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Paleogeography, 180 million years ago to the present

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ABSTRACT

We have produced a series of paleogeographic maps at 20-m.y. intervals from 180 m.y. ago to the present. The location of the ancient shoreline has been indicated on the maps. The continents are placed in their correct relative positions using seafloor spreading data and the original positions of the continents in the supercontinent Pangaea. Their absolute location with respect to the spin axis of the earth is derived by using average paleomagnetic pole positions. Three conformal maps are presented for each time interval, such that the whole earth is displayed. These reconstructions are significantly different from previous global reconstructions, mainly because many more data were used in their generation. However, there are still areas where considerable controversy remains, because the data do not constrain the models. We have discussed in detail the data which we have used to produce the maps and have given some justification for the choice of data.

ZUSAMMENFASSUNG

Wir haben eine Reihe paläogeographischer Karten konstruiert, die im Abstand von 20 Millionen Jahren die letzten 180 Millionen Jahre umfassen. Die Karten zeigen den alten Verlauf der Küstenlinien. Die relative Lage der Kontinente wurde aus der Vergrösserungsrate des Meeresbodens und der ursprünglichen Lage der Kontinente im Superkontinent Pangäa ermittelt. Ihre abolute Position relativ zur Erdachse wurde aus den mittleren ehemaligen Positionen der Magnetpole abgeleitet. Für jeden Zeitraum sind drei konforme Kartenprojektionen gewählt, die die gesamte Erde darstellen. Diese Rekonstruktionen unterscheiden sich insofern von älteren globalen Rekonstruktionen, als sie auf wesentlich mehr Daten beruhen. Die Darstellungen sind jedoch weiterhin mit beträchtlichen Unsicherheiten behaftet, weil die Daten die Modelle nicht eindeutig festlegen. Wir diskutieren ausführlich die Daten, die zur Konstruktion der Karten benutzt wurden, und versuchen die Auswahlkriterien zu rechtfertigen.

RÉSUMÉ

Nous avons produit pour les 180 derniers millions d'années une suite de cartes paléogéographiques se succédant à intervalles de 20 millions d'années. L'emplacement de l'ancienne ligne de côte a été indiquée sur les cartes. Les continents sont placés dans leur position relative correcte à partir de données de l'expansion des fonds océaniques et des positions primitives des continents dans le supercontinent Pangéa. Leur position absolue par rapport à l'axe de rotation de la terre est basée sur la position moyenne du pôle paléomagnétique. Trois cartes «conformales» sont présentées pour chaque intervalle de temps de telle manière que la totalité du globe soit visible. Ces reconstructions diffèrent sensiblement des reconstructions globales antérieures, principalement parce qu'elles ont été produites à partir d'un

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bien plus grand nombre de données. Cependant il existe encore certaines régions, où d'importantes controverses demeurent, les données ne constreignant pas les modèles. Les données sur lesquelles sont basées les cartes sont discutées en détail et des justifications sont apportées quant à leur choix.

Introduction

Global plate tectonic reconstructions of the surface of the earth for the Mesozoic and Cenozoic are limited to paleocontinental maps such as those produced by SMITH & BRIDEN (1977). Paleogeographic maps, rather than paleocontinental maps, are required in order to investigate paleoclimatology, biogeography, sedimentation and sea level variations through time. Global paleogeographic maps, indicating the maximum extent of marine sediments at specific time intervals, have been reconstructed on "fixed" continents by STRAKHOW (1948) and TERMIER & TERMIER (1952).

Paleogeographic maps are presented at 20-m.y. increments, from 180 m.y. to the present, based on reconstructions of the relative positions of continents with respect to North America, a paleomagnetic reference frame to fix the continents with respect to the earth's spin axis, and regional compilations of the record of marine sequences on the continents. These reconstructions differ significantly from previous paleocontinental or paleogeographic reconstructions largely because a considerably more comprehensive data set has been used. Several aspects of these reconstructions, however, continue to be poorly constrained by the available data.

These paleogeographic reconstructions are designed as base maps for the purpose of plotting and examining various types of geologic data on the continents. Similar tectonic models of all the ocean basins, which are required for a global analysis of geologic data have not yet been completed, although there are now regional analyses of the Indian and Atlantic Oceans (e.g. SCLATER et al. 1977; NORTON & SCLATER 1979; BARRON & HARRISON 1980).

Relative continental positions

The reconstructions of the relative positions of the continents with respect to North America are based on the initial fit of continental elements prior to the opening of the Atlantic, Indian and Arctic Oceans, constraints on the timing of continental breakups and compilations of geological and geophysical data from the seafloor.

The initial fit of two continents is not usually well constrained by data from the seafloor. This is partly because the typical marine magnetic anomalies produced by seafloor spreading are not well developed during the early stages of continental breakup. Geological correlations, such as concurrent depositional facies, basement lineations and the distribution of shield and "geosynclinal" areas may constrain initial reconstructions in some cases. The match of Australia and Antarctica by LAIRD et al. (1977) is a good example of a fit determined by juxtaposing the axes of depositional basins. Geometric fits (e.g. BULLARD et al. 1965) may be compelling evidence in the cases of long and sinuous continental outlines such as the fit of South America and Africa.

Continental breakup is associated with uplift, extrusion and intrusion of basic and alkaline igneous rocks, rift formation and marine sedimentation. Peak volcanism, the age of permanent marine incursions or other correlations of breakup events are used to determine the age of continental separation (SMITH & HALLAM 1970; DIETZ & HOLDEN 1970; SCRUTTON 1973; BURKE & DEWEY 1973). Extrapolation of a constant spreading rate over the width of the magnetic quiet zone adjacent to continental margins is another method of estimating the timing of initial separation.

Oceanic magnetic lineations coupled with the strike of fracture zones are the best data to use to determine subsequent plate motions. Smooth rotation vectors are used to determine plate motions between sets of magnetic anomalies. In all cases, the time scale of the magnetic anomaly identifications have been modified to that of LA BRECQUE et al. (1977) for the Cenozoic and LARSON & HILDE (1975) for the Mesozoic. Recognition of fracture zones gives additional evidence concerning the relative movement between plates, but the data must be used with caution (MCKENZIE & MORGAN 1969; HARRISON 1972).

The initial fit of continental elements, the timing of continental breakup and subsequent continental motions used to reconstruct the relative positions of the continents are described below.

The reconstruction of the Atlantic Ocean

a) Reconstruction of Africa with respect to North America

BULLARD et al. (1965) proposed a best fit of the 500-fathom isobath for Africa and North America. In order to line up the Guinea and Bahama fracture zones, LE PICHON et al. (1977) proposed a revised fit that shifts Africa approximately 250 km to the north with respect to the BULLARD et al. (1965) reconstruction. The fit of LE PICHON et al. (1977) uses the 3000-m isobath to account for subsidence and modification of the continental margins. One of the most important differences between these initial reconstructions is that the BULLARD et al. (1965) fit assumes that the Blake-Bahama platform and southern Florida are underlain by oceanic crust whereas the LE PICHON et al. (1977) reconstruction does not overlap these platforms. The large amount of subsidence of the Bahama platform and the presence of basalt at the base of a well 18,600 feet deep in South Florida argue for this aspect of the BULLARD et al. (1965) reconstruction. The evolution of the Gulf of Mexico is problematic in both reconstructions. It is conceivable that the early breakup history involves a slight counterclockwise rotation of Africa with respect to North America. In this case, the "initial" fit may be dependent on the exact time chosen to reconstruct these continents. At 180 m.y. the BULLARD et al. (1965) fit of Africa and North America is assumed.

A third interesting possibility, presented in Paleozoic reconstructions (ZIEGLER et al. 1979; BAMBACH et al. 1980) fits Africa to North America such that South America fills the Gulf of Mexico. The Mesozoic history of relative motions was not presented by these authors. The lack of consensus of the fit of Africa and North America is further demonstrated by the work of RICKARD & BELBIN (1980) which has Africa rotated sufficiently counterclockwise to bring Iberia adjacent to Libya in the initial reconstruction as compared to a position next to Morocco in most reconstructions (e.g. SCLATER et al. 1977).

Geologic features on the margin of the United States may suggest an initial phase of rifting between Africa and North America starting in the late Triassic (PITMAN & TALWANI 1972). Extrapolation of magnetic anomaly data places the time of initial seafloor spreading at 165 m.y. (SCLATER et al. 1977). A breakup time of 180 m.y. is used in this reconstruction.

The rotations from 180 m.y. to the present (Table 1) are those of PITMAN & TALWANI (1972), who used the initial fit of BULLARD et al. (1965).

b) Reconstruction of Greenland with respect to North America

The Greenland-North America fit is that proposed by BULLARD et al. (1965) which is consistent with more recent geophysical evidence (e.g. LE PICHON et al. 1977) for features such as marginal fracture ridges. Seafloor spreading data between Europe and Greenland and the requirement to close the reconstruction of Greenland, North America and Europe places the initial separation of Greenland and North America at 95 m.y. (SCLATER et al. 1977). The oldest well-defined magnetic anomaly recorded in the Labrador Sea is number 24 (VOGT & AVERY 1974), approximately 56 m.y. in age. The rotation of Greenland with respect to North America is poorly constrained. The rotations given in Table 1 are those of SCLATER et al. (1977).

c) Reconstruction of Europe with respect to Greenland

An initial fit of Europe to Greenland has been proposed by BULLARD et al. (1965) using the 500-fathom contour. SCLATER et al. (1977) moved Europe along the marginal fracture south of Svalbard until Europe-Iberia fit to the Grand Banks. The Rockall Bank is assumed to fit into the gap between Greenland and Ireland. LE PICHON et al. (1977) also included the Rockall Bank but the fit of Greenland and Europe is based on the 2000-m contour. The overlap between northern Norway and Greenland is slightly less than in the case of SCLATER et al. (1977). The fit of Greenland to North America and Europe to Greenland has important implications for the evolution of the Arctic (see discussion in later section) but unfortunately the initial fit is not well constrained.

