PHANEROZOIC WORLD MAPS

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ABSTRACT. Provisional world maps have been drawn for eight past periods: Tertiary (Eocene); Cretaceous; Jurassic; Triassic; Permian; Lower Carboniferous; Lower Devonian; Cambrian/Lower Ordovician. Maps of Permian and later time show the major continents in their original palaeolatitudes and with their relative longitude separations. Though the palaeolatitudes can be estimated for the pre-Permian continents, the relative longitude separations are not known. Three maps have been drawn for each period: Mercator, symmetrical about the inferred palaeoequator; and two stereographic projections centred on the inferred north and south palaeopoles. The data used are tabulated and their limitations are discussed.

THE paper describes a series of world maps, based on topographic, tectonic, and palaeomagnetic data, and discusses their limitations. The maps have been used in many other papers in this symposium volume, though small changes have subsequently been made to the Jurassic and Tertiary maps in this paper as a result of further work. These maps are believed to be the first attempt at constructing a Phanerozoic world atlas in which the ancient latitude–longitude grid has been estimated from palaeomagnetic measurements.

PLATE TECTONICS

A revolution in earth sciences was triggered by the addition of the concept of ocean-floor spreading (Hess 1962) to the longstanding theories of continental drift. Quantitative geophysical support for the new concept (Vine and Matthews 1963, Vine 1966) together with new developments in seismology (Isacks, *et al.* 1968) rapidly led to the synthesis of global tectonic behaviour now known as plate tectonics (McKenzie and Parker 1967, Morgan 1968, Le Pichon 1968, McKenzie and Morgan 1969). In plate tectonics the earth's crust and uppermost mantle are regarded as being fragmented into only a small number of rigid pieces called plates. These fragments make up the spherical outer shell of the earth known as the lithosphere, though parts of the lithospheric plates penetrate the hotter underlying upper mantle along slip zones, where they are incorporated into the surrounding mantle. The only significant deformation of the earth's crust occurs at or near active plate margins.

Although plate tectonics is primarily a theory based mostly on seismic observations that have been obtained over a period of less than ten years, the geological record supports its extrapolation to past periods. The ocean-floor spreading record shows that new oceanic crust forms along narrow zones and that these zones have existed at least as far back in time as the Cretaceous period. Though much wider than oceanic plate margins, the width of orogenic belts in island arcs or continents shows that compressional deformation is also restricted to relatively narrow zones. From evidence such as this it is inferred that plates and plate margins have existed throughout much of the earth's history, and certainly throughout the entire Phanerozoic. Though the shapes, relative positions, and numbers of plates evolve with time,

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the geographic relations between the margins of a plate and the points within a plate evolve in simple ways. These facts, and the fact that at any one instant most of the Phanerozoic continental crust belonged to a small number of large plates, make the task of drawing world maps tractable. For example, large areas of the continents have not been deformed since Pre-Cambrian time and consequently their shapes throughout the Phanerozoic were the same as their present-day shapes.

