure 12. Outline base map of the Pacific Hemisphere 180 Ma b.p. Trizenithal projection centred on the North and South geographic poles, and the intersection of the 0° latitude and 180° longitude constructed for that time. Diameter of the Earth is 80% of current mean value. Positions of continental regions are shown represented by their modern 1000 m isobath and coast line for ease of recognition. More detailed maps of individual areas are given in figures 6*a*, 7*a*, 9*a* and 10*a*.

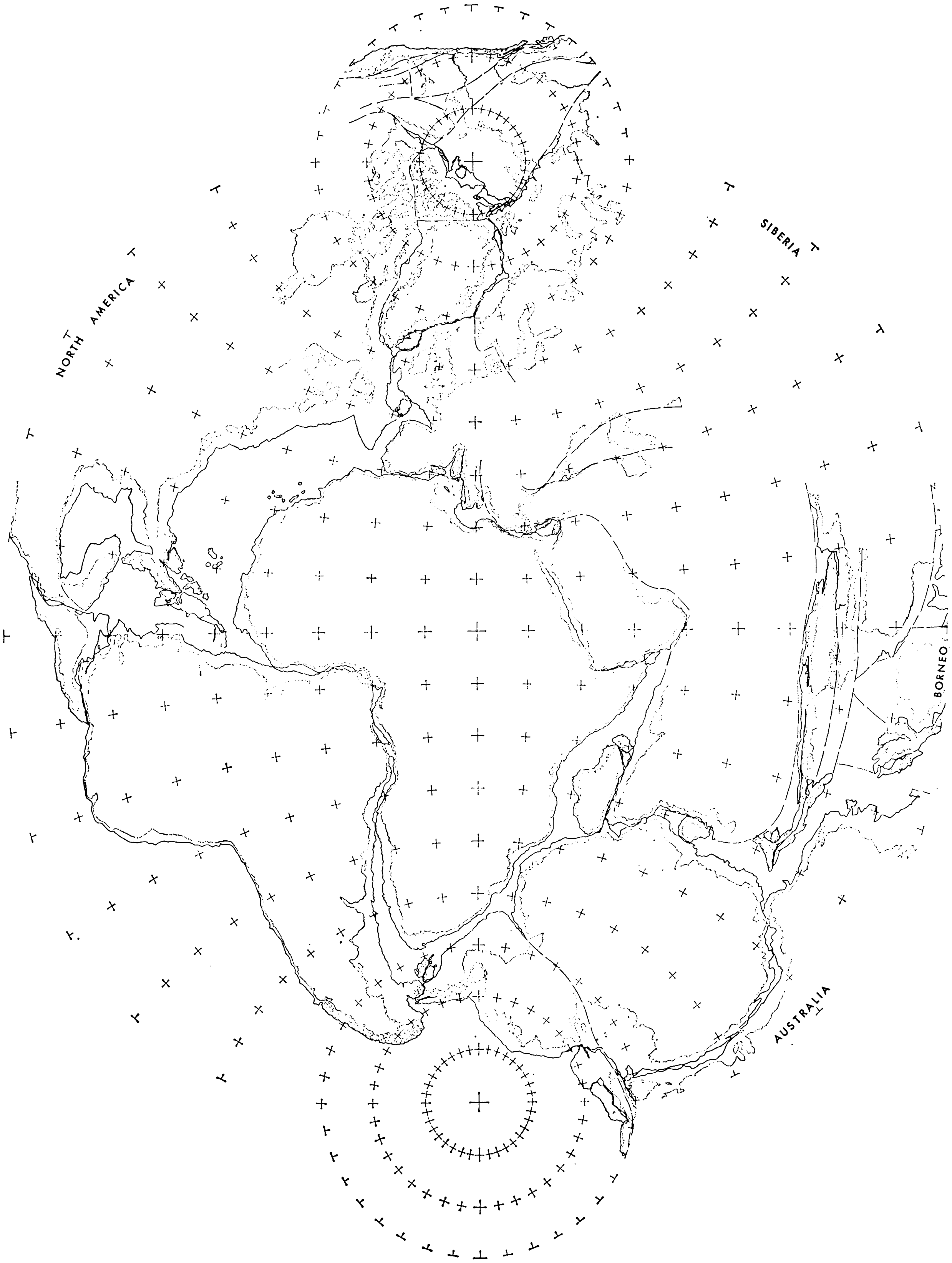

FIGURE 13. Outline base map of the Pangaea–Atlantic Hemisphere in the Lower Cretaceous (Hauterivian) 120 Ma B.P. Trizenithal projection centred on the North and South geographic poles and the intersection of the 0° latitude and longitude constructed for that time. Diameter of the Earth is approximately 87 % of current mean value. Positions of continental regions are shown represented by their modern 1000 m isobath and coast line for ease of recognition. More detailed maps of individual areas are given in figures 6*b*, 7*c*, 8*b*, 9*b* and 10*b*.

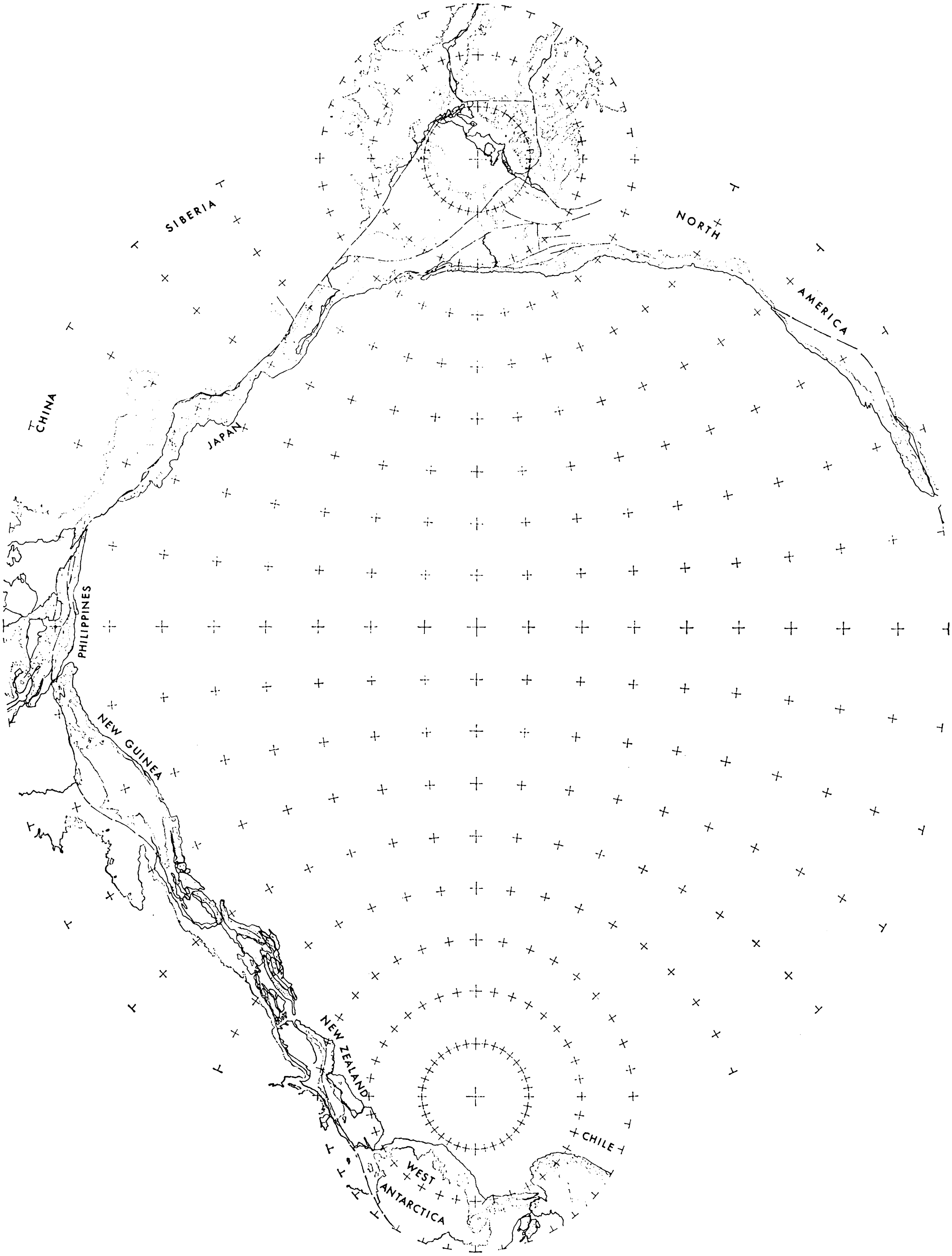

FIGURE 14. Outline base map of the Pacific Hemisphere in the Lower Cretaceous (Hauterivian) 120 Ma B.P. Trizenithal projection centred on North and South geographic poles and the intersection of the 0° latitude and 180° longitude constructed for that period. Diameter of the Earth is approximately 87 % of current mean value. Positions of continental regions are shown represented by their modern 1000 m isobath and coast line for ease of recognition. More detailed maps of individual areas are given in figures 6*b*, 7*c*, 9*b* and 10*b*.