Magnetic anomaly data between Greenland and Europe have been presented by VOGT & AVERY (1974) and PITMAN & TALWANI (1972). The oldest anomaly adjacent to the Voring Plateau Escarpment and adjacent to Greenland is number 24 (TALWANI & ELDHOLM 1973, 1977) and the oldest anomaly in the North Atlantic is number 34 (KRISTOFFERSON 1978) dated at 80 m.y. The spreading rate prior to anomaly 24 is very small and SCLATER et al. (1977) assumed an initial breakup at 95 m.y. The rotations for Europe to Greenland (TALWANI & ELDHOLM 1977) are given in Table 1.

d) Reconstruction of Iberia with respect to Europe

The precise fit of Iberia to Europe is controversial (WILLIAMS 1975; LE PICHON et al. 1977; SCLATER et al. 1977). The most important constraint is the Europe-

Table 1: *Rotation vectors for the reconstruction of the relative positions of the continents with respect to North America. A positive angle is counterclockwise.*

TIME MYBP	ANOMALY NO.	LATITUDE (°N)	LONGITUDE (°E)	ANGLE (°)
Rotations for Africa to North America				
0 - 9.0	- 5	69.7	-33.4	- 3.6
9.0 - 35.6	5 - 13	77.1	53.5	- 6.3
35.6 - 49.9	13 - 21	72.2	16.0	- 4.2
49.9 - 58.9	21 - 25	66.2	11.8	- 3.2
58.9 - 75.5	25 - 33	57.8	-42.0	-15.1
75.5 - 153.0	33 - QZ	59.4	-22.8	-36.9
153.0 - 180.0	QZ -	56.8	73.3	- 8.9
Rotations for Greenland to North America				
0 - 35.6	- 13			0.0
35.6 - 52.7	13 - 22	8.5	34.1	2.1
52.7 - 95.0	22 -	72.7	-73.3	-17.9
95.0 - 180.0				0.0
Rotations for Europe to Greenland				
0 - 9.0	- 5	68.0	137.0	- 2.5
9.0 - 35.6	5 - 13	68.0	126.5	- 5.3
35.6 - 49.9	13 - 21	- 5.3	117.4	- 2.5
49.9 - 54.3	21 - 27	- 5.3	117.4	- 1.2
54.3 - 95.0	27 -	-82.1	157.9	9.7
95.0 - 180.0				0.0
Rotations for Iberia to Europe				
0 - 64.6	- 29			0.0
64.6 - 95.0	29 -	45.0	0.0	-27.0
95.0 - 125.0		32.5	135.5	- 2.6
125.0 - 180.0				0.0
Rotations for South America to Africa				
0 - 35.6	- 13	57.4	-37.5	13.4
35.6 - 80.0	13 - 34	66.6	-37.4	20.5
80.0 - 108.5	34 - MO	24.1	-15.7	22.1
108.5 - 125.5	MO-	17.9	- 9.6	4.4
125.5 - 180.0				0.0
Rotations for Lord Howe Rise to Australia				
0 - 55.2				0.0
55.2 - 60.2		- 1.5	138.5	- 2.6
60.2 - 64.9		8.1	-38.1	4.1
64.9 - 69.3		17.7	-38.1	6.2
69.3 - 74.0		19.4	-37.9	6.3
74.0 - 180.0				0.0
Rotations for Arabia to Africa (Nubia)				
0 - 16.0		36.5	18.0	- 6.1
16.0 - 180.0				0.0
Rotations for Madagascar to Africa				
0 - 100.0		44.0	3.5	- 6.0
100.0 - 180.0				0.0
Rotations for Antarctica to Africa				
0 - 33.6	- 12	10.0	-41.0	5.0
33.6 - 140.0	12 -	10.0	-41.0	32.7
140.0 - 180.0				0.0
Rotations for India to Seychelles				
0 - 40.0	- 17	16.0	48.3	-22.4
40.0 - 54.3	17 - 23	13.1	12.0	- 7.6
54.3 - 63.7	23 - 28	13.1	12.0	-18.3
63.7 - 180.0	28 -			0.0
Rotations for Seychelles to Madagascar				
0 - 63.7	- 28			0.0
63.7 - 100.0	28 -	15.3	42.7	-17.9
100.0 - 180.0				0.0
Rotations for Australia to Antarctica				
0 - 9.0	- 5	9.7	36.5	- 6.8
9.0 - 19.5	5 - 6	19.2	32.7	- 5.4
19.5 - 27.1	6 - 8	16.1	29.4	- 4.0
27.1 - 32.6	8 - 12	2.1	38.8	- 3.0
32.6 - 35.6	12 - 13	5.0	33.2	- 1.6
35.6 - 42.1	13 - 18	- 0.3	34.8	- 3.2
42.1 - 55.0	18 -	14.1	25.4	- 8.1
55.0 - 180.0				0.0
Rotations for Campbell Plateau to Antarctica				
0 - 9.0	- 5	68.7	-79.7	9.4
9.0 - 19.5	5 - 8	76.7	-56.8	6.4
19.5 - 35.6	8 - 13	77.3	-32.8	12.3
35.6 - 42.1	13 - 18	-14.1	225.3	4.3
42.1 - 58.9	18 - 25	13.6	259.1	6.8
58.9 - 66.0	25 - 30	65.6	- 8.0	14.3
66.0 - 75.6	30 - 33	71.4	0.0	23.8
75.6 - 180.0	33 -			0.0
Rotations for Somalia to Arabia				
0 - 21.0		26.5	21.5	7.6
21.0 - 180.0				0.0
Rotations for Kolyma to Asia				
0 - 120.0				0.0
120.0 - 180.0		4.2	-111.0	15.2

Greenland-North America fit and the requirement to close Portugal to the Grand Banks. Because the fit of these continents is based on SCLATER et al. (1977), their initial configuration for Iberia is assumed in this reconstruction.

The initial motion between Europe and Iberia is equally controversial. The magnetic anomaly sequence in the North Atlantic (extending to number 34) suggests that a triple junction at the Bay of Biscay existed between 95 and 83 m.y. (KRISTOFFERSON 1978). Simple extrapolation of spreading rates from younger anomaly sequences places the initial motion near 125–130 m.y. (WILLIAMS 1975). However, marine sediment data may suggest an opening ocean in the Bay of Biscay as early as Jurassic (see RIES 1978, for review).

The rotations (Table 1) are derived from SCLATER et al. (1977) with initial motion commencing 125 m.y. ago. Although not of serious consequence for paleogeographic reconstructions, these rotations, which are based on the anomaly sequences in the Bay of Biscay, result in considerable mismatch of anomaly 33 between Iberia and North America, and should result in some error in paleobathymetric reconstructions of the North Atlantic.

e) Reconstruction of South America with respect to Africa

The initial reconstruction is that of BULLARD et al. (1965). The first recorded marine sequences on the margin of South America are Aptian (HERZ 1977). Based on the identification of magnetic anomaly M 11, LARSON & LADD (1973) and RABINOWITZ (1976) have placed the time of initial separation at 125.5 m.y. The rotations of South America with respect to Africa (Table 1) determined from fracture zones and compilations of magnetic lineations are those of SIBUET & MASCLE (1978). The Falkland Plateau as defined by the 3000-m contour is included in the reconstruction (BARRON et al. 1978). The continental nature of this plateau has been established by geophysical research and by deep-sea drilling (EWING et al. 1970; BARKER et al. 1976; RABINOWITZ et al. 1976).

The reconstruction of Indian Ocean

a) Reconstruction of Madagascar with respect to Africa

The paleoposition of Madagascar is one of the most poorly constrained aspects of Mesozoic plate tectonic reconstructions. Three possibilities are frequently cited: 1. Madagascar fixed with respect to Africa as it is at present, 2. a northerly fit adjacent to Kenya and 3. a southerly fit adjacent to Mozambique. An extensive review of the evidence for each of these possibilities has been presented by BARRON et al. (1978).

Much of the discussion has concerned the paleomagnetic data for the paleoposition of Madagascar, once thought to be unequivocal evidence for a northerly derivation (MCELHINNY & EMBLETON 1976). In particular, BARRON et al. (1978) and TARLING & KENT (1976) point out the inconclusive nature of the paleomagnetic data from Madagascar.

The magnetic anomalies in the Mozambique Basin have been used to support a northerly derivation (DELTEIL et al. 1978; SIMPSON et al. 1979) but the anomalies correlate poorly and cannot be considered to give conclusive evidence. Interestingly, there is no reduction of amplitude of the anomalies along several of the profiles over crust supposed to have been created during the Cretaceous quiet interval. Line 1 (Fig. 4 of SIMPSON et al. 1979) shows magnetic anomalies over the supposed Cretaceous quiet zone as large as those over crust assumed to have formed during M 0 to M 22 time. Since this model does not correctly identify the Cretaceous quiet zone, it is plausible that the identification of the rest of the anomalies is also incorrect. Their identification of lineations also appears to conflict with DSDP drilling results on Leg 25.

BUNCE & MOLNAR (1977), assuming N-S motion, termed some of the topographic features in the Somali Basin fracture zones. The supposed fracture zones have been frequently cited as evidence for N-S motion (e.g. SCRUTTON 1978).

Much of the geologic data both from Mozambique and Kenya are supportive of a southerly position (e.g. KENT 1972, 1973; FLORES 1973). In particular the sediment record of site 241 (KENT 1972, 1973) and geophysical surveys (FRANCIS et al. 1964; SCHLICH et al. 1974) indicated a wedge of sediments 4 km thick extending 300-400 km offshore. Site 241 penetrated only 1174 m yet reached late Cretaceous sediment. The 3 km of remaining undrilled sediment is inconsistent with a late Jurassic northerly fit of Madagascar. Either the proposed timing of separation (e.g. NORTON & SCLATER 1979) or the northerly derivation must be in error.