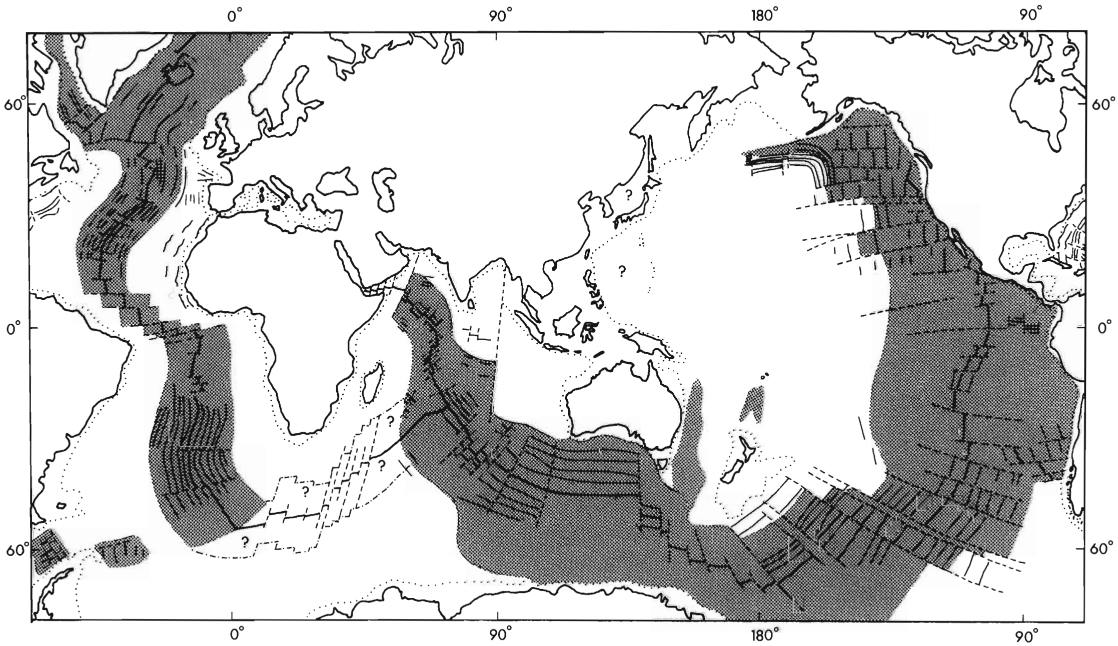
Present-day plate margins are extensional, translational, or compressional. Extensional margins exist where two adjacent plates are moving apart from one another. These margins are the sources of new oceanic crust and in general give rise to oceanic ridges. Compressional margins exist where two adjacent plates are moving toward each other. The motion is taken up generally by one plate plunging beneath the other along a zone of seismic activity. This process, known as subduction, is believed to give rise to orogenic belts. Only oceanic parts of plates appear to sink to any significant depth in the mantle. For this reason, a well-defined orogenic belt is believed to mark the site of one or more former oceans. There is as yet no sufficiently precise method for estimating the amount of oceanic crust that has been consumed at a compressional plate margin from the stratal shortening or other effects in the resulting orogenic belt. Translational margins form where two plates slide past one another. Motion occurs along transform faults. Crust is conserved; that is, it is neither created nor destroyed along translational margins.

The most recent movements along present-day extensional and translational margins can be determined from the spreading record of the oceanic parts of plates, or in the transform faults that cut continents. By assuming rigid body motion, the recent movements along present-day compressional margins may be inferred from the known motions on oceanic ridges (Le Pichon 1968). The movements cannot be determined directly for seismic events more than ten years old because older records are not sufficiently precise. For the purposes of making maps, therefore, compressional margins alone, or their presumed fossil analogues in orogenic belts, cannot be used to reposition pieces that lie on either side of orogenic belts. However, those orogenic belts that cross continents do suggest where former continental fragments and island arcs have been welded together.

OCEAN-FLOOR SPREADING DATA

We require to draw outline maps of the continents at arbitrary times in the past. The most precise guide to the former relative positions of two continents is given by the magnetic anomaly history of the ocean-floor separating them, provided that the piece of ocean concerned contains only extensional and translational plate margins (ridge segments and transform faults). Oceanic areas such as these make up a considerable proportion of the Arctic, Atlantic, and Indian oceans, and are termed aseismic. They are contrasted with oceans like the Pacific that are bordered by active slip zones at compressional margins.

In the simplest aseismic ocean, two continents have moved apart from one another and ocean-floor has grown from a single oceanic ridge lying between them. The continents belong to two plates whose areas are continuously being increased by the addition of new oceanic crust at the mid-ocean ridge. Because plates are rigid, the path followed by one continent relative to the other is fixed by the ocean-floor spreading pattern between them. The growth history of the ocean-floor may be described by the fitting together of successively older anomalies. Going back in time from the present, it is possible to chart the evolution of such oceans, or of aseismic oceans with more complex ridge systems. The growth pattern also determines the relative positions of the continents around these oceans. The Tertiary spreading history is known best. The data for earlier periods is sparse and the time-scale in pre-Upper Cretaceous time is uncertain. However, it is likely that none of the present-day aseismic ocean basins is older than Jurassic. By the beginning of the Jurassic period then, the present Arctic, Atlantic, and Indian oceans did not exist, and the present Pacific was much larger, covering about two-thirds of the earth's surface. A summary of the spreading data and larger transform faults known in 1970 is given by Vine (1971, fig. 16.10, p. 243). More recent data have been added to this diagram to form text-fig. 1.