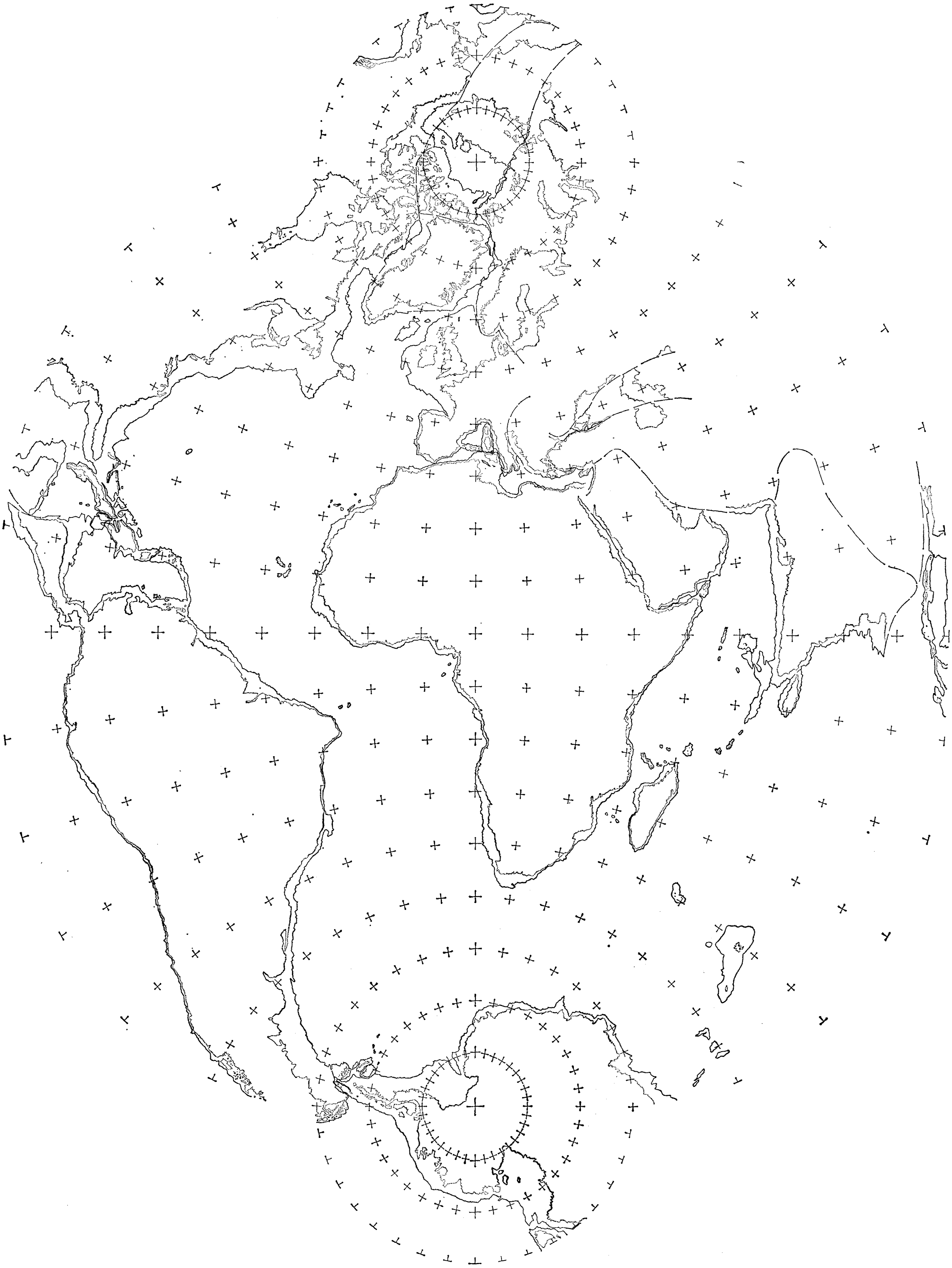

FIGURE 15. Outline base map of the Atlantic Hemisphere in the early Tertiary (Palaeocene) 60 Ma B.P. Tri-zenithal projection centred on North and South geographic poles and the intersection of the 0° latitude and longitude constructed for that time. Diameter of the Earth is approximately 93 % of current mean value. Positions of continental regions are shown represented by their modern 1000 m isobath and coast line for ease of recognition. More detailed maps of individual areas are given in figures 6*d*, 7*d*, 8*c*, 9*d* and 10*d*.

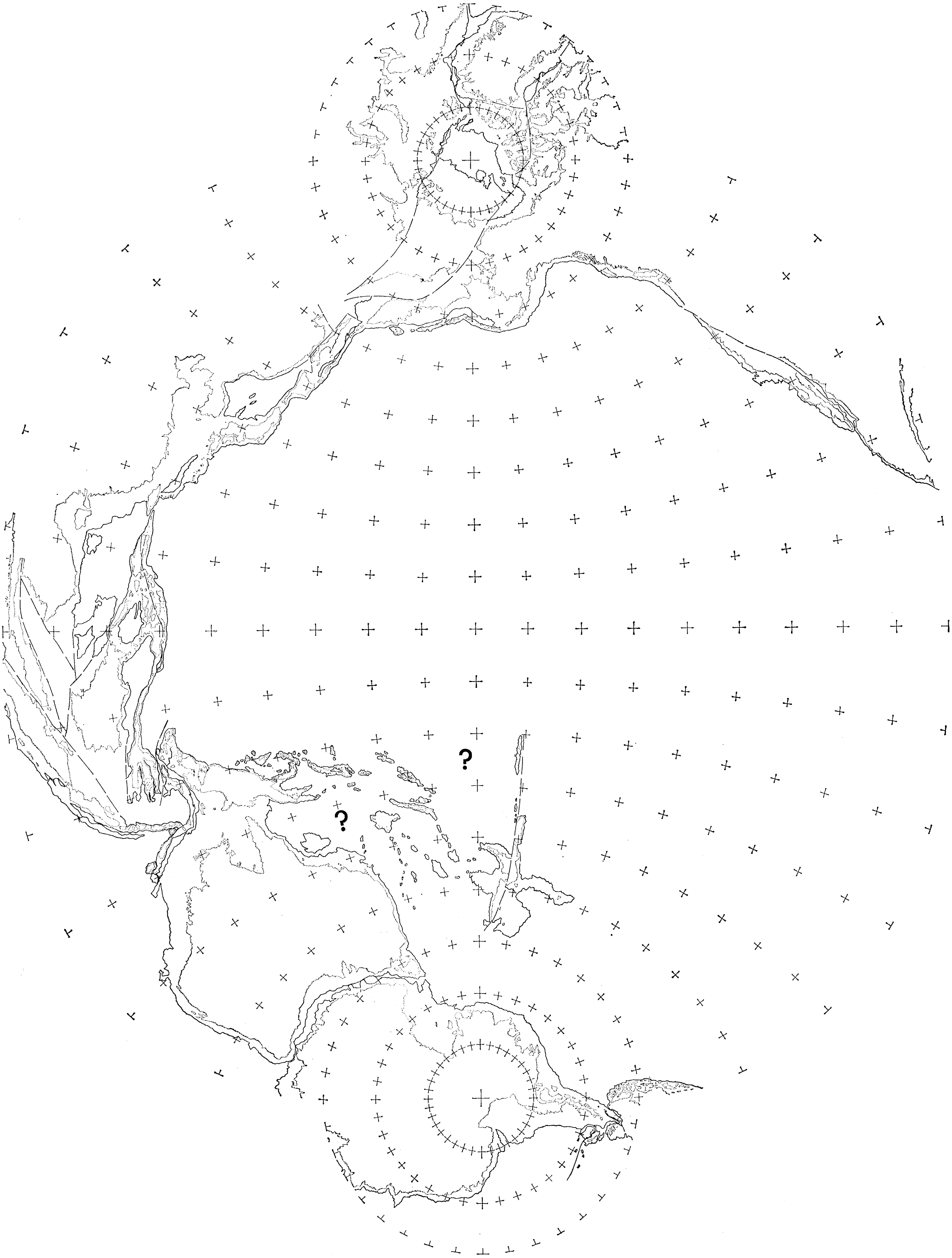

Figure 16. Outline base map of the Pacific Hemisphere in the early Tertiary (Palaeocene) 60 Ma B.P. Trizenithal projection centred on the North and South geographic poles and the intersection of the 0° latitude and 180° longitude constructed for that time. Diameter of the Earth is approximately 93 % of current mean value. Positions of continental regions are shown represented by their modern 1000 m isobath and coast line for ease of recognition. It is possible that the Coral Sea and Fiji Basin did not fully develop until some period between the Eocene and the Pliocene. More detailed maps of individual areas are given in figures 6*d*, 7*d*, 9*d* and 10*d*.