None of the three possibilities can be eliminated based on present data. In the reconstruction at 180 m.y. (Pl. 1), the southerly derivation is used. A position fixed with respect to Africa is equally acceptable geometrically with the fit of the southern continents and depends only on the nature of the crust of the southern Seychelles platform (Figure). The continental nature of this crust is questionable (SHOR & POLLARD 1963; DAVIES & FRANCES 1964; MATTHEWS & DAVIES 1966). POWELL et al. (1980) have recently presented a fit of the southern continents similar to BARRON et al. (1978) but with Madagascar in a northerly position. This suggests that the paleoposition of Madagascar may be less critical than originally indicated by BARRON et al. (1978).

The initial separation, based on a major episode of volcanic activity in Mozambique (COX 1970) and marine incursions recorded in Mozambique and Madagascar (FLORES 1970; FORSTER 1975), is placed at 140 m.y. Due to the lack of constraining data, a smooth rotation vector is derived to move Madagascar from its position adjacent to Mozambique to its present position with respect to Africa (Table 1).

b) Reconstruction of Antarctica with respect to Africa

The initial reconstruction of Antarctica to Africa is dependent on the paleoposition of Madagascar and on the evolution of the Antarctic Peninsula. The previously proposed reconstructions have been reviewed by BARRON et al. (1978). Most of these reconstructions are unacceptable because the Antarctic Peninsula overlaps with the Falkland Plateau (e.g. SMITH & HALLAM 1970) which is continental (see discussion on the fit of South America and Africa). For at least the last 100 m.y. there has not been relative motion between east Antarctica and the Antarctic Peninsula (WEISSEL et al. 1977; KELLOGG & REYNOLDS 1978). On the basis of paleomagnetic data

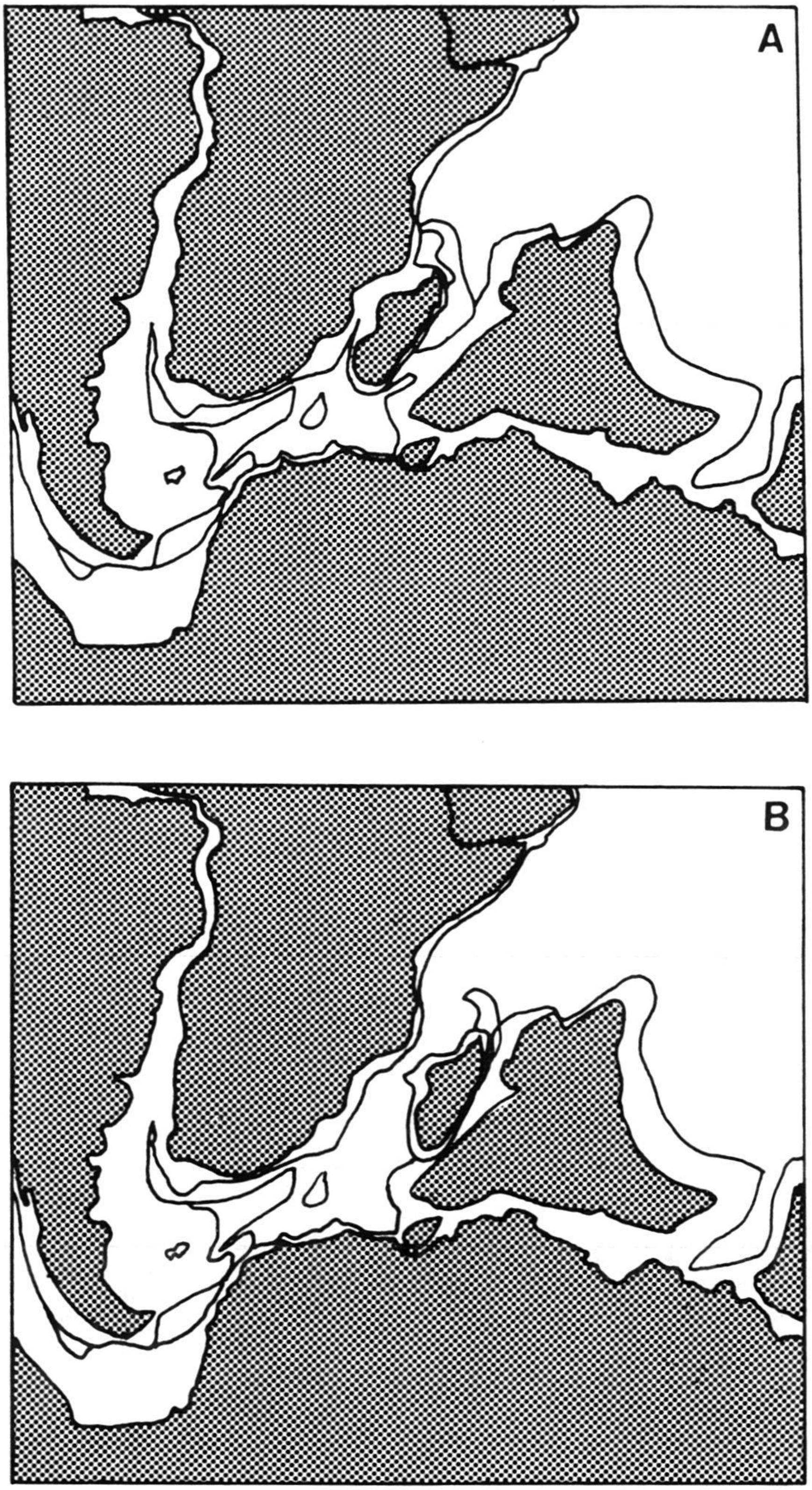

Fig. 1. Reconstruction of India, Madagascar, Seychelles, Africa, South America and Antarctica with *A* Madagascar rotated to a position adjacent to Mozambique, and *B* Madagascar fixed in its present position with respect to Africa. Note that in case *A* the southern Seychelles platform is considered to be continental and in case *B* the southern portion of the platform is formed after breakup of India and Madagascar. The reconstruction is the same as for 180 m.y. in Plate 1.

(KELLOGG & REYNOLDS 1978; VALENCIO 1979) and on the basis of Gondwanide orogenic trends (KATZ 1973), the curvature of the Antarctic Peninsula is probably primary. For these reasons the Antarctic Peninsula is placed adjacent to the western margin of South America and Antarctica is considered a single unit. This aligns eastern Antarctica with the Falkland Plateau. This reconstruction was discussed in detail by BARRON et al. (1978), HARRISON et al. (1979) and HARRISON et al. (1980). This is controversial, as some authors prefer to consider the Antarctic Peninsula as numerous microplates (e.g. DALZIEL 1980, in press). In some reconstructions with Madagascar in a northerly position adjacent to Kenya, the Antarctic Peninsula was rotated relative to Antarctica such that the peninsula was aligned with the Falkland Plateau and continuous with the southern Andes (DE WIT 1977).

The oldest magnetic anomaly lineations between Africa and Antarctica are 113-121 m.y. old (BERGH 1977). The separation of Antarctica from South America-Africa is associated with late Jurassic volcanic activity and marginal basin formation in the southern Andes and Antarctic Peninsula. Based on an extrapolation from the magnetic anomaly sequence of BERGH (1977) the initial separation of Africa and Antarctica occurred at 150 m.y. The initial breakup is placed at 140 m.y.

HARRISON et al. (1979) determined that the present day instantaneous pole (MINSTER & JORDAN 1978; NORTON 1976), the total rotation pole to close up Antarctica to Africa according to the fit of BARRON et al. (1978) and an intermediate pole proposed by BERGH (1977) were almost coincident. HARRISON et al. (1979) proposed that the relative rotation pole describing the movement between Antarctica and Africa has remained stationary since the two continents split apart. Little is known about the rates of rotation. NORTON (1976) suggested a half spreading rate of 0.8 cm/yr for the recent past, and BERGH (1977) suggested that the spreading rate for Mesozoic crust between 113 and 121 m.y. old was 1.75 cm/yr. Half spreading rates of 0.8 and 1.8 cm/yr are used with the change between them occurring at the time of anomaly 12/13, at which time there was a major change in the directions and rates of opening in the Indian Ocean (MCKENZIE & SCLATER 1971). The rotations are described in Table 1.

c) Reconstruction of India with respect to Seychelles

The fit of India to the Seychelles is based on the magnetic anomalies of WHITMARSH (1972) and SCHLICH (1974). The separation of the two elements occurred near anomaly 28 at 63.7 m.y. The rotations of India to Seychelles (Table 1) are based on the work of MCKENZIE & SCLATER (1971), SCHLICH (1974) and WHITMARSH (1972).

d) Reconstruction of the Seychelles with respect to Madagascar

The island of Mahe is composed of Precambrian hornblende granite (BAKER 1963; BAKER & MILLER 1964) and must be included in continental reconstructions. The nature of the crust of the Saya de Malha bank is open to speculation (see BARRON et al. 1978). The entire platform defind by the 2000-m contour is included in the maps presented here. The initial fit is determined by the reconstruction of

India to Antarctica as proposed by SMITH & HALLAM (1970) and Antarctica to Africa as discussed previously. This results in a reasonable reconstruction of Seychelles–India to Madagascar–Africa. If Madagascar has always been fixed in its present position with respect to Africa, no change in our reconstruction would be required. This modification would only imply that the Saya de Malha Bank is not continental. Due to the lack of magnetic anomaly data older than 71 m.y., the rotation of Seychelles to Madagascar is based on a single smooth rotation vector (Table 1).

e) Reconstruction of Australia with respect to Antarctica

The computer "best fit" of the edges of Australia and Antarctica (SPROLL & DIETZ 1969) is degraded in order to match the detailed geologic correlation of LAIRD et al. (1977). This also results in a more uniform seafloor spreading history (GRIFFITHS 1971). The oldest seafloor in this region is 55 m.y. (WEISSEL & HAYES 1972). A discussion of the magnetic quiet zone adjacent to the margins may be found in KONIG & TALWANI (1977). The rotations (Table 1) of WEISSEL et al. (1977) are used for motions back to anomaly 18. From anomaly 18 to the initial reconstruction, the rotation is based on the conclusions of GRIFFITHS (1971).

f) Reconstruction of the Campbell Plateau with respect to Antarctica

In some previous reconstructions (MOLNAR et al. 1975), East and West Antarctica were separated into two plates to accommodate the fit of Australia, Antarctica, the Campbell Plateau and the Lord Howe Rise. In the revised reconstruction of BARRON et al. (1978) most of the problematic overlap is removed because of the revised fit of Australia and Antarctica (discussed above). BARRON & HARRISON (1979) have shown that if the offset of the Stokes Magnetic Anomaly on the Campbell Plateau is accounted for, the separation of East and West Antarctica is no longer required.