TEXT-FIG. 1. The stippled area shows the probable distribution of ocean-floor formed since the beginning of Tertiary time (about 65 m.y.b.p.). Queries indicate other areas that may be of Tertiary age. Figure modified from Vine (1971, fig. 16.10, p. 243) with some additions. About half of the present-day ocean-floor has formed during this period. Mercator map with present-day coordinates.

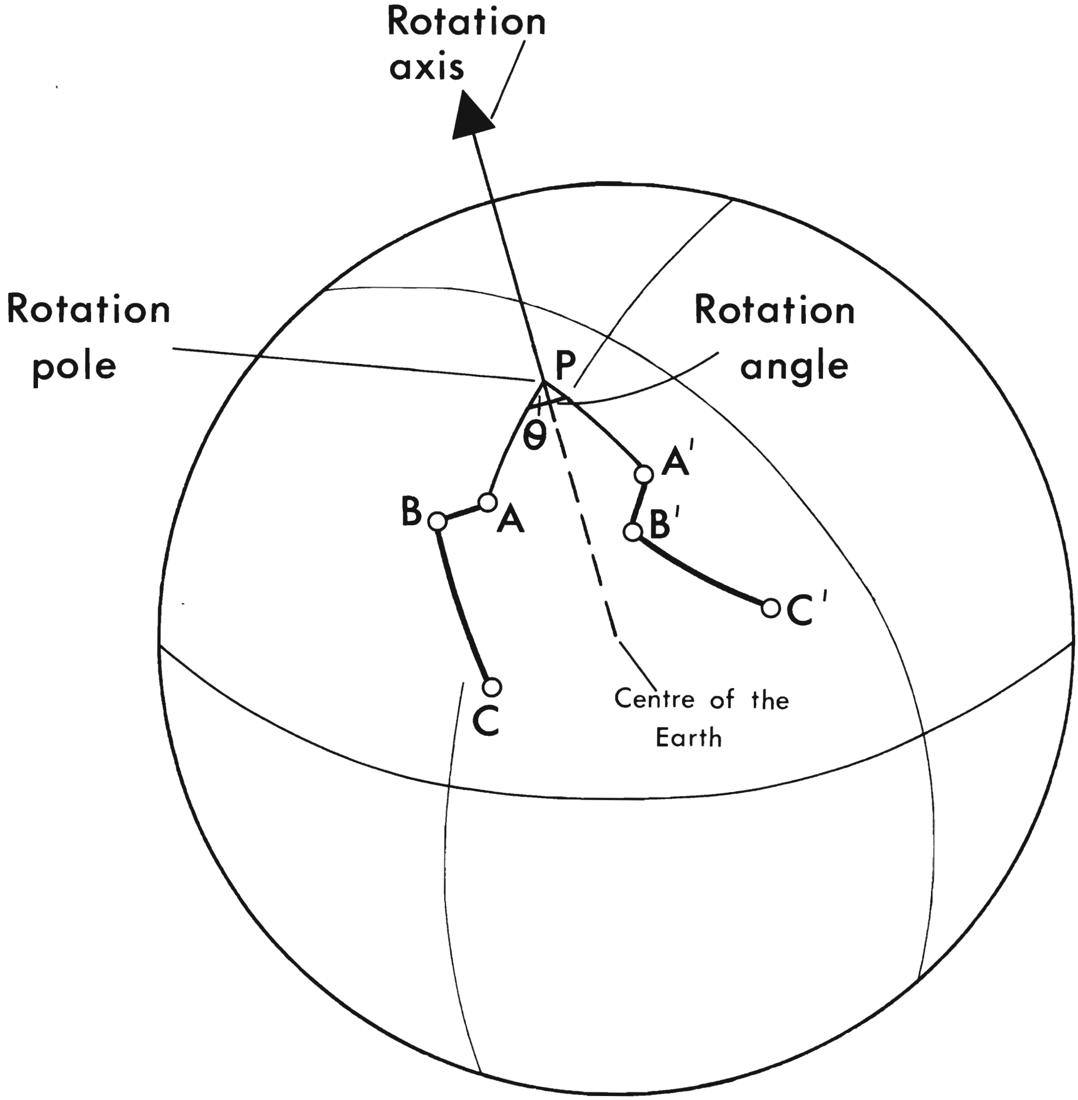
Because the early history of all the present aseismic oceans is unknown, it would at first sight seem impossible to determine the relative positions of the continents around them at earlier periods. However, the aseismic continental margins mark the initial break that later developed into a mid-oceanic ridge, and their best fit provides a good estimate of the original relative positions of the continents bordering the aseismic oceans.