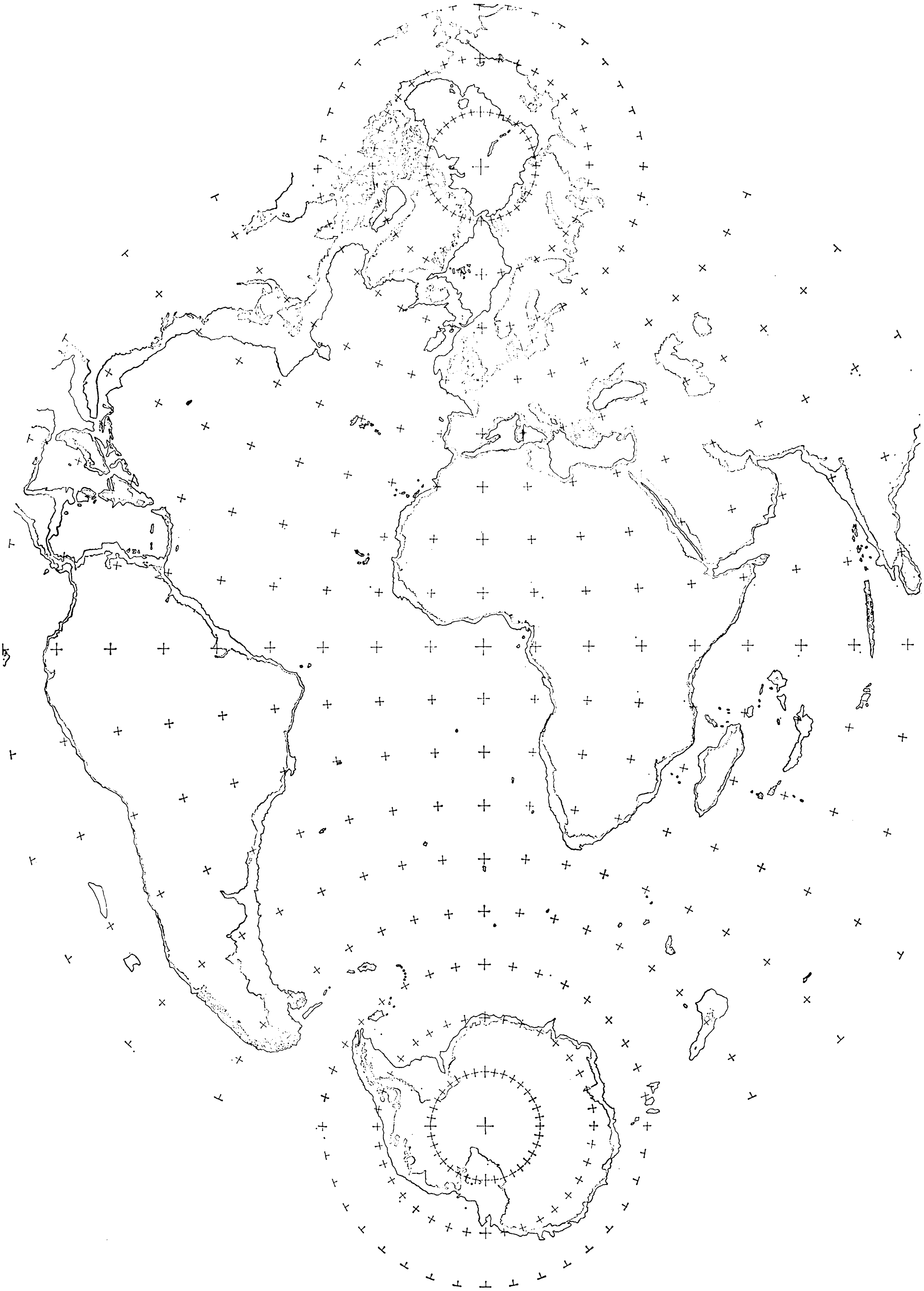

FIGURE 17. Atlantic Hemisphere at the present day. Trizenithal projection centred on the North and South geographic poles and the intersection of the 0° latitude and longitude. More detailed maps of individual areas are given in figures 2, 3, 6*f*, 7*e*, 8*e*, 9*f* and 10*e*.

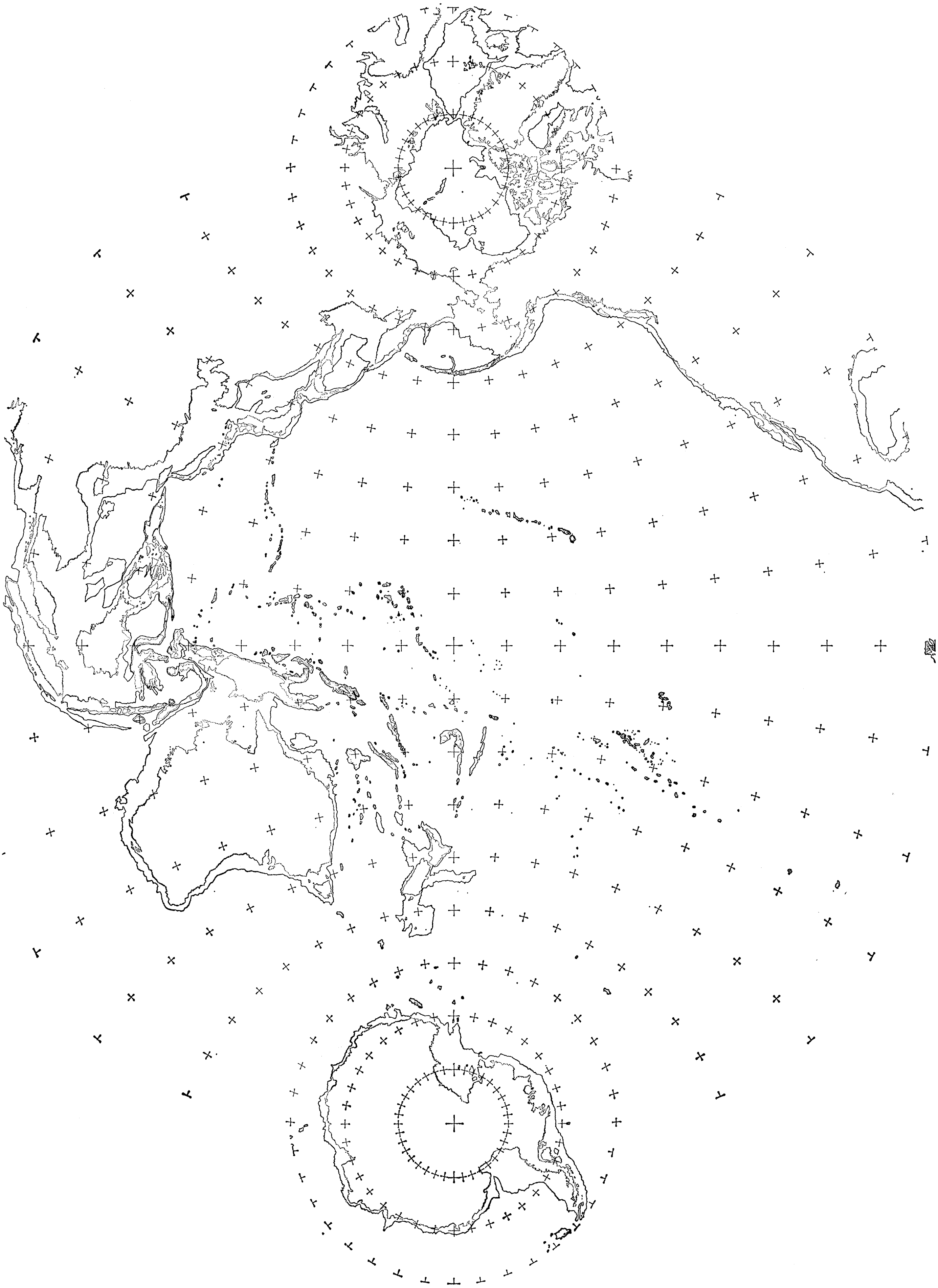

FIGURE 18. Pacific Hemisphere at the present day. Trizenithal projection centred on the North and South geographic poles and the intersection of the 0° latitude and 180° longitude. More detailed maps of individual areas are given in figures 3, 4, 6*f*, 7*e*, 9*f* and 10*e*.

If expansion of the Universe has occurred it would affect progressively the distance between the Earth and the Sun. The distance that the Earth travels along its orbital track round the Sun would be progressively shorter as one goes back through time. However, one complete orbit would still produce a 'year', although that year would be much shorter in time relative to the present year. The velocity and spin rate of the Earth would also become progressively faster as the orbital distance decreased back through time and thus produce a shorter 'day' relative to our modern day. Changes in these functions through time would produce changes in the value of the Earth's Newtonian gravity, and perhaps significant changes in the atmospheric, terrestrial and perhaps marine environments in which various forms of life have developed, flourished and become extinct.