The oldest magnetic anomaly between the Campbell Plateau and Antarctica is numer 33 and we assume that breakup occurred at 74 m.y. The rotations of MOLNAR et al. (1975) are modified (Table 1) as described by BARRON & HARRISON (1979).

g) Reconstruction of the Lord Howe Rise with respect to Australia

The initial fit and rotation parameters (Table 1) are those of WEISSEL & HAYES (1972). The initial separation, based on the oldest sequence of magnetic anomalies, occurred at approximately 74 m.y. ago.

h) Reconstruction of Arabia with respect to Africa

The position of the rotation pole is obtained from MCKENZIE et al. (1970), and the rotation angle is obtained by measurement of the distance across the Red Sea, which is closed up by this movement. The actual movement is quite small, and we have not bothered to allow for any of the proposed more complicated seafloor spreading patterns of the Red Sea (RICHARDSON & HARRISON 1976; GIRDLER

& STYLES 1974). The time for opening of the Red Sea at 16 m.y. was calculated so that the present spreading rate closes up the Red Sea. The rotations are given in Table 1.

i) Reconstruction of Somalia with respect to Arabia

The pole and rotation angle is that used by MCKENZIE et al. (1970) from the work of LAUGHTON (1966). The age of the start of spreading in the Gulf of Aden was calculated from the present spreading rate, which would close the Gulf at 21 m.y. The rotations are given in Table 1.

In a comprehensive model of the seafloor spreading pattern of the Indian Ocean, BARRON & HARRISON (1980) have demonstrated that these rotations for the southern continents are consistent with available data pertaining to the Indian Ocean evolution.

The reconstruction of Arctic Ocean

a) Reconstruction of Kolyma with respect to Asia

An unavoidable consequence of the evolution of the North Atlantic Ocean is the requirement for a plate boundary between Asia and North America. SMITH & BRIDEN (1977) placed the boundary in the Bering Sea. This must be rejected on the basis of geologic correlations between Alaska and Asia and on the basis of dredge samples in the Bering Sea (see CHURKIN 1972, for review of the data). The Verkhoyansk Mountains may be considered as a second possible plate boundary. This suture is dated at approximately 120 m.y. (NALVIKIN 1973). Between 180 and 120 m.y. there must have existed a plate boundary between the block east of Verkhoyansk (Kolyma) and Eurasia, but since the suture is older than the opening of the North Atlantic (95 m.y.), a plate boundary separating Asia from North America is still required by the geometry.

FUJITA (1978) proposed a complicated geometry, with several pre-Cenozoic plates, based on the geology of northeastern USSR. No poles of rotation were presented because there is no seafloor record. Prior to the formation of the Verkhoyansk Mountains, a three plate geometry is required as a minimum. Although a more complicated scenario is possible, we have assumed the simplest geometry. The Siberian or Kolyma block is defined by the Verkhoyansk suture and the Penzhina suture between Kolyma and Kamchatka (see FUJITA 1978); this zone is extended through the Bering Sea along the structure of the Chukotka Range of Siberia and the Brooks Range of Alaska. Thus the Siberia or Kolyma block includes the region in Alaska north of the Brooks Range.

The rotation of the Kolyma block with respect to North America or with respect to Eurasia is speculative. Paleomagnetic data suggest a lower latitude origin prior to the Triassic but the data are largely confined to the margins of the sutures (MCELHINNY 1973; FUJITA 1978). This motion is poorly constrained within the framework of the other plates.

The northern Canadian margin is a rifted margin (CHURKIN 1969) characterized by marine incursions and sill and dyke complexes (e.g. BALKWILL 1973) of Triassic and Jurassic age. FUJITA (1978) suggested that the Canadian Basin is oceanic, formed by the separation of a small plate (Novosibirsk) from the Canadian margin. A late Triassic or early Jurassic separation is supported by the geologic data. In using a simple three plate geometry, the entire Kolyma block is rotated to a position adjacent to the northern Canadian margin prior to 180 m.y. ago. This is similar to the proposal of HERRON et al. (1974), but the plate boundaries are defined to include eastern Siberia and northern Alaska. This is supported by the fact that there are no distinguishable differences between paleofloras and paleofaunas of the late Paleozoic and early Mesozoic between Kolyma and Asia (MEYEN 1973; KRASSILOV 1977). This would be expected if Kolyma had a far southerly derivation as suggested by FUJITA (1978). The Kolyma block fits extremely well into the Arctic Basin with the reconstructed positions of Greenland, North America and Asia. There is some overlap between Asia and Kolyma if the suture is drawn at the Verkhoyansk Mountains. The overlap is larger if the SCLATER et al. (1977) fit of the North Atlantic is used rather than the BULLARD et al. (1965) fit. As the main arc complex is considerably east of the Verkhoyansk Mountains (e.g. VINOGRADOV et al. 1968) this may not be a problem.

A simple scenario is proposed: firstly, separation of Kolyma from North America approximately 180 m.y. ago; secondly, formation of the Verkhoyansk Mountain belt at 120 m.y. ago; and finally, with the opening of the North Atlantic, Asia (including the portion of Alaska north of the Brooks Range) converges with North America resulting in the present day configuration. The character of this final stage of deformation is described by PATTEN & TAILLEUR (1977). With the opening of the North Atlantic, the convergence is dependent on the rotation of Europe with respect to North America. It should be noted that there is some overlap between the Kolyma block and Alaska (40 m.y.) indicating some error in the motions suggested by the magnetic anomaly sequence in the North Atlantic.

A smooth rotation vector (Table 1) is used to describe the motion of Kolyma with respect to Asia from 180 to 120 m.y. when the Kolyma block becomes attached to Asia.

Southeast Asia, the Mediterranean, Caribbean and other regions

a) Southeast Asia

From geologic data, the fusion of southeast Asia to Eurasia was probably completed prior to the late Jurassic (BURRETT 1974). For this reason, Southeast Asia is fixed with respect to Eurasia in our reconstructions. In an alternative hypothesis based largely on the assumption of a "Greater" India large enough to fill Sinus Australia, POWELL & JOHNSON (1980) require a 550 km westward motion of the entire Southeast Asia block during the last 50 m.y. Without this motion "Greater" India will overlap Southeast Asia during the northward motion of India. Paleomagnetic data may indicate that Southeast Asia was not fixed with respect to Asia in the Cretaceous (MCELHINNY et al. 1974).

There is evidence for seafloor spreading in the South China Sea and BEN-AVRAHAM & UYEDA (1973) have reconstructed Borneo to China but this is in conflict with the geology of the Indonesian region (see AUDLEY-CHARLES 1978, for review). There do not appear to be any significant displacements between Sumatra, Java and Borneo and the western China Sea since the Paleozoic and consequently we have defined the continental outline of this block by the 200-m contour which is close to the boundary of the pre-Tertiary core described by MURPHY (1975). The evolution of the eastern segment of Indonesia, including Sulawesi and the Philippines, remains complicated. MURPHY (1973) has proposed that the Philippines developed during the Oligocene with the coalescence of arc-trench complexes. Conversely, in a model similar to that for the evolution of Japan, the Philippines may have formed as an arc on the margin of China during the Triassic and Jurassic (AUDLEY-CHARLES 1978).

b) Southern Europe

The plate tectonic evolution of the southern European-Mediterranean region is extremely complicated. The evolution has been described both from the viewpoint of a single evolving plate boundary with continuous tectonic zones (SMITH 1971) and from the viewpoint of numerous microplates (DEWEY et al. 1973).

Only a large scale evolution is presented, primarily because of the difficulty in positioning the small continental fragments either in their correct initial configuration or within any temporal framework. Poles of rotation have not been presented for individual continental fragments because of the scarcity of constraining data. Following BIJU-DUVAL et al. (1978) the following constraints are considered: 1. Pre-Triassic Tethys existed between the Hercynian foldbelt and the Arabic-African-Anatolian-Apulian plate. 2. Apulia-Anatolia rifted from Africa-Arabia approximately 180 m.y. ago. 3. Apulia-Anatolia collided with Eurasia during the Albian-Cenomanian. 4. During the Miocene, Sardina-Corsica separated from the south of France.

c) The Caribbean and Gulf of California

Despite an abundance of data the plate tectonic reconstruction of the Caribbean remains poorly constrained. The present day easterly motion of the Caribbean plate with respect to South America and North America started in the Eocene-Oligocene. This is characterized by numerous northwest trending right lateral strike-slip faults and some component of thrusting on the northern margin of South America and left lateral motion along the Motagua fracture zone in Guatemala (JORDAN 1975).

The early history is more speculative. Basement of at least Paleozoic age extends southward from Mexico to southern Guatemala and northern Honduras (MALFAIT & DINKELMAN 1972). The segment of older crust south of the Motagua fault is probably a fragmented section of southern Mexico which was displaced eastward since the Cretaceous (MALFAIT & DINKELMAN 1972) along a transform on the Yucatan coast.