GEOMETRICAL METHODS OF REASSEMBLY

Bullard *et al.* (1965) used Euler's Theorem to make a geometrical best-fit of the continents around the Atlantic. This theorem states that any line on the surface of a sphere may be transposed to any other position and orientation on the sphere by means of a single rotation about a suitably chosen axis passing through the centre of the sphere. In terms of the earth, it is possible to describe the movement of any point on its surface (such as a fossil locality) or any line (such as a continental outline) from one position to another by a rotation through a unique angle about a uniquely defined axis. The point at which this axis cuts the earth's surface is defined as the rotation pole, centre of rotation (text-fig. 2), or the Euler pole (Chase 1971). In the present context we are concerned with repositioning continents relative to one another by a series of rotations. We shall call these rotation poles the Euler poles. Chase (1971) equated Euler poles with tectonic rotation poles. We prefer to modify his usage by applying the term Euler pole to any rotation on a sphere, and to restrict the term tectonic rotation pole to those Euler poles that trace out the actual path taken by the continents concerned. Tectonic rotation poles are simply particular kinds of Euler poles. Euler poles and tectonic rotation poles should not be confused with the rotation pole (spinning axis) of the earth as a whole; this is the geographic pole. Nor should they be confused with the geomagnetic or palaeomagnetic pole. Euler, tectonic, geographic, geomagnetic, and palaeomagnetic poles are all different entities.

The angle through which a point or line is rotated from its initial to its final position is known as the rotation angle or Euler angle. Successive rotations about different Euler poles and through different Euler angles can always be combined into a unique equivalent single rotation about a unique Euler pole and through a unique Euler angle. Thus the spreading motions on a mid-ocean ridge at a given instant of geological time may be described geometrically as though they occurred about a fixed Euler pole at a fixed rate of rotation. In this case the Euler is also the tectonic rotation pole. It may be that the same pole describes the spreading pattern for successive instants of geological time that may amount to several millions of years, but this is not necessarily so. As an ocean grows, tectonic rotation poles may change their position abruptly (e.g. Le Pichon and Fox 1971), or migrate continuously. The net movement may be found by summing the sequential rotations and combining them into a unique Euler rotation. When the sequential rotations involve different tectonic rotation poles, then the rotation about the unique Euler pole does not trace out the actual spreading pattern; it merely describes the net changes that have taken place in the interval concerned, by means of a single rotation. Because plates are rigid, the Euler rotations describe the relative positions of every part of the corresponding plates. Thus the relative movement of two continents on either side of a spreading ridge is also described by the same Euler rotations as apply to the ridge itself.

Euler poles and angles may be found directly by fitting together features known to be of the same age which have subsequently been separated from one another. At least four numerical methods have been developed to do this (Bullard *et al.* 1965, Le Pichon 1968, McKenzie *et al.* 1970, Sproll and Dietz 1969). All the methods



TEXT-FIG. 2. A line from the centre of the Earth cuts the surface at point P. ABC is a line on the Earth's surface. Rotation of ABC through an angle θ about the axis shown brings ABC to A′B′C′. The axis is known as the rotation axis. Its intersection with the surface P is known as the tectonic rotation pole or Euler pole (see text). The angle θ is known as the rotation angle or the Euler angle.

are capable of bringing identical curves into coincidence. However, because the criteria of best-fit differ, all give slightly different answers to the problem of fitting together similar but not identical curves, such as magnetic anomalies or continental margins. The answers differ little from those obtained by visual inspection, but have the advantage of accuracy, reproducibility, and they give some quantitative estimate of the goodness of fit. Except for detailed work, the differences among the fitted positions of the continents found by all methods are insignificant.