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REFERENCES

Abdel-Gawad, M. 1971 *Bull. geol. Soc. Am.* **82**, 1235–1250.
Arden, D. D., Jnr 1969 *Trans. Gulf Cst Ass. geol. Socs.* **19**, 295–309.
Arkell, W. J. 1956 *Jurassic geology of the World.* Edinburgh, London: Oliver & Boyd.
Asmus, H. E. & Ponte, F. C. 1973 The Brazilian marginal basins. In *The ocean basins and margins.* 1. *The South Atlantic* (ed. A. E. M. Nairn & F. G. Stehli), pp. 87–133. New York, London: Plenum Press.
Atlasov, I. P. *et al.* 1969 *Tectonic map of the Arctic and Subarctic* (in Russian). Moskva: Ministry of Geology. (1:5000000 in 6 sheets.)
Atwater, T. & Menard, H. W. 1970 *Earth planet. Sci. Lett.* **7**, 445–450.
Auden, J. B. 1974 Afghanistan-West Pakistan. In *Mesozoic-Cenozoic orogenic belts*, pp. 235–253. London: Geological Society.
Audley-Charles, M. G., Carter, D. J. & Milsom, J. S. 1972 *Nature, Phys. Sci.* **239**, 35–39.
Auzende, J. M., Olivet, J.-L. & Bonnin, J. 1970 *C. r. hebd. séanc. Acad. Sci. Paris* D **271**, 1063–1066, pls **I**, **II**.
Auzende, J. M., Olivet, J.-L. & Bonnin, J. 1974 *Tectonophysics* **21**, 357–374.
Bader, R. G., Gerard, R. D., *et al.* 1970 *Initial Reports of the Deep Sea Drilling Project. Leg 4.* Washington: U.S. Government Printing Office.
Ball, M. M. & Harrison, C. G. A. 1969 *Trans. Gulf Cst Ass. geol. Socs.* **19**, 287–294.
Ball, M. M., Harrison, C. G. A., Supko, P. R., Bock, W. & Maloney, N. J. 1971 *Mem. geol. Soc. Am.* **130**, 1–33.
Ballard, R. D. & Uchupi, E. 1972 *Bull. geol. Soc. Am.* **83**, 2285–2301.
Barker, P. F. 1970 *Nature, Lond.* **228**, 1293–1296.
Barker, P. F. 1972*a* *Earth planet. Sci. Lett.* **15**, 123–132.
Barker, P. F. 1972*b* *Antarctic geology and geophysics* (ed. R. J. Adie), **B.1**, 17–26. Oslo: International Union of Geological Sciences.
Barnett, C. H. 1962 *Nature, Lond.* **195**, 447–448.
Belyi, V. F. 1973 *Mem. Am. Ass. Petrol. Geol.* **19**, 252–258.
Ben-Avraham, Z., Bowin, C. & Segawa, J. 1972 *Nature, Lond.* **240**, 453–455.
Bernoulli, D., Laubscher, H. P., Trümpy, R. & Wenk, E. 1974 *Central Alps and Jura Mountains* in *Mesozoic-Cenozoic orogenic belts*, pp. 85–108. London: Geological Society.
Besairie, H. & Collignon, M. 1971 *Ann. geol. Madagascar* **35**, 463 pp. 89 pls.
Biq, C. 1974 Taiwan. In *Mesozoic-Cenozoic orogenic belts*, pp. 501–511. London: Geological Society.
Birkenmajer, K. 1974 Carpathian Mountains. In *Mesozoic-Cenozoic orogenic belts*, pp. 127–157. London: Geological Society.
Blundell, D. J., Davey, F. J. & Graves, L. J. 1971 *J. geol. Soc.* **127**, 339–371.
Boccaletti, M., Elter, P. & Guazzone, G. 1971 *Nature, Phys. Sci.* **234**, 108–111.
Brinkman, R. 1972 *Bull. geol. Soc. Am.* **83**, 819–826.
Brunnschweiler, R. O. 1974 Indoburman Ranges. In *Mesozoic-Cenozoic orogenic belts*, pp. 279–299. London: Geological Society.
Bullard, E., Everett, J. E. & Gilbert Smith, A. 1965 *Phil. Trans. R. Soc. Lond.* A **258**, 41–51.
Burke, K., Dessauvageie, T. F. J. & Whiteman, A. J. 1971 *Nature, Phys. Sci.* **233**, 51–55.

Burns, R. E., Andrews, J. E., *et al.* 1973 *Initial Reports of the Deep Sea Drilling Project. Leg 21.* Washington D.C.: U.S. Government Printing Office.

Caire, A. 1974 Eastern Atlas. In *Mesozoic-Cenozoic orogenic belts*, pp. 47–59. London: Geological Society.

Caputo, M., Panza, G. F. & Postpischl, D. 1970 *J. geophys. Res.* **75**, 4919–4923.

Carey, S. W. 1955 *Pap. Proc. R. Soc. Tasm.* **89**, 255–288.

Carey, S. W. 1958 In *Continental Drift—A Symposium*, pp. 177–355 (reprinted 1959). Hobart: University of Tasmania.

Carey, S. W. 1970 *Search* **1**, 178–189.

Carey, S. W. 1975 *Earth Sci. Rev.* **11**, 105–143.

Choubert, B. 1969 *Bull. Bur. Rech. géol. miner.* (**2**) **IV**, 36–69 map.

Choubert, G. & Faure-Muret, A. 1974 *Moroccan Rif* in *Mesozoic-Cenozoic orogenic belts*, pp. 37–46. London: Geological Society.

Choudhuri, A. & Milner, M. W. 1971 *Nature, Lond.* **232**, 154–155.

Choukroune, P., Le Pichon, X., Seguret, M. & Sibuet, J.-C. 1973 *Earth planet Sci. Lett.* **18**, 109–118.

Christoffel, D. A. & Falconer, R. K. H. 1972 *Antarctic Res. Ser. Washington* **19**, 197–209.

Christoffel, D. A. & Ross, D. I. 1970 *Earth planet. Sci. Lett.* **8**, 125–130.

Comninakis, P. E. & Papazachos, B. C. 1972 *Bull. geol. Soc. Am.* **83**, 1093–1101.

Coney, P. J. 1971 *Nature, Lond.* **233**, 462–465.

Craddock, C., *et al.* 1969–70 *Geologic maps of Antarctica, Antarctic Map Folio Series* **12**. New York: American Geographical Society.

Creer, K. M. 1965 *Nature, Lond.* **205**, 539–544.

Demenitskaya, R. M. & Hunkins, K. L. 1970 In *The sea* (ed. A. E. Maxwell), 4 (ii), 223–249. New York, London: Wiley Interscience.

Desio, A. 1974 Karakorum Mountains. In *Mesozoic-Cenozoic orogenic belts*, pp. 255–266. London: Geological Society.

Dewey, J. F., Pitman, W. C., III, Ryan, W. B. F. & Bonnin, J. 1973 *Bull. geol. Soc. Am.* **84**, 3137–3180.

Dickson, G. O., Pitman, W. C., III & Heirtzler, J. R. 1968 *J. geophys. Res.* **73**, 2087–2100.

Dietz, R. S. & Holden, J. C. 1970 *J. geophys. Res.* **75**, 4939–4956.

Dietz, R. S. & Holden, J. C. 1971 *Nature, Lond.* **229**, 309–312.

Dietz, R. S. & Shumway, G. 1961 *Bull. geol. Soc. Am.* **72**, 1319–1330.

Dingle, R. V. 1972 *Nature, Phys. Sci.* **235**, 60.

Dingle, R. V. & Klinger, H. C. 1971 *Nature, Phys. Sci.* **232**, 37–38.

Du Toit, A. L. 1937 *Our wandering continents: an hypothesis of continental drifting.* Edinburgh, London: Oliver & Boyd.

Elliot, D. H. 1972 In *Antarctic geology and geophysics* (ed. R. J. Adie), **B1**, 849–858. Oslo: International Union of Geological Sciences.

Ewing, W. M., Worzel, J. L., *et al.* 1969 *Initial Reports of the Deep Sea Drilling Project. Leg 1.* Washington D.C.: U.S. Government Printing Office.

Falcon, N. L. 1974 Southern Iran: Zagros Mountains. In *Mesozoic-Cenozoic orogenic belts*, pp. 199–211. London: Geological Society.

Fisher, R. L., Bunce, E. T., *et al.* 1972 *GeoTimes* **17**(9), 17–21.

Fisher, R. L., Sclater, J. G. & McKenzie, D. P. 1971 *Bull. geol. Soc. Am.* **82**, 553–562.

Flores, G. 1970 *Trans. geol. Soc. S. Afr.* **73**, 1–16.

Freeland, G. L. & Dietz, R. S. 1971 *Nature, Lond.* **232**, 20–23.

Furon, R. 1960 *Géologie de l'Afrique*, 2nd ed. Paris: Payot.

Gansser, A. 1964 *Geology of the Himalayas.* London, New York: Wiley Interscience.

Gansser, A. 1974 Himalaya. In *Mesozoic-Cenozoic orogenic belts*, pp. 267–278. London: Geological Society.

Gass, I. G. 1968 *Nature, Lond.* **220**, 39–42.

Goddard, E. N., *et al.* 1965 *Geologic Map of North America.* Washington D.C.: U.S. Geological Survey (1:5000000 in 2 sheets).

Grant, A. C. 1972 *Can. J. Earth Sci.* **9**, 1394–1430.

Grant, N. K. 1972 *J. geophys. Res.* **77**, 3171–3173.

Green, A. G. 1972 *Nature, Phys. Sci.* **236**, 19–21, 32.

Griffiths, D. H. & Barker, P. F. 1972 In *Antarctic geology and geophysics* (ed. R. J. Adie), **B1**, 3–11. Oslo: International Union of Geological Sciences.

Grindley, G. W. 1974 New Zealand. In *Mesozoic-Cenozoic orogenic belts*, pp. 387–416. London: Geological Society.

Haller, J. 1969 *Mem. Am. Ass. petrol. Geol.* **12**, 852–858.