Reconstructions of Africa and South America to North America (e.g. BULLARD et al. 1965; SCLATER et al. 1977) still result in overlap of South America and southern Mexico. SMITH & BRIDEN (1977) eliminate the overlap with southern Mexico by rotating the entire Yucatan Peninsula into the Gulf of Mexico. It appears more logical, because displacement of the Yucatan Peninsula is required in order to remove the overlap, that the displacement should be along a series of left lateral transforms, thus preserving the general tectonic framework indicated by the motion of the segment south of the Motagua fault. ZIEGLER et al. (1979) have hypothesized a major transform system through Mexico and along the western margin of the United States in order to fit South America into the Gulf of Mexico. An initial fit of this sort may be necessary, at some time prior to the Jurassic, in order to explain the development of the Ouachita Mountains. In the reconstructions presented here portions of Mexico have not been displaced with respect to North America due to a lack of constraining data.

Extension of the trench along the western Mexico boundary in the Eocene (MALFAIT & DINKELMAN 1972) resulted in andesitic volcanism which links South America and North America by the Isthmus of Panama. EMILIANI et al. (1972) estimated that the oceanic connection was eliminated approximately 6 m.y. ago.

Based on DSDP leg 64 results, the initial formation of the Gulf of California occurred in the late Miocene (CURRAY, MOORE et al. 1979).

d) The problem of Sinus Australis

In the SMITH & HALLAM (1970) reconstruction of the southern continents an oceanic seaway, Sinus Australis, existed between India and Australia. The magnetic anomaly data (HEIRTZLER et al. 1978; MARKL 1974; LARSON 1975, 1977) and the geology of western Australia (VEEVERS et al. 1971, 1975) indicate that this seaway did not exist.

The numerous solutions to this problem were discussed by BARRON et al. (1978). Most of the discussion centers around the pre-collision size of India. Only the amount of crustal shortening in the Himalayas which can be measured, estimated to be 300–500 km (GANSSER 1966, 1974; LEFORT 1975), is palinspastically reconstructed. A portion of western Australia which should be adjacent to continent remains juxtaposed with ocean.

e) Japan

The timing of the separation of Japan from the margin of Asia has been postulated as ranging from the Cretaceous to the Miocene (see UYEDA & MIYASHIRO 1974, for review). The predominant view is that the Japan Sea originated during the Oligocene–early Miocene (KARIG et al. 1975).

f) Palinspastic reconstruction

Palinspastic reconstruction is very significant for cases of continent–continent collisions. Within the time frame considered, major continental collisions, resulting in crustal shortening, have occurred in the Alpine–Mediterranean region, the Himalayas and the Verkhoyansk Range. Continental outlines are typically defined by the suture or plate boundary between two converging continental elements. Thus the northern margin of India is logically defined by the Indus suture, as is the southern margin of Tibet.

Gansser (1966, 1974) has estimated 300-500 km of crustal shortening resulting from the Himalayan orogeny, based on tectonic windows in overthrust belts, folding and the character of the thrusted blocks. The paleogeographic maps in Plates 1-9 include a 300 km wide strip surrounding the northern margin of India as an estimate of the pre-collision outline of India. Several other lines of evidence indicate that this overly simplified palinspastic reconstruction is conservative. 1. The spreading rate on the India-Antarctica and India-Seychelles Ridge decreases from 100-180 mm/yr to only about 50 mm/yr at 40 m.y. ago. Molnar & Tapponnier (1975) have suggested that this indicates the time of initial collision between Asia and India. The position of India and Asia at 40 m.y. (Pl. 8) indicates several hundred kilometers of additional crustal shortening would be required if India and Asia were in contact at this time. Molnar & Tapponnier (1975) described a model for crustal shortening in Asia of more than 1000 km. 2. The problem of Sinus Australis (discussed previously) indicates that India must have been larger in order for India and Australia to be contiguous prior to 140 m.y. ago (see Pl. 3). Veevers et al. (1975) have proposed a "Greater" India to satisfy this constraint.

The outlines of India and Asia are also unlikely to be as smooth as the present plate boundary, in which case the most deformation must have occurred in the areas of first contact (Dewey & Bird 1970). In addition to the difficulty in determining the actual shape of the pre-collision margins, the extent to which these areas were inundated by shallow seas is not possible to estimate. Similar problems are encountered in any attempts to reconstruct palinspastically the Alpine region (e.g. Laubscher 1971; Trümpy 1975). In the case of the Alpine orogeny, the shapes of the pre-collision continents are less constrained by initial reconstructions and seafloor spreading evidence is lacking. The continental shortening in the Austroalpine region may also exceed several hundred kilometers.

Establishment of paleolatitudes

All of the relative rotations are performed using a frame of reference fixed with respect to North America. Paleomagnetic pole positions are used to determine the correct paleolatitude lines.

The mean paleomagnetic pole for any epoch is thought to be closely aligned to the spin axis of the earth. This assumption of an axially geocentric dipole is valid for archaeomagnetic data (McElhinny 1973) and evidence for its applicability to past epochs has also been presented. For instance, when the distribution of Phanerozoic paleoclimatic indicators, such as reefs and evaporites, are compiled with respect to paleomagnetic pole positions, their distribution becomes much more restricted with respect to latitude, approaching modern zonal patterns (Irving & Briden 1962; Briden & Irving 1964).

Paleomagnetic pole positions listed by geologic period, except for the Tertiary which is divided into the Neogene and Paleogene, are given by McElhinny (1973). Thus for the time period under consideration, the data are in five groups of paleomagnetic poles, the Neogene, Paleogene, Cretaceous, Jurassic and Triassic. The relative rotations, with respect to North America, of all plates were calculated at ages corresponding to the midpoints of these time intervals, and used to rotate all non-North American poles for each epoch. A mean pole was determined using Fisher's (1953) statistics, regarding each study (including those of North America) as a single independent measurement of the mean pole. Van Alstine & de Boer (1978) and Harrison (1979) have pointed out that it is incorrect to give unit weight to each study, but since the data from all the different continents are combined (rather than comparing studies to reconstruct the position of two continents with respect to each other) the error in doing this is minor. The average paleomagnetic pole position for each map, produced at 20-m.y. increments, is based on a linear interpolation along the great circles connecting consecutive poles (Table 2).

These mean poles are then used as origins for the map projections. A transverse Mercator projection is plotted using the paleomagnetic pole as the pole of the projection. This means that the paleolatitude lines can be drawn horizontally across the map. The mean pole is used as the center for the stereographic projections, in which case the paleolatitude lines can now be drawn as circles about the paleomagnetic pole. Longitude is not given, because absolute longitude is meaningless in the context of the paleomagnetic method.

In order to draw additional paleolatitude lines on the Mercator projection, the following formula gives the distance of the paleolatitude line from the paleoequator:

$$x = 0.288\, h \log_e \tan(\lambda/2 + \pi/4),$$

where h is the total height of the map, and λ is the paleolatitude in radians. In order to draw additional paleolatitude lines on the stereographic projection, the

Table 2: *Paleopole positions.*

A) Paleopole positions at 20 million year increments.

TIME MYBP	LATITUDE (°N)	LONGITUDE (°E)
180	71.9	103.0
160	79.0	101.6
140	79.7	128.0
120	78.6	160.0
100	76.0	176.9
80	77.2	177.1
60	78.2	177.2
40	80.2	174.0
20	83.2	160.0

B) Mid-point ages and positions for the five groups of paleomagnetic poles, the Neogene, Paleogene, Cretaceous, Jurassic and Triassic.

TIME MYBP	LATITUDE (°N)	LONGITUDE (°E)
12	84.8	157.0
52	78.6	177.3
102	76.1	176.9
158	79.7	101.5
209	61.6	104.4

following formula gives the radius of the paleolatitude line from the paleogeographic pole:

$$y = 0.576\, w \tan(\pi/4 - \lambda/2),$$

where w is the total width of the map. Both the map projections are conformal, which means that small areas retain their correct shapes. In order to move small areas of land about on these maps, the only thing which needs to be taken care of is a change in scale on moving from one paleolatitude to another on the same map, or on moving from one map to another. The maps are plotted so that the largest scale conversion factor is the same on each projection (i.e. the equator on the Mercator, and the pole on the Stereographic). The Mercator scale is given by

$$S_M = \frac{4 \times 10^9 \cos\lambda}{d},$$

where d [cm] is the width of the Mercator projection map. The scale for the Stereographic projection is

$$S_S = \frac{2.21 \times 10^9 \cos^2\left(\frac{\pi}{4} - \frac{\lambda}{2}\right)}{w}$$

if w is measured in cm.

Other methods of fixing the absolute positions of the continents have been proposed. MORGAN (1971) has suggested that deep mantle plumes (hot spots) remain fixed with respect to each other. MINSTER et al. (1974) and CHASE (1978) suggested that the hot spot frame of reference is stationary with respect to the rotational axis of the earth, but MOLNAR & ATWATER (1973) and BURKE et al. (1973) have shown that motions between hot spots have occurred during the Tertiary and that the rate of relative motion may approach 0.8–2 cm/yr.

These conclusions concerning the motions of hot spots are dependent on the choice of continental paleopositions and the determination of relative motions. In particular, in order to compare Pacific hot spot traces with those in the Atlantic and Indian Oceans, the relative rotations must be based on the poorly constrained history of Antarctica (e.g. see discussion by BARRON & HARRISON 1979). With the exception of the last 5–10 m.y. (MINSTER et al. 1974; CHASE 1978) the relationship between the hot spot frame of reference and the rotational axis has not been demonstrated.

VAKHRAMEEV (1975) used the characteristics of leaf shape and size to determine the paleoposition of the Arctic circle. Plants adapted to the conditions of polar night have highly distinctive morphologic characteristics which can be readily rcognized. It is interesting to note that the paleoposition of the north pole for the Jurassic, which is based on Soviet paleobotanical data, is only a few degrees from the result generated for our 180-m.y. map. The pole position of SMITH & BRIDEN (1977), which was generated from a considerably different set of relative continental positions (the reconstruction of the southern continents was that of SMITH & HALLAM 1970) is far from that predicted by the paleobotanical data.

The record of marine sequences

Because global tectonic data, including ocean basin bathymetry through time, are not adequate, the shoreline position cannot be predicted theoretically. Paleogeographic maps must be constructed by analysis of transgressive-regressive sequences on the continents and the analysis of sedimentary basins.