In the case of the continental edges we have used the empirical method developed by Everett in Bullard *et al.* (1965). He showed that the submarine contour giving the best topographical fit between South America and Africa was the 500-fathom (~1000-metre) contour. The 1000-fathom contour is almost as good a fit, but the 100-fathom and 2000-fathom contours are much worse fits. For the purposes of making world maps we have adopted the 500-fathom contour as the standard submarine contour to be used for fitting purposes. The only exception is that of the Red Sea margin, where, for obscure reasons, the present coastlines seem to form a much better estimate of the original edge of the continent. On geological grounds it is possible to argue that some other contour should be used to define the edge in particular areas. Similarly, some geophysical arguments suggest the 2000-metre line to be the theoretical edge of the continent (Sproll and Dietz 1969). But world maps that use modified or alternative contours will not differ significantly from those that use the empirically determined 500-fathom line employed in this paper.

The tectonic rotation poles and angles that describe the net relative motions during the past 10 m.y. have been estimated from the spreading patterns in the major ocean basins (Le Pichon 1968). Le Pichon also determined the Euler poles and angles needed for a partial world map during Palaeocene time (Le Pichon 1968, fig. 8). Euler poles and angles describing the relative positions of the continents just before the beginning of spreading in the Atlantic and Indian oceans are given by Bullard *et al.* (1965) and Smith and Hallam (1970). To extend the problem further back in time, or to fill the interval between 10 m.y. and the beginning of spreading of the main aseismic oceans, it is necessary to determine the positions of the continents in these intervals. In other words, the past positions of a sufficient number of plate margins are necessary to reposition all the continents relative to one another. Also required are estimates of the sequence of a sufficient number of rotations that describe how these margins have changed in time. The extent to which these objectives are attainable is discussed in the next section.

FACTORS LIMITING THE MAKING OF REASSEMBLIES

All reassemblies can be made by applying a series of Euler rotations to present-day continents or to pieces of these continents. The precision of ocean-floor spreading data, together with the rigour of plate tectonics might lead one to suppose that really accurate reassemblies could be made for much of Mesozoic and Tertiary time, and somewhat less readily for the Palaeozoic era. The reality is less ideal, and many approximations and assumptions underlie the plotting of even the more recent maps.

For example, the magnetic anomaly time-scale is known relatively well only back to Late Cretaceous time (Heirtzler *et al.* 1968), and much of the ocean-floor created since that time has not yet been mapped (text-fig. 1). The earlier history of the preserved ocean-floor is less well known. Some trends have been observed and tentative magnetic anomaly time-scales have been proposed (e.g. Vogt *et al.* 1971), but these are not yet well supported by direct sampling or other independent methods.

It follows from the discussions of plate margins given above that the relative positions of two plates (or of two continents separated by plate margins) can be uniquely determined if a route can be plotted between them which crosses only plate margins of which the net Euler rotations are known. Present understanding of orogenic belts, which include compressional margins, is insufficient to determine the rotations that have accompanied their development. Smith (1972, in press) has developed simple geometrical methods that limit the positions of tectonic rotation poles of compressional margins, but these are not sufficiently accurate for our present purposes.