Harland, W. B. 1969*a* *Mem. Am. Ass. petrol. Geol.* **12**, 817–851.

Harland, W. B. 1969*b* *Trans. N.Y. Acad. Sci.* (2) **31**, 25–41.

Harland, W. B. 1971 *Geol. Mag.* **108**, 27–42.

Hasnain, I. & Qureshy, M. N. 1971 *J. geophys. Res.* **76**, 4786–4795.

Hayes, D. E. 1972 *Antarctic Res. Ser. Washington* **19**, 119–124.

Hayes, D. E. & Ewing, M. 1970 *Bull. Am. Ass. petrol. Geol.* **54**, 2120–2150.

Hayes, D. E., Frakes, L. A., *et al.* 1973 *Geo Times* **18**(**6**), 19–24.
Hayes, D. E., Pimm, A. C., *et al.* 1972 *Initial Reports of the Deep Sea Drilling Project. Leg 14.* Washington D.C.: U.S. Government Printing Office.
Hayes, D. E. & Pitman, W. C., III 1970 *Mem. geol. Soc. Am.* **126**, 291–314, pls 1–3.
Hayes, D. E. & Ringis, J. 1973 *Nature, Lond.* **243**, 454–458.
Heezen, B. C. & Ewing, M. 1961 In *Geology of the Arctic* (ed. G. O. Raasch), **1**, 622–642. Toronto: University of Toronto Press.
Heezen, B. C., Gray, C., Segre, A. G. & Zarudski, E. F. K. 1971 *Nature, Lond.* **229**, 327–329.
Heezen, B. C. & Tharp, M. 1965 *Phil. Trans. R. Soc. Lond.* A **258**, 90–106.
Heirtzler, J. R., Dickson, G. O., Herron, E. M., Pitman, W. C., III & Le Pichon, X. 1968 *J. geophys. Res.* **73**, 2119–2136.
Herron, E. M. 1971 *Antarctic Res. Ser. Washington* **15**, 229–237.
Herron, E. M. 1972 *Bull. geol. Soc. Am.* **83**, 1671–1691.
Hilgenberg, O. C. 1933 *Vom Wachsenden Erdball.* Berlin.
Hilgenberg, O. C. 1966 *Geol. Rdsch.* **55**, 878–924.
Hollister, C. D., Ewing, J. I., *et al.* 1972 *Initial Reports of the Deep Sea Drilling Project. Leg 11.* Washington D.C.: U.S. Government Printing Office.
Hoyle, F. 1972 *Q. Jl R. astr. Soc.* **13**, 328–345.
Hsü, K. J. 1971 *Nature, Lond.* **232**, 44–48.
Hsü, K. J. & Schlanger, S. O. 1971 *Bull. geol. Soc. Am.* **82**, 1207–1217.
Huffman, O. F. 1972 *Bull. geol. Soc. Am.* **83**, 2913–2946.
Hunting Survey Corporation Ltd 1961 *Reconnaisance Geology of part of West Pakistan* (ed. A. G. Jones). Toronto: Government of Canada.
Hutchinson, R. W. & Engels, G. G. 1972 *Bull. geol. Soc. Am.* **83**, 2989–3001.
Hyndman, R. D. 1973 *Can. J. Earth Sci.* **10**, 637–644.
Ilhan, E. 1974 Eastern Turkey. In *Mesozoic-Cenozoic orogenic belts*, pp. 187–197. London: Geological Society.
Jeffreys, H. 1962 *Nature, Lond.* **195**, 448.
Johnson, G. L. & Vogt, P. R. 1973 *Mem. Am. Ass. Petrol. Geol.* **19**, 161–170.
Johnson, G. L., Vogt, P. R. & Avery, O. E. 1971 *Rep. Inst. Geol. Sci.* **70/14**, 57–65.
Jones, J. G. 1971 *Nature, Lond.* **229**, 400–403.
Keen, C. E., Barrett, D. L., Manchester, K. S. & Ross, D. I. 1972 *Can. J. Earth Sci.* **9**, 239–256.
Keen, M. J., Johnson, J. & Park, I. 1972 *Can. J. Earth Sci.* **9**, 689–708.
Kent, P. E. 1969 In *The exploration for petroleum in Europe and North Africa*, pp. 3–17. London: Institute of Petroleum.
Kent, P. E. 1972 *Nature, Lond.* **238**, 147–148.
King, L. 1958 In *Continental Drift: A Symposium* (ed. S. W. Carey), pp. 63–102. Hobart: University of Tasmania.
King, P. B., *et al.* 1969 *Tectonic Map of North America.* Washington D.C.: U.S. Geological Survey 1:5000000 in 2 sheets with an explanatory memoir – *Prof. Pap. U.S. geol. Surv.* **628**.
Kirkland, D. W. & Gerhard, J. E. 1971 *Bull. Am. Ass. Petrol. Geol.* **55**, 680–686.
Klerkx, J. & Paepe, P. de 1971 *Nature Phys. Sci.* **233**, 117–118.
Kraft, J. C., Sheridan, R. E. & Maisano, M. 1971 *Bull. Am. Ass. Petrol. Geol.* **55**, 658–679.
Krasny, L. I. 1973 *Mem. Am. Ass. Petrol. Geol.* **19**, 189–193.
Krause, D. C. 1971 *Mem. geol. Soc. Am.* **130**, 35–54.
Ladd, J. W., Dickson, G. O. & Pitman, W. C., III 1973 In *The ocean basins and margins.* 1. *The South Atlantic* (ed. A. E. M. Nairn & F. G. Stehli), pp. 555–573. New York: Plenum Press.
Larson, R. L. & Chase, C. G. 1972 *Bull. geol. Soc. Am.* **83**, 3627–3644.
Larson, R. L. & Ladd, J. W. 1973 *Nature, Lond.* **246**, 209–212.
Larson, R. L. & Pitman, W. C., III 1972 *Bull. geol. Soc. Am.* **83**, 3645–3662.
Lattimore, R. K., Rona, P. A. & de Wald, O. E. 1974 *J. geophys. Res.* **79**, 1207–1209.
Laughton, A. S. 1971 *Nature, Lond.* **232**, 612–617.
Laughton, A. S. & Berggren, W. A. 1971 In *Histoire Structurale du Golfe de Gascogne* **2**, VI. 1–1 to VI. 1–4. Paris: L'Institut Français du Pétrole, Editions Technip.
Laughton, A. S., Berggren, W. A., *et al.* 1972 *Initial Reports of the Deep Sea Drilling Project. Leg 12.* Washington D.C.: U.S. Government Printing Office.
Lee, L. P. 1947 *N.Z. Geogr.* **3**, 41–58.
Le Pichon, X. & Fox, P. J. 1971 *J. geophys. Res.* **76**, 6294–6308.
Le Pichon, X. & Hayes, D. E. 1971 *J. geophys. Res.* **76**, 6283–6293.
Le Pichon, X. & Heirtzler, J. R. 1968 *J. geophys. Res.* **73**, 2101–2117.
Le Pichon, X., Hyndman, R. D. & Pautot, G. 1971 *J. geophys. Res.* **76**, 4724–4743.
Leyden, R., Ewing, M. & Simpson, E. S. W. 1971 *Bull. Am. Ass. Petrol. Geol.* **55**, 651–657.
Lowell, J. D. 1972 *Bull. geol. Soc. Am.* **83**, 3091–3101.
Lowell, J. D. & Genik, G. J. 1972 *Bull. Am. Ass. Petrol. Geol.* **56**, 247–259.
Luyendyk, B. P., Davies, T. A., *et al.* 1973 *Geo Times* **18**(**3**), 16–19.
Maack, R. 1969 *Kontinentaldrift und Geologie des südatlantischen Ozeans.* Berlin: Walter de Gruyter.

Machens, E. 1970 *Abh. hess. Landesamt. Bodenforsch.* **56**, 97–111.

McElhinny, M. W., Haile, N. S. & Crawford, A. R. 1974 *Nature, Lond.* **252**, 641–645.

McIver, N. L. 1972 *Can. J. Earth Sci.* **9**, 54–70.

McKenzie, D. P. 1970 *Nature, Lond.* **226**, 239–243.

McKenzie, D. P. & Sclater, J. G. 1971 *Geophys. J. R. Astr. Soc.* **25**, 437–528.

Malahoff, A. & Handschumacher, D. W. 1971 *J. geophys. Res.* **76**, 6265–6275.

Malfait, B. T. & Dinkelman, M. G. 1972 *Bull. geol. Soc. Am.* **83**, 251–271.

Mascle, J. & Phillips, J. D. 1972 *Nature, Lond.* **240**, 80–84.

Matsumoto, T. & Kimura, T. 1974 Southwest Japan. In *Mesozoic-Cenozoic orogenic belts*, pp. 513–541. London: Geological Society.

Mattauer, M. & Henry, J. 1974 Pyrenees. In *Mesozoic-Cenozoic orogenic belts*, pp. 3–21. London: Geological Society.

Matthews, D. H. & Williams, C. A. 1968 *Earth Planet. Sci. Lett.* **4**, 315–320.

Mattson, P. H. 1972 *Nature, Lond.* **235**, 155–156.

Mattson, P. H. 1974*a* Cuba. In *Mesozoic-Cenozoic orogenic belts*, pp. 625–638. London: Geological Society.