The land-sea distribution at 20-m.y. increments is based on the following regional analyses: *North America:* SCHUCHERT (1955), MCCROSSAN & GLAISTER (1966), NELSON (1970), MALLORY (1972) and COOK & BALLY (1975); *Greenland:* SCHUCHERT (1955), COOK & BALLY (1975) and BIRKELUND & PERCH-NIELSEN (1976); *Europe:* TERMIER & TERMIER (1952) and BRINKMAN (1960); *USSR:* VINOGRADOV et al. (1967, 1968); *South America:* HARRINGTON (1962); *Africa:* TERMIER & TERMIER (1952); *Madagascar:* TERMIER & TERMIER (1952), FLORES (1970); *India:* TERMIER & TERMIER (1952), ESCAP Proceedings (1976); *Southeast Asia:* PUPILLI (1973), MURPHY (1975), AUDLEY-CHARLES (1978), FLETCHER & SOEPARJADI (1976) and WOOLLANDS & HAW (1976); *Australia:* TERMIER & TERMIER (1952), BROWN et al. (1968) and AUDLEY-CHARLES (1978). The paleogeography of *Antarctica* is not specified due to a lack of data. Sub-ice topography is not considered because of the difficulty in extrapolating the paleogeographic evolution through time. The paleogeography used for Greenland is based only on evidence from the margins of the continent. The detail of the shoreline configuration is reduced from that described in some of these regional compilations because of the scale of the global paleogeographic maps.

The stratigraphic subdivisions of each author were converted to millions of years using the time scale of VAN HINTE (1976*a*, *b*) for the Jurassic and the Cretaceous and of BERGGREN (1972) for the Cenozoic. Table 3 gives the stratigraphic time interval in millions of years, used for each of the 20-m.y. increment maps, for the major sources of paleogeographic data. Even in cases where the stratigraphic interval (e.g.

Table 3: *Stratigraphic intervals in millions of years, used to plot land-sea configurations at each 20-m.y. increment, for several of the major data sources.*

TIME MYBP	AUTHORS					
	Schuchert (1955)	Cook and Bally (1975)	Termier and Termier (1952)	Harrington (1962)	Vinogradov et al. (1967, 1968)	Brown et al. (1968)
180	192 -171	192 -171	192 -176	189 -178	183 -178	192 -171
160	171 -149	171 -149	176 -156	165 -156	171 -156	171 -149
140	143 -135	143 -135	143 -135	141 -140	141 -135	149 -135
120	121 -107	135 -112	121 -108	135 -115	121 -115	135 -100
100	107 - 92	112 - 97	108 - 92	115 - 92	108 -100 100 - 92	
80	86 - 78	86 - 78	82 - 70	82 - 65	83 - 78	100 - 65
60	65 - 53.5	65 - 53.5	65 - 53.5	65 - 53.5	65 - 60	
40	43.0- 37.5	53.5- 37.5	53.5- 37.5	49 - 30	43.0- 37.5	
20	22.5- 5.0	22.5- 5.0	22.5- 5.0	22.5- 16.0	22.5- 16.0	
Total Number of Maps (192-0 m.y.)						
	19	14	15	23	30	6

121-107 m.y.) is poorly centered about the map time (e.g. 120 m.y.), the data from the various authors have not been interpolated between stratigraphic intervals.

Whereas the rotations in Table 1 are used to determine paleocontinental positions at specific times, the paleogeography is an average of several million years because the land-sea distribution is based on stratigraphic subdivisions. These subdivisions are also of unequal time lengths. In addition, each continent has not been described with equal detail in time and space, and consequently the degree to which a shoreline is smoothed and the time interval represented for individual continents is also a variable. For instance, BROWN et al. (1968) mapped the distribution of marine basins in Australia by period, providing a total of five maps during the last 192 m.y., whereas VINOGRADOV et al. (1967, 1968) give a total of 30 maps for the USSR over the same length of time. However, this difference in the length of the time segment may not necessarily lead to large errors. During the entire Tertiary period marine sedimentation in Australia is limited to several relatively small basins (Carnavon, Eucla, Murry, St. Vincent, Otway, Bass and Gippsland Basins) for which a description of the sedimentary sequence (BROWN et al. 1968) is sufficient to produce accurate paleogeographic maps at 20-m.y. increments.

In general, the less known the area and the larger the time segment, the greater the smoothing of the shoreline position. There is also a greater possibility that the paleogeography does not represent synchronous shoreline positions if the interval represented by the map is large compared to regional tectonic effects. WISE (1972) demonstrated a systematic increase in the apparent percentage of flooded continent, measured on paleogeographic maps, for longer time slices.

WISE (1972, 1974) notes the following additional errors in determining the land-sea distribution through time: 1. The record is obscured by erosion, burial and metamorphism. 2. Continental and upland deposits are more subject to erasure. 3. Palinspastic reconstruction is rarely considered. Because of these sources of error, the farther back in time we go, the greater the degree of inaccuracy.

Paleogeographic maps

Three map projections at each 20-m.y. increment, from 180 m.y. to the present, are given in Plates 1-9. The paleogeography at each time interval is plotted using a Mercator projection, extending to 70° in latitude, and northern and southern hemisphere stereographic projections. Both the present-day land outline and the edge of each continental element are indicated. For continents bordering the Indian, Atlantic and Arctic Oceans, the edge of the continent is assumed to be the 2000-m contour except for the Falkland Plateau which is outlined by the 3000-m contour. The continental margin in Southeast Asia and adjacent to China is the 200-m isobath. The outlines of Somalia, India, Tibet, southern Europe and northern Saudi Arabia are plate boundaries or suture zones. A line is drawn around the northern margin of India in order to illustrate its extent with a conservative amount of crustal shortening (300 km). The present day, 5° latitude longitude grid, which was used as the basis to plot land-sea distribution for each continent, is also given. The areas of exposed land at each time increment are indicated by shading. Paleolatitude lines at

0°, 30° and 60° are plotted on each map and the pole position is plotted on the stereographic projections.

At 180 m.y. (Pl. 1) there exists essentially one single exposed continental mass which is continuous from pole to pole. The continental fit is based on the 2000-m contour, and the land area is shown to be continuous between these reconstructed continents. Likewise, continental platforms such as the Falkland Plateau, the Lord Howe Rise, the Campbell Plateau and the Seychelles are arbitrarily considered to be exposed land when these fragments are reconstructed to pre-rift configurations. The area of crust connecting Alaska with Kamchatka, which is presently shallow shelf, is also considered to be exposed land, connecting two known areas of land.

At this time marine deposition on the continents is limited to areas bordering the Tethys Ocean and the Pacific Ocean. It should be noted that present day outlines along active margins, such as Kamchatka or the Aleutian arc, give a misleading impression of the area of epicontinental seas because they are sites of active accretion.

At approximately 180 m.y. ago, North America and Africa began to separate, the Kolyma block was rifted from the northern margin of North America and the Anatolia-Apulia block, which has been rigidly reconstructed to a position adjacent to North Africa also began to separate.

The paleogeographic reconstruction at 160 m.y. (Pl. 2) shows the increase in the area of epicontinental seas associated with the formation of the early Atlantic and Arctic Oceans. In particular, the rifting of the Kolyma block from North America is associated with extensive inland seas extending into the area between Greenland and Norway and into western North America. There is likely to be a shallow marine connection between Tethys and the proto-Atlantic. The nature of the connection to the Pacific is dependent on the evolution of the Caribbean region which is not yet adequately understood.

The reconstruction at 140 m.y. (Pl. 3) illustrates further increase in the area of epicontinental seas. The reconstruction indicates a connection between Tethys and the Pacific Ocean through the opening Atlantic. The Arctic Ocean has increased considerably in size but deep water connections into this ocean basin apparently do not exist at this time.

At approximately 140 m.y. the breakup of the southern continents into three land masses, Australia-Antarctica, South America-Africa and Madagascar-India, was initiated. This is associated with marine incursions in all the areas of initial rifting.

The formation of the proto-Indian Ocean is illustrated in Plate 4 (120 m.y.). At this time the margins of Antarctica probably were characterized by marine deposition, but, unfortunately, the paleogeography of this continent is very poorly constrained. At 125 m.y. the initial separation of Iberia and North America occurs and South America and Africa begin to separate.

It is notable that the increase in the area of marine sedimentation does not appear necessarily as a global phenomenon. Whereas much of Australia becomes inundated at 120 m.y., the area of marine deposition in Asia apparently has decreased from 140 m.y. to 120 m.y. (compare Pl. 3 and 4).

At 120 m.y. the Kolyma block converged with Asia forming the Verkhoyansk Mountains. A deepwater connection between the Pacific and the Arctic Oceans may have existed at this time.

The largest area of epicontinental seas occurs at 100 m.y. (Pl. 5). Extensive marine transgression in Africa was associated with the increased separation of Africa and South America. In the previous two maps the Antarctic Peninsula was diverging from South America but, because of the opening of the South Atlantic, these two elements have begun to converge. There is clearly a deepwater connection between the Pacific and the Tethyan seaway through the proto-Indian Ocean. The South Atlantic is restricted in the north in the area of the Romanche fracture zone and in the south by the Falkland Plateau.

At 100 m.y. Madagascar was fixed with respect to Africa and Seychelles-India began to separate from Madagascar. Anatolia-Apulia had converged with the European continent.

The earth is still characterized by extensive shallow seas at 80 m.y. (Pl. 6). At 95 m.y. North America, Greenland and Europe had begun to rift apart. Any deepwater connection to the Arctic was limited at 80 m.y. because of the marginal offset of the Svalbard fracture zone south of Spitsbergen. In this reconstruction the Antarctic Peninsula and the southern Andes form a continuous chain eliminating the Pacific-Indian deepwater connection. HARRISON et al. (1979) have discussed the geologic and plate tectonic evolution of this region in detail.

At approximately 75 m.y. ago the Lord Howe Rise and the Campbell Plateau begin to rift from Australia and Antarctica. This is in part characterized by local marine transgressions shown on Plate 6.