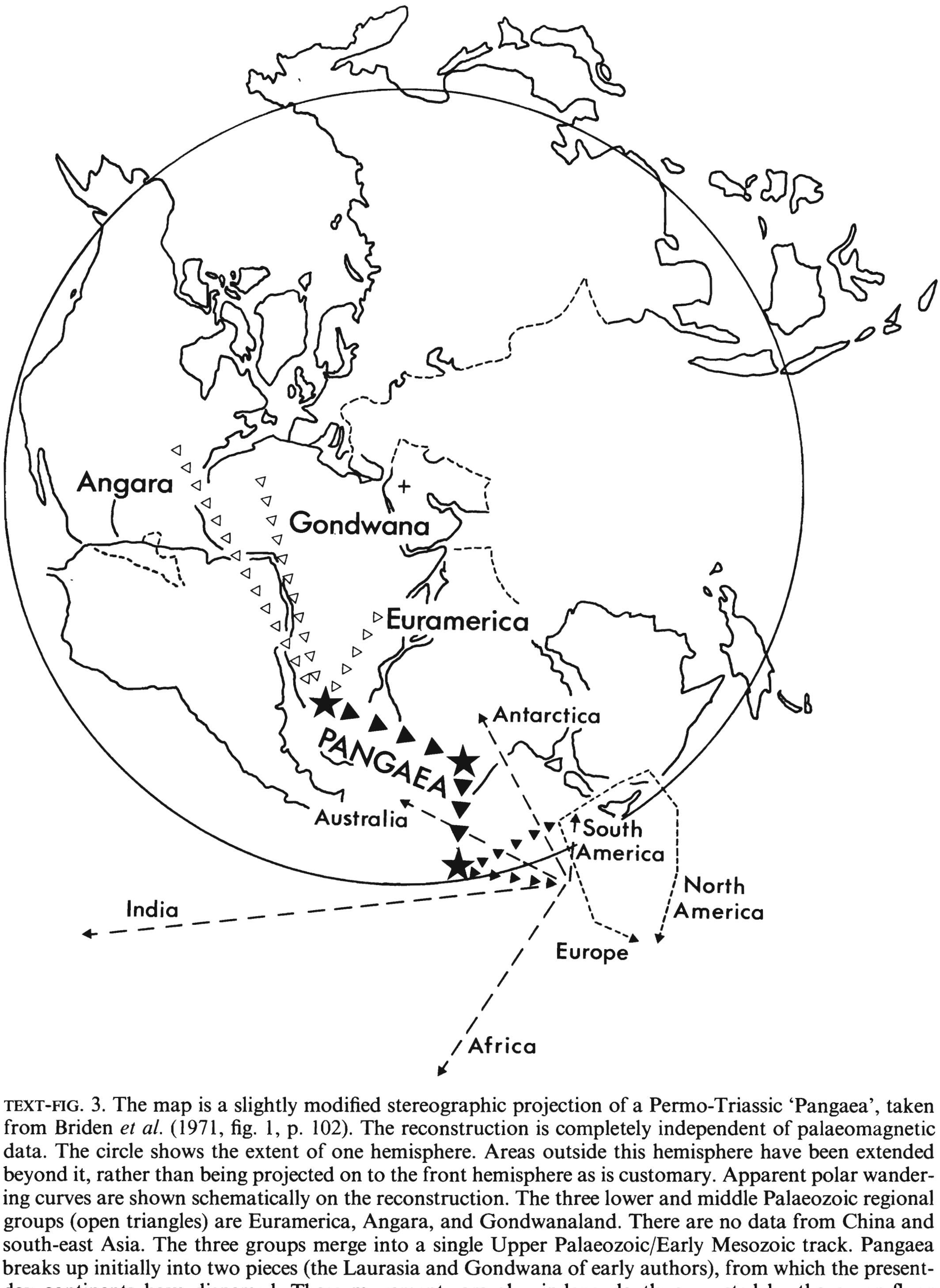
It might at first sight appear impossible to reposition the continents on either side of the Alpine–Himalayan chain. This chain was formed mostly as the result of the consumption of the Tethyan ocean in Mesozoic and Tertiary time. It is not known how much oceanic crust has been consumed at compressional margins within the chain. However, this lack of knowledge does not hinder the making of Mesozoic and Tertiary world maps because the relative positions of the continents to the north and south of the Alpine–Himalayan belt can be calculated via the spreading histories of the Atlantic and Indian oceans. The Mesozoic and younger plate margins in these oceans are mostly extensional or translational and therefore amenable to plate tectonic solution. Our present ignorance of what happens at the compressional margins in the Alpine–Himalayan chain merely deprives us of what would have been a useful double-check on the maps.

In principle the spreading history of the aseismic oceans is determinable. When known it will allow all the major continents to be precisely repositioned as far back in time as the age of the oldest preserved ocean-floor bordering an aseismic continental margin. The oldest known aseismic margin is that adjacent to the eastern United States (and presumably west Africa), where it appears to be of Early Jurassic age (Anon. 1970). These methods lead to a reassembly of all the major continents into one supercontinent, Pangaea, before Early Jurassic time (text-fig. 3). Briden *et al.* (1971) have suggested that Pangaea may have existed as an entity throughout most of the Permian and Triassic. We argue here that, prior to the Permian, Pangaea did not exist. Instead, there existed a number of continents whose approximate outlines may be found by dividing Pangaea along boundaries lying within the pre-Permian orogenic belts. It is clear that because compressional margins of Permian or younger age lie on the boundaries of all pre-Permian continents, then the method of repositioning the continents by fitting together the magnetic anomalies cannot be used; there is no ocean-floor preserved other than fragments.