Mattson, P. H. 1974*b* Puerto Rico–Virgin Islands. In *Mesozoic-Cenozoic orogenic belts*, pp. 639–661. London: Geological Society.

Maxwell, A. E., Von Heerzen, R. P., *et al.* 1970 *Initial Reports of the Deep Sea Drilling Project. Leg 3*. Washington D.C.: U.S. Government Printing Office.

Meservey, R. 1969 *Science, N.Y.* **166**, 609–611.

Milsom, J. S. 1970 *Earth planet. Sci. Lett.* **8**, 258–260.

Milsom, J. S. 1974 East New Guinea. In *Mesozoic-Cenozoic orogenic belts*, pp. 463–474. London: Geological Society.

Ostenso, N. A. 1963 In *Proceedings of the Arctic Basin Symposium October 1962*. Washington D.C.: Arctic Institute of North America, 9–40.

Ostenso, N. A. 1973 In *Implications of continental drift to the earth sciences* (ed. D. H. Tarling & S. K. Runcorn) **1**, 165–173. London: Academic Press.

Ostenso, N. A. & Wold, R. J. 1971 *Mar. geophys. Res.* **1**, 178–219.

Owen, H. G. 1973 *Geol. J. Spec. Issue* **5**, 145–154.

Oxburgh, E. R. 1974 Eastern Alps. In *Mesozoic-Cenozoic orogenic belts*, pp. 109–126. London: Geological Society.

Parke, M. L., Emery, K. O., Szymakiewicz, R. & Reynolds, L. M. 1971 *Bull. Am. Ass. Petrol. Geol.* **55**, 723–751.

Peter, G., Lattimore, P. K., de Wald, O. E. & Merrill, G. 1973 *Nature, Phys. Sci.* **245**, 129–131.

Peterson, M. N. A., Edgar, N. T., *et al.* 1970 *Initial Reports of the Deep Sea Drilling Project. Leg 2*. Washington D.C.: U.S. Government Printing Office.

Pinet, P. R. 1972 *Bull. geol. Soc. Am.* **83**, 1911–1921.

Pitman, W. C., III & Talwani, M. 1972 *Bull. geol. Soc. Am.* **83**, 619–645.

Pitman, W. C., III, Talwani, M. & Heirtzler, J. R. 1971 *Earth planet Sci. Lett.* **11**, 195–200.

Plauchut, B. P. 1973 *Mem. Am. Ass. Petrol. Geol.* **19**, 76–82.

Reyment, R. A. & Tait, E. A. 1972 *Phil. Trans. R. Soc. Lond.* B **264**, 55–95, pls 3–5.

Ridd, M. F. 1970 *Nature, Lond.* **229**, 51–52.

Ridd, M. F. 1971 *Nature, Lond.* **234**, 531–533.

Robb, J. M. 1971 *Bull. Am. Ass. Petrol. Geol.* **55**, 643–650.

Robinson, P. L. 1971 *Palaeontology* **14**, 131–153.

Rona, P. A., Brakl, J. & Heirtzler, J. R. 1970 *J. geophys. Res.* **75**, 7412–7420.

Rondeel, H. E. & Simon, O. J. 1974 Betic Cordilleras. In *Mesozoic-Cenozoic orogenic belts*, pp. 23–35. London: Geological Society.

Ross, D. A., Whitmarsh, R. B., *et al.* 1972 *GeoTimes* **17**(**7**), 24–26.

Rutland, R. W. O. 1974 Andes: Antofagasta Segment (20°–25° S). In *Mesozoic-Cenozoic orogenic belts*, pp. 733–743. London: Geological Society.

Rutland, R. W. O. & Walter, M. R. 1974 Philippine Archipelago. In *Mesozoic-Cenozoic orogenic belts*, pp. 491–500. London: Geological Society.

Ryan, W. B. F., Hsü, K. J., *et al.* 1973 *Initial Reports of the Deep Sea Drilling Project. Leg 13*. Washington D.C.: U.S. Government Printing Office.

Schouten, J. A. 1971 *Mar. geophys. Res.* **1**, 111–144.

Sclater, J. G., Hawkins, J. W., Mammerickx, J. & Chase, C. G. 1972 *Bull. geol. Soc. Am.* **83**, 505–517.

Sestini, G. 1974 Northern Apennines. In *Mesozoic-Cenozoic orogenic belts*, pp. 61–84. London: Geological Society.

Simpson, E., Schlich, R., *et al.* 1972 *GeoTimes* **17**(**11**), 21–24.

Smith, A. G. 1971 *Bull. geol. Soc. Am.* **82**, 2039–2070.

Smith, A. G., Briden, J. C. & Drewry, G. E. 1973 *Palaeontology. Spec. Pap.* **12**, 1–42.

Smith, A. G. & Hallam, A. 1970 *Nature, Lond.* **225**, 139–144.

Sowerbutts, W. T. C. 1972 *Nature, Phys. Sci.* **235**, 435–436.

Sproll, W. P. & Dietz, R. S. 1969 *Nature, Lond.* **222**, 345–348.

Stauffer, K. W. & Tarling, D. H. 1971 In *Histoire Structurale du Golfe de Gascogne* **1**, II. 2–18. Paris: L'Institut Français du Pétrole, Editions Technip.

Steers, J. A. 1962 *An introduction to the study of map projections*, 13th edn. University of London Press.

Steiner, J. 1967 *Jl geol. Soc. Australia* **14**, 99–132.

Storetvedt, K. M. 1973 *Earth planet Sci. Lett.* **21**, 22–28.

Tailleur, I. L. 1973 *Mem. Am. Ass. Petrol. Geol.* **19**, 526–535.

Tarling, D. H. 1971 *Nature, Lond.* **229**, 17–21, 71.

Tazieff, H., Varet, J., Barberi, F. & Giglia, G. 1972 *Nature, Lond.* **235**, 144–147.

Uchupi, E., Milliman, J. D., Luyendyk, B. P., Bowin, C. O. & Emery, K. O. 1971 *Bull. Am. Ass. Petrol. Geol.* **55**, 687–704.

Uyeda, S. & Ben-Avraham, Z. 1972 *Nature, Phys. Sci.* **140**, 176–178.

Van der Voo, R. & Zijderveld, J. D. A. 1971 *J. geophys. Res.* **76**, 3913–3921.

Veevers, J. J. 1971 *J. geol. Soc. Aust.* **18**, 87–96.

Veevers, J. J., Heirtzler, J. R., *et al.* 1973 *Geo Times* **18**(**4**), 16–17.

Veevers, J. J., Jones, J. G. & Talent, J. A. 1971 *Nature, Lond.* **229**, 383–388.

Vereschagin, V. N. & Ronov, A. B. (ed.) 1968 *Atlas of the lithological-palaeogeographical maps of the U.S.S.R.* III. Triassic, Jurassic & Cretaceous Maps 1–71. Moskva: Ministry of Geology and Academy of Sciences U.S.S.R

Vischer, A. 1943 *Meddr. grønland* **133**(**1**).

Vogt, P. R., Anderson, C. N. & Bracey, D. R. 1971 *J. geophys. Res.* **76**, 4796–4823.

Vogt, P. R. & Avery, O. E. 1974 *J. geophys. Res.* **79**, 363–389.

Vogt, P. R., Higgs, R. H. & Johnson, G. L. 1971 *J. geophys. Res.* **76**, 3207–3228.

Vogt, P. R. & Johnson, G. L. 1971 *Nature, Lond.* **234**, 22–25.

Vogt, P. R. & Ostenso, N. A. 1970 *J. geophys. Res.* **75**, 4925–4937.

Von der Borch, C., Sclater, J. G., *et al.* 1972 *Geo Times* **17**(**6**), 15–17.

Weissel, J. K. & Hayes, D. E. 1972 *Antarctic Res. Ser. Washington* **19**, 165–196.

Wensink, H. & Klootwijk, C. T. 1971 *Tectonophysics* **11**, 175–190.

Westphal, M., Bardon, C., Bossert, A. & Hamzeh, R. 1973 *Earth planet Sci. Lett.* **18**, 137–140.

Wheeler, J. O., Charlesworth, H. A. K., Monger, J. W. H., Muller, J. E., Price, R. A., Reesor, J. E., Roddick, J. A. & Simony, P. S. 1974 Western Canada. In *Mesozoic-Cenozoic orogenic belts*, pp. 591–623. London: Geological Society.

Whitmarsh, R. B., Weser, O. E., *et al.* 1972 *Geo Times* **17**(**7**), 24–26.

Wilhelm, O. & Ewing, M. 1972 *Bull. geol. Soc. Am.* **83**, 575–599.

Williams, C. A. 1971 In *Histoire Structurale du Golfe de Gascogne.* **2**, VI. 4-1 to VI. 4-6. Paris: L'Institut Français du Pétrole, Editions Technip.

Williams, C. A. & McKenzie, D. 1971 *Nature, Lond.* **232**, 168–173.

Winterer, E. L. 1973 *Bull. Am. Ass. Petrol. Geol.* **57**, 265–282.

Wood, A. & Woodland, A. W. 1969 *Nature, Lond.* **219**, 1352–1354.