The reconstruction at 60 m.y. (Pl. 7) clearly shows a dramatic decrease in the area of shallow seas. A deep water connection to the Arctic ceased to exist from the Pacific because of the convergence of Asia and Alaska, with the opening of the North Atlantic. The Atlantic connection to the Arctic continued to be limited by the marginal offset in the Svalbard region. The Lord Howe Rise and the Campbell Plateau had separated from the Australia-Antarctica block and are assumed to have subsided largely below sea level. The Seychelles became fixed with respect to Africa at 64 m.y. and began to rift away from India. The Antarctic Peninsula and South America remained linked in a continuous chain. The nature of the link between the Mediterranean and the North Atlantic is open to question but there is a distinct Pacific-Atlantic connection and the South Atlantic is unrestricted to the north and south.

At 40 m.y. (Pl. 8) there is a slight increase in the area of epicontinental seas. Australia had rifted from Antarctica (55 m.y.) but this was apparently not associated with extensive development of marine basins on the southern margin of Australia. The initial collision of India and Asia probably occurred at this time (see previous discussion) eliminating the old Tethyean seaway. As South America and the Antarctic Peninsula diverged the Scotia arc began to form. Japan began to separate from Asia in the Oligocene.

At 20 m.y. (Pl. 9) the configuration of the continents and ocean basins is very similar to the present. This is the time of maximum exposed continental area. This area is larger than at present because of the extensive shelf seas at high latitudes in the northern hemisphere areas, presently rebounding after unloading of the glaciers. During the middle Miocene the Scotia arc ceased to be a barrier to circumpolar flow. The Gulf of California began to form and the Philippines came in to existence.

Discussion

These maps differ significantly from previous paleocontinental or paleogeographic reconstructions largely because of a considerably more comprehensive data set. Several aspects continue to be poorly constrained. In particular, there is considerable controversy over the nature of the initial reconstruction of continents, even concerning frequently cited fits of North America and Africa. In terms of the numbers of continental reconstructions proposed for the southern continents (see BARRON et al. 1978), the evolution of the Indian Ocean is probably the most controversial. In other areas, such as the Caribbean and southern Europe there is an abundance of data, yet initial configurations and subsequent motions are not well constrained. These reconstructions are the best defined over the last 100 m.y. The reconstructions prior to this time period are one possible interpretation of the data from continents and the seafloor.

It is interesting to note that these reconstructions result in some new interpretations of existing data. As one example, based on previous reconstructions (e.g. SMITH & BRIDEN 1977), FRAKES (1979) interpreted the distribution of evaporite deposits during the Cretaceous to indicate that the down-going branch of the subtropical circulation pattern was displaced 10–15° poleward. In these revised reconstructions the evaporite deposits are limited to the zone 30° north and south of the equator (similar to today), suggesting that the Hadley cell is a relatively stable feature of the atmospheric circulation. A second example is that isofloras (e.g. VAKHRAMEEV 1975) separating floral provinces, during the Jurassic and Cretaceous, appear much more as zonal elements (parallel to paleolatitude lines) in these reconstructions than previously.

Plotting and examining various types of geologic data using these paleogeographic reconstructions can result in a more accurate interpretation of the geologic record. When tectonic models of the evolution of the ocean basins are available, global synthesis of different stratigraphic intervals will be possible for the first time.

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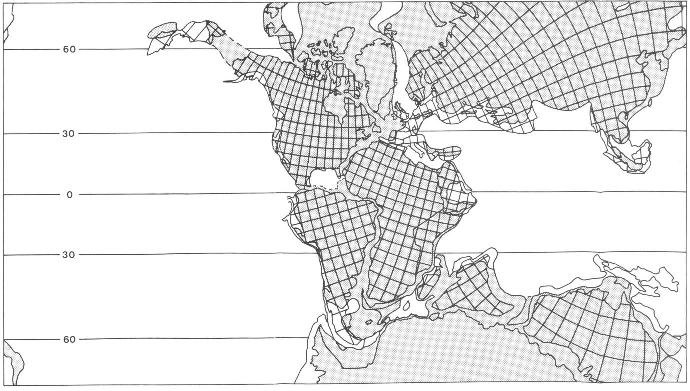
Plates 1–9

Paleogeographic maps at 180, 160, 140, 100, 80, 60, 40 and 20 m.y. Each time increment is illustrated with a Mercator and a north and south polar Stereographic projection. 30° paleolatitude lines are indicated. The maps and map projections are described in the text.

MERCATOR AT 180 MILLION YEARS



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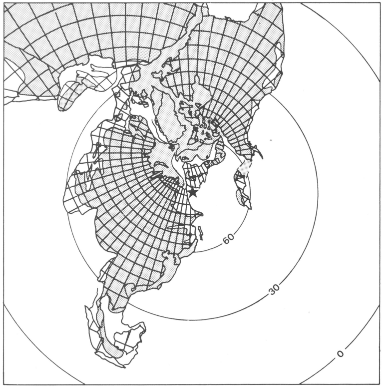

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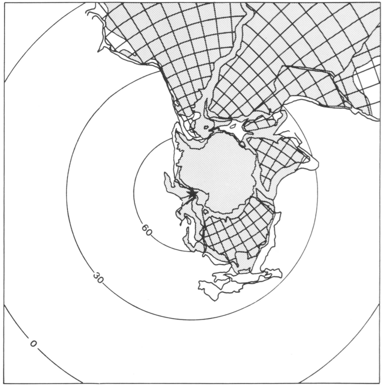

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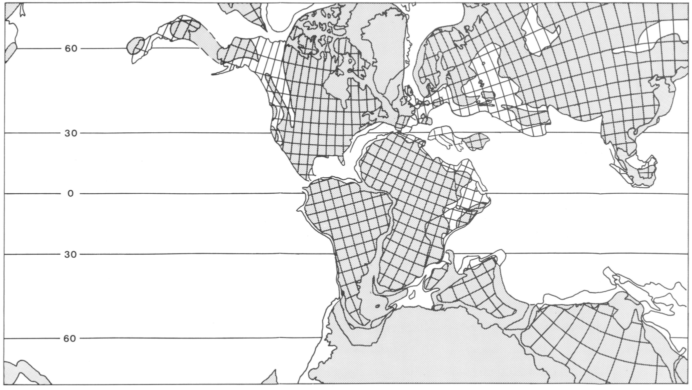

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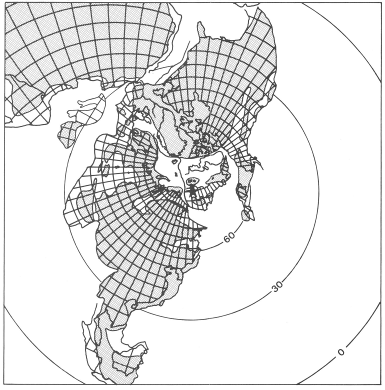

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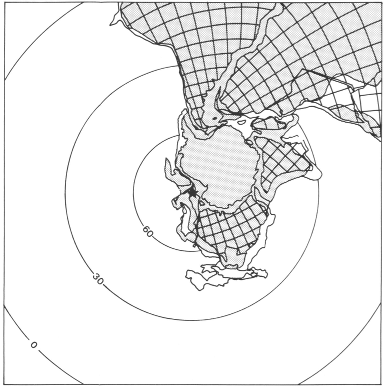

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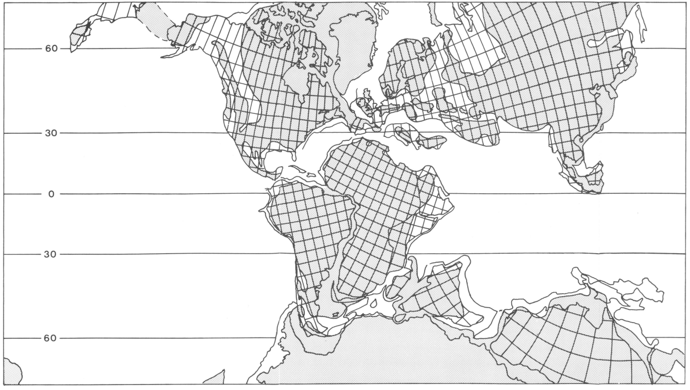

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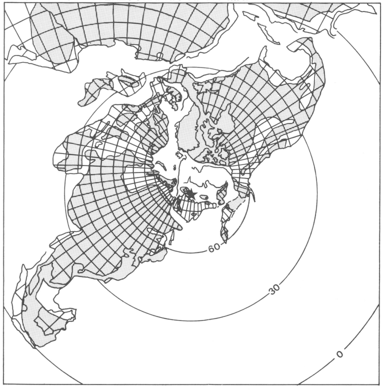

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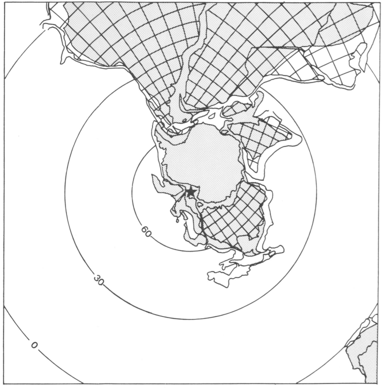

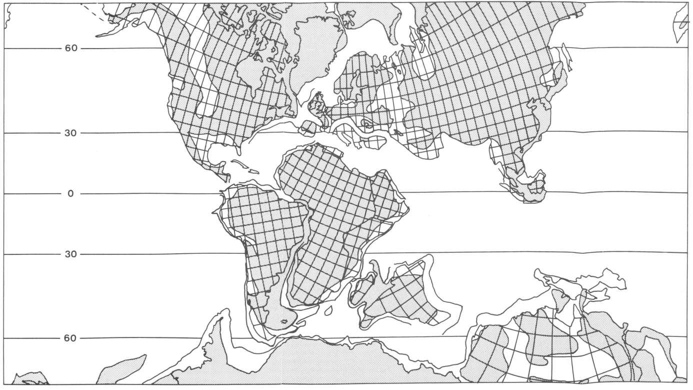

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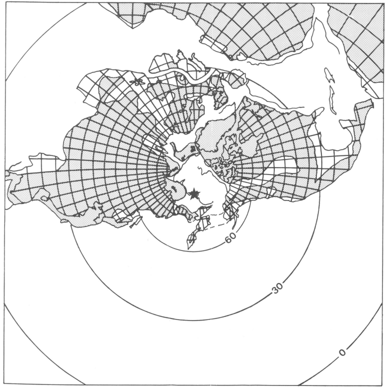