Worzel, J. L., Bryant, W., *et al.* 1973 *Initial Reports of the Deep Sea Drilling Project. Leg 10.* Washington D.C.: U.S. Government Printing Office.

Appendix. Description of trizenithal map projection

The construction of the graticule used in figures 11–18 is as follows. The prime meridian of each hemisphere is drawn to true scale length of $\frac{1}{2}\pi D$ and bisects at right angles a line of equal length marking the equator. Each prime meridian (0° and 180°), or whatever meridian is chosen as standard, together with the equator, is marked-off in units of $2\pi r(X^\circ/360^\circ)$ where X° represents the required interval of latitude and longitude. For the purpose of this paper, the prime meridians and the equator are marked-off in intervals of 10°. Originating at the North and South geographic poles, a zenithal equidistant projection is constructed outwards to latitudes 60° N and 60° S respectively. Lines of longitude are then constructed from the points of intersection on the equator to join up with the corresponding lines of longitude on the polar equidistant graticule, such that for any given degree of latitude their distances apart are $2\pi r(X^\circ/360^\circ)$ where X° represents the desired interval of longitude. Lines of latitude are then constructed between the equator and the 60° N and S latitudes such that each line of latitude intersects with each line of longitude at equal distances from each other.

Distortion is inevitable as one moves away from the prime 0° and 180° meridians towards 90° E and W in the sectors between 0° and 60° N and S latitudes. However, the amount of distortion tends to decrease with reduction of diameter of the globe, the projection possesses excellent directional properties, and it displays the polar regions exceptionally well.

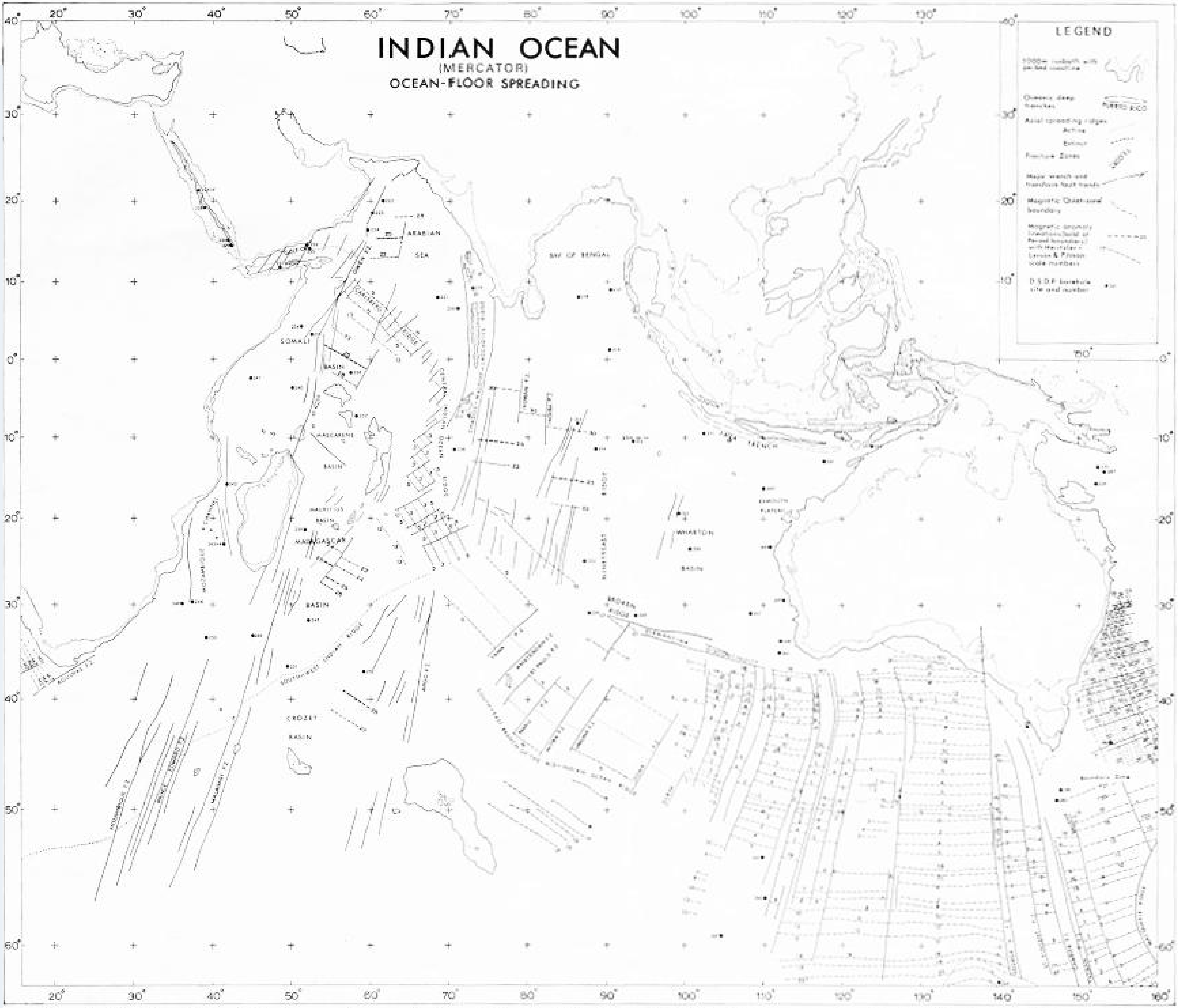

Figure 3. Indian Ocean (Mercator's) showing ocean floor spreading data and Deep Sea Drilling Project (D.S.D.P.) borehole sites, compiled essentially from Fisher, Sclater & McKenzie (1971), Hayes (1972), Heezen & Tharp (1965), Heirtzler *et al.* (1968), Le Pichon & Heirtzler (1968), McKenzie & Sclater (1971), Weissel & Hayes (1972) and JOIDES. The magnetic reversal anomaly sequence is given in table 1 (p. 228) with approximate ages.

(*Facing p. 228*)

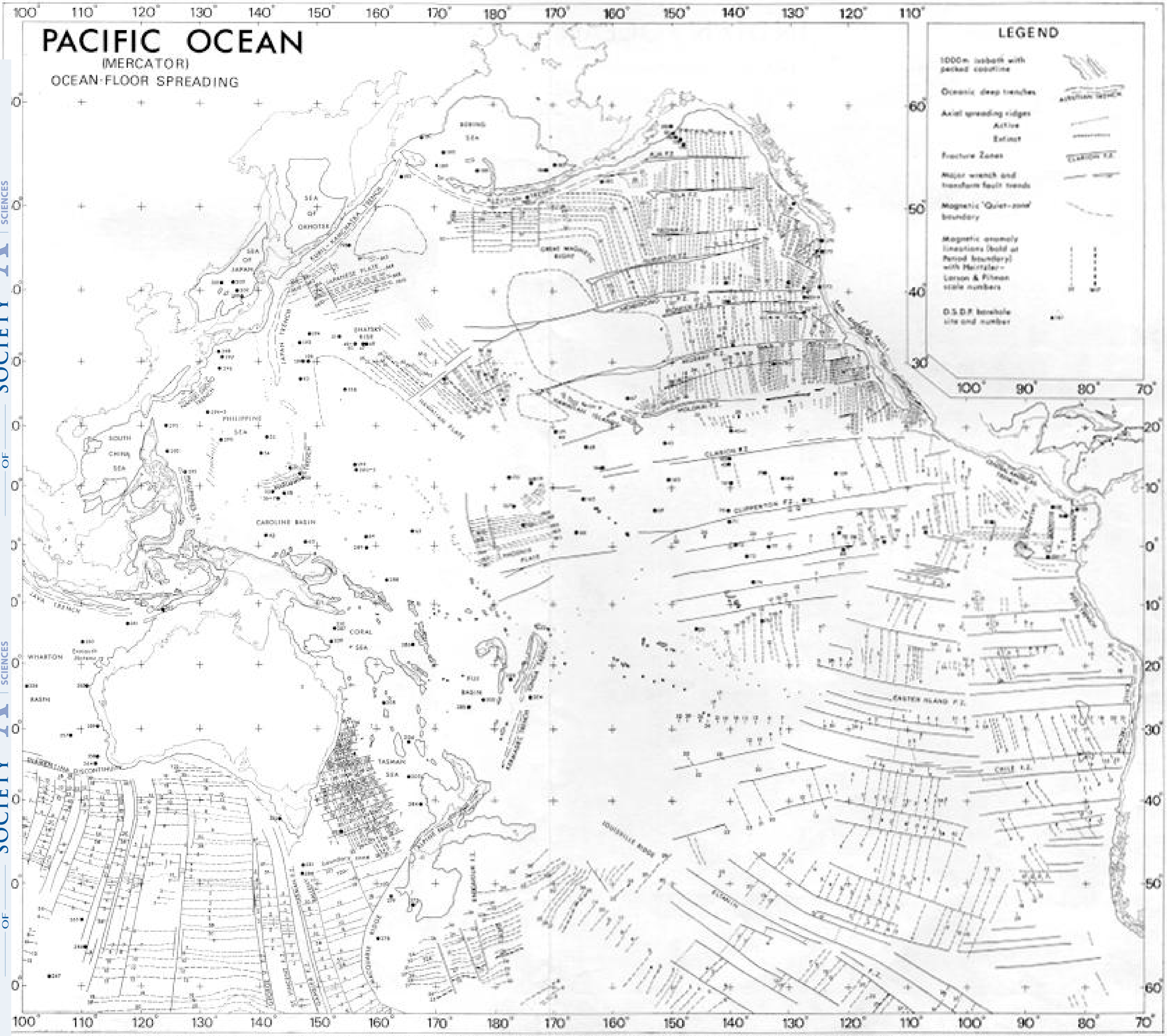

FIGURE 4. Pacific Ocean (Mercator's) showing ocean floor spreading data and Deep Sea Drilling Project (D.S.D.P.) borehole sites, compiled essentially from Atwater & Menard (1970), Ben-Avraham, Bowin & Segawa (1972), Christoffel & Falconer (1972), Christoffel & Ross (1970), Hayes & Pitman (1970), Hayes & Ringis (1973), Herron (1971, 1972), Larson & Chase (1972), Malahoff & Handschumacher (1971), Weissel & Hayes (1972), and JOIDES. The magnetic reversal anomaly sequence is given in table 1 (p. 228) with approximate ages.

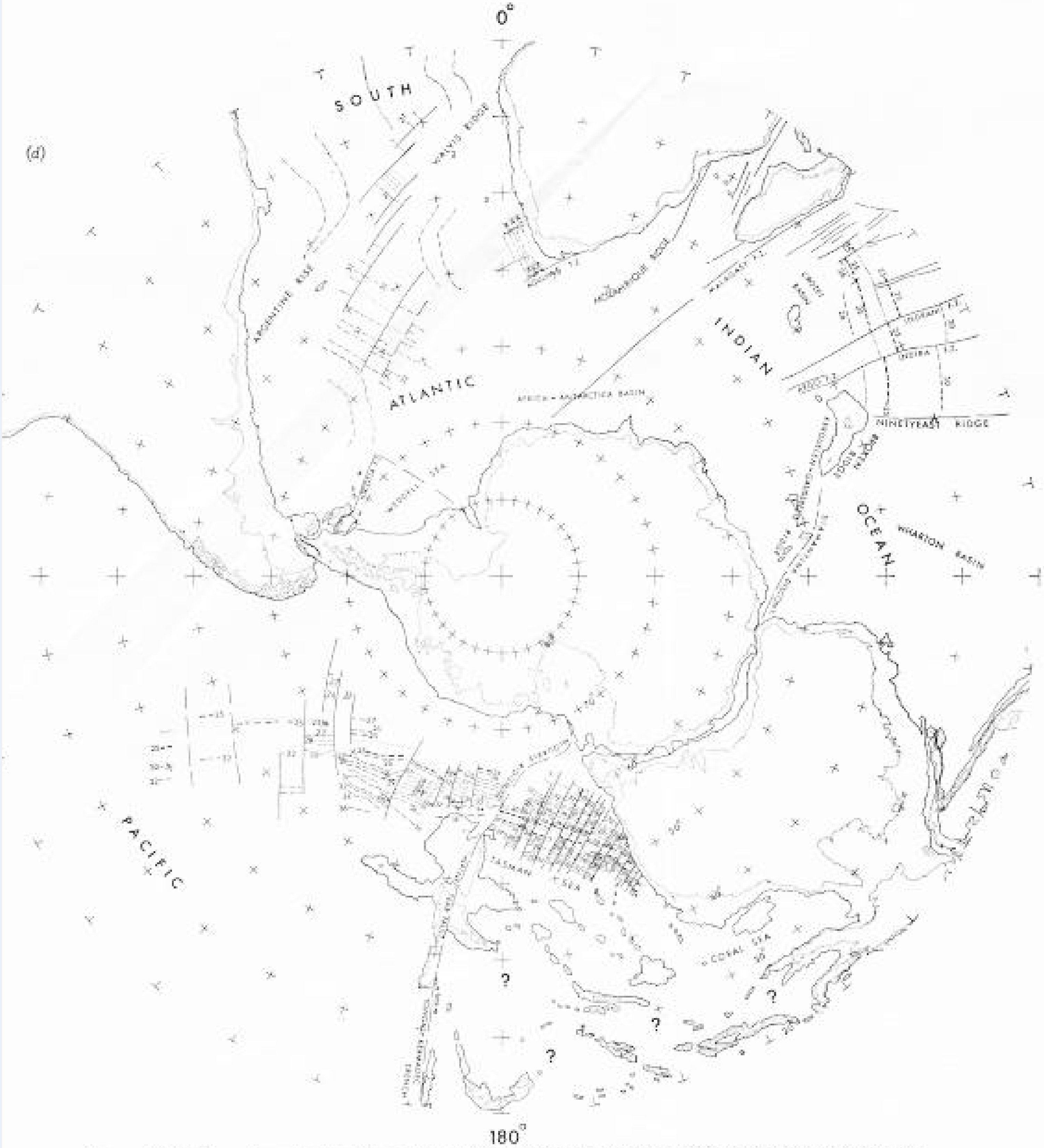

FIGURE 10*d*. The southern hemisphere north to 20° S latitude in the early Tertiary (Palaeocene) 60 Ma B.P. Projection centred on the South geographic pole constructed for that time. Diameter of the Earth is approximately 93% of current mean value.

(*Facing p. 216*)

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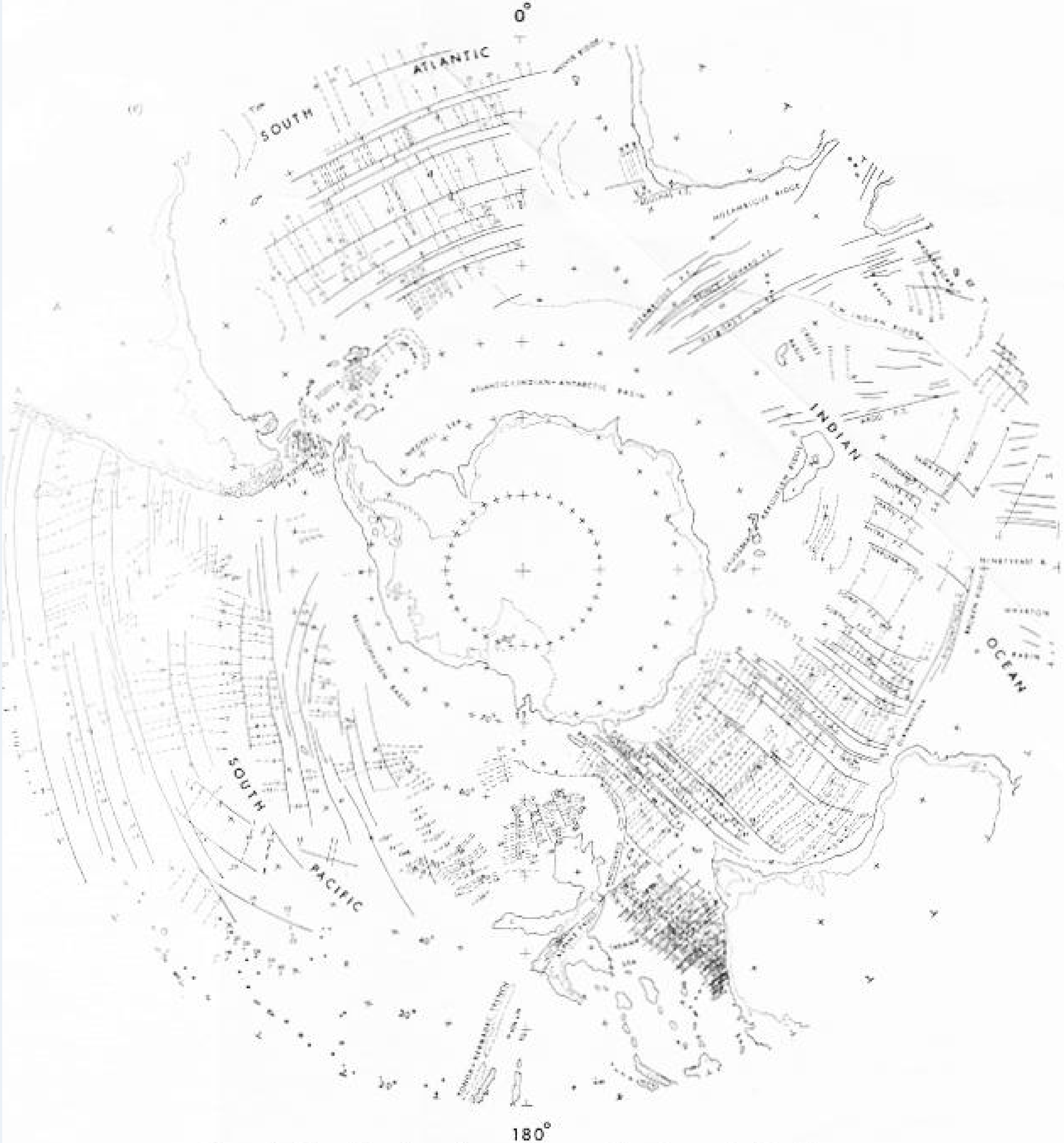

Figure 10e. Geographic and ocean floor spreading map of the modern southern hemisphere north to 20° S latitude.