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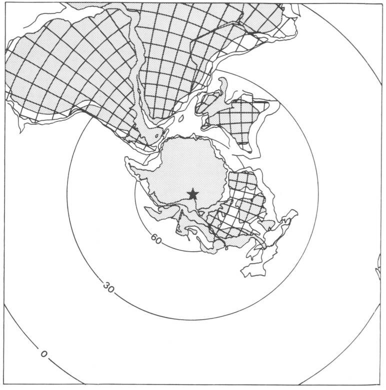

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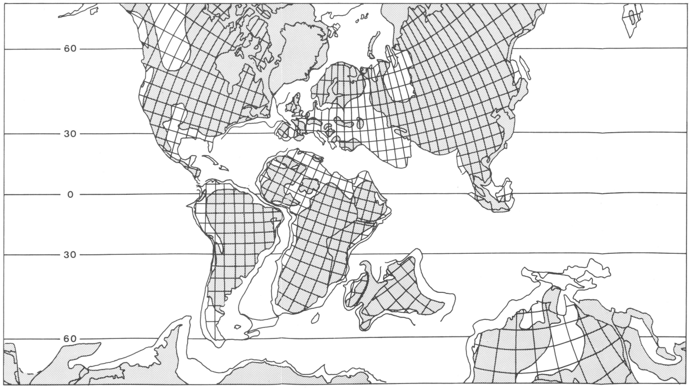
MERCATOR AT 100 MILLION YEARS



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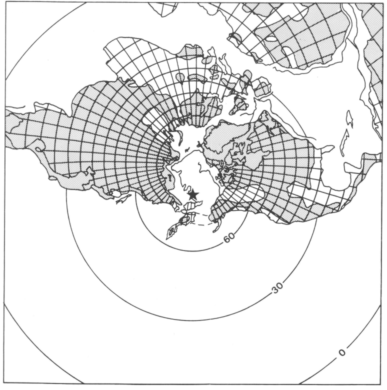

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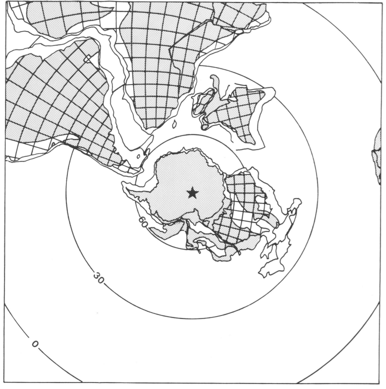

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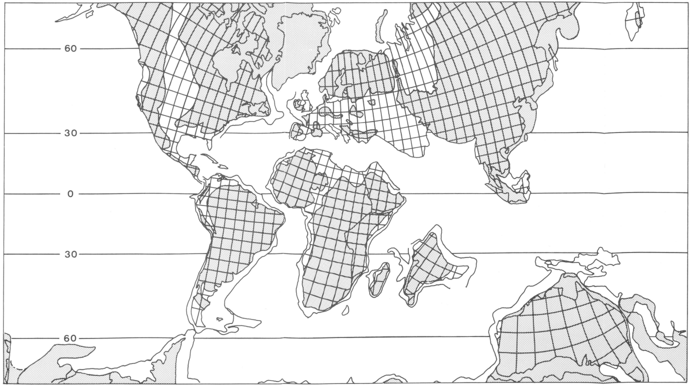

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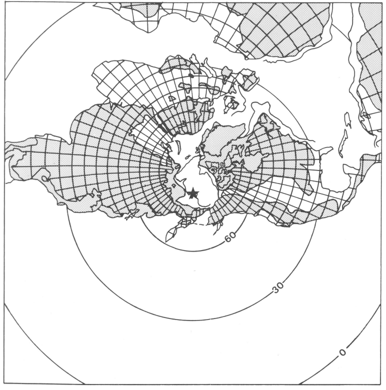

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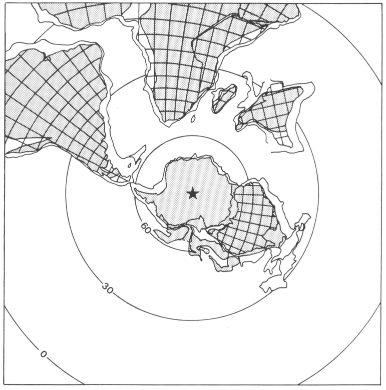

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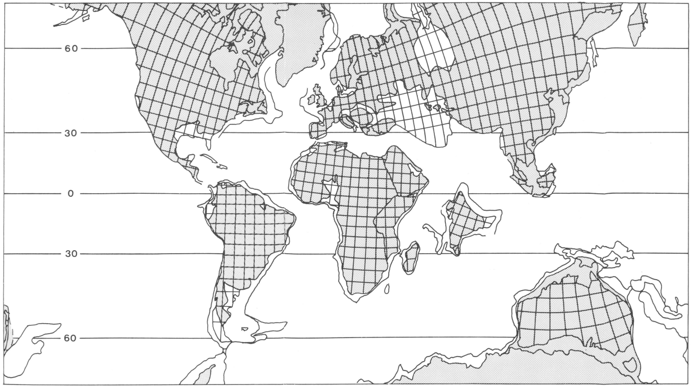

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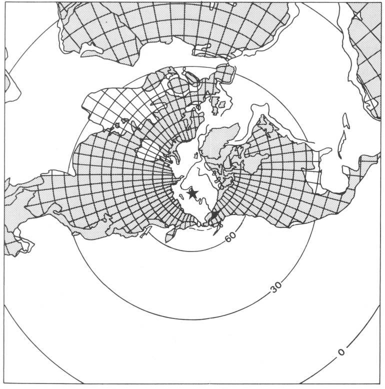

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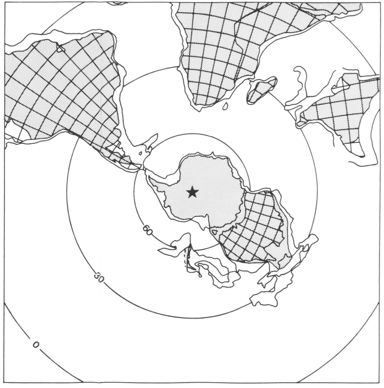

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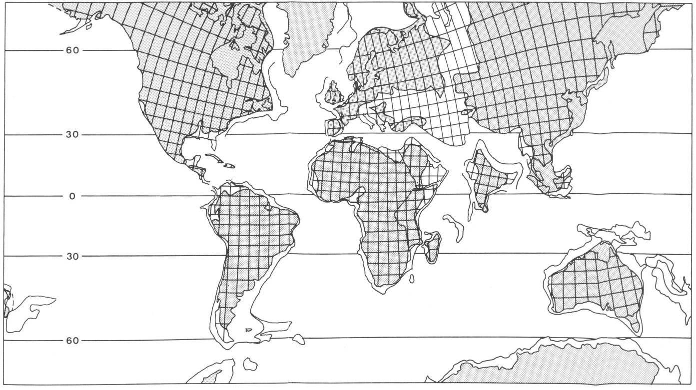

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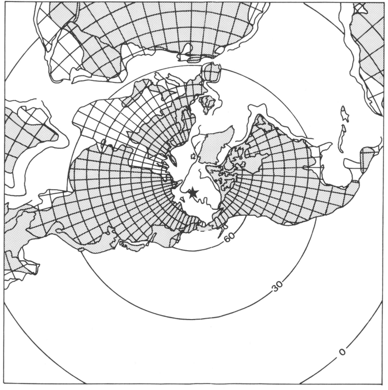

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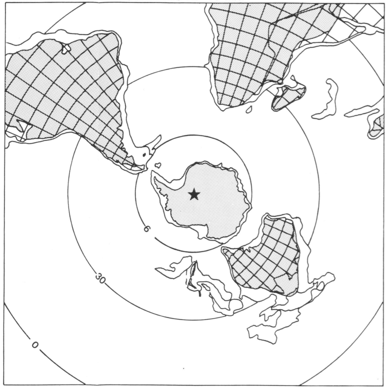

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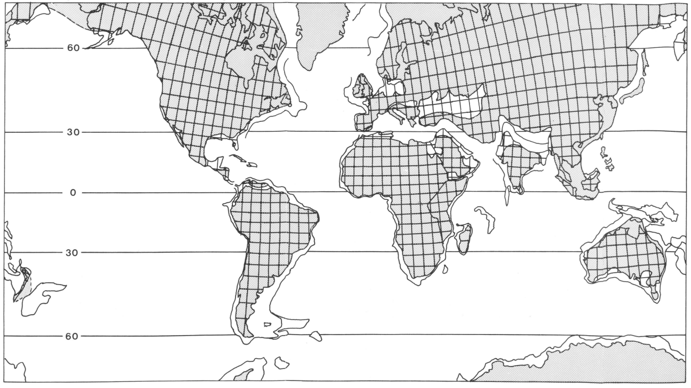

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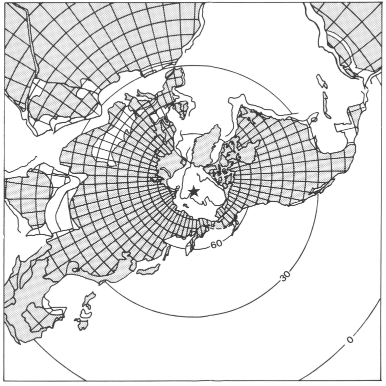

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