To sum up: Permian and younger reassemblies of the major continents can be made from the ocean-floor spreading data and the best-fit of the continental edges, and pre-Permian continental outlines can be suggested by dividing Pangaea along pre-Permian orogenic belts. How all of these are converted into maps is discussed in the next two sections.

ORIENTATION OF THE REASSEMBLIES

To convert the reassemblies into maps that are of palaeogeographic value it is necessary to relate them to the contemporary latitude–longitude grid. To do this we equate the mean palaeomagnetic pole of the reassembly with the geographic pole. This method is equivalent to applying an additional Euler rotation to the



TEXT-FIG. 3. The map is a slightly modified stereographic projection of a Permo-Triassic 'Pangaea', taken from Briden *et al.* (1971, fig. 1, p. 102). The reconstruction is completely independent of palaeomagnetic data. The circle shows the extent of one hemisphere. Areas outside this hemisphere have been extended beyond it, rather than being projected on to the front hemisphere as is customary. Apparent polar wandering curves are shown schematically on the reconstruction. The three lower and middle Palaeozoic regional groups (open triangles) are Euramerica, Angara, and Gondwanaland. There are no data from China and south-east Asia. The three groups merge into a single Upper Palaeozoic/Early Mesozoic track. Pangaea breaks up initially into two pieces (the Laurasia and Gondwana of early authors), from which the present-day continents have dispersed. These movements are also independently suggested by the ocean-floor and plate tectonic data.

TABLE 1. Palaeomagnetic data

Mean palaeomagnetic South pole

Source region	*Number of studies*	*Relative to present coordinates*	a_{95} (*Note 1*)	*Relative to map* (*Note 2*)	a_{95} (*Note 1*)	*Reference numbers* (*Note 3*)
MAP 1. 'TERTIARY' (EOCENE)						
North America	4	81S 20E	..	84S 144E	..	9/29 10/46 11/25 (11/30–31)
Greenland	1	63S 354E	..	76S 351E	..	9/27
Western Europe	9	75S 338E	4·6	81S 265E	4·6	11.013 11.014 11.016 11.017 11.019 11.024 11.027 11/28 12/49
Spain	3	72S 11E	..	86S 353E	..	10/42 10/43 11/29
Italy	1	75S 34E	..	84S 86E	..	9/28
Russia, excluding Siberia	2	69S 29E	..	81S 45E	..	12/69 12/70
Siberia	1	57S 332E	..	66S 303E	..	12/67
China	1	77S 203E	..	64S 186E	..	10/44
Japan	1	62S 41E	..	72S 51E	..	10/40
Australia	2	67S 134E	..	80S 230E	..	11.124 11/27
India	2	34S 101E	..	53S 92E	..	8/34 8/42
Faeroes	1	77S 341E	..	83S 251E	..	12/50
North Pacific	1	61S 245E	..	83S 298E	..	12/48
Total and means	29	79S 18E	7·6	South pole	5·9	

1. It is not normally admissible to calculate a_{95} for $N < 5$.
2. Mean poles constrained to coincide with pole of the map are referred to as the South pole. Over-all mean poles differing from the South pole incorporate data obtained after the maps had been drawn. None is more than 4 degrees from the map pole.
3. References are taken from compilations of palaeomagnetic data by Irving (1964), with numbers of the form 5.06; McElhinny (1968*a*, *b*, 1969, 1970, 1972*a*), with numbers of the form 9/10. See also notes 3a–g.

Source region	*Number of studies*	*Relative to present coordinates*	a_{95} (*Note 1*)	*Relative to map* (*Note 2*)	a_{95} (*Note 1*)	*Reference numbers* (*Note 3*)
MAP 2. 'CRETACEOUS'						
Australia	7	48S 146E	7·4	75S 73E	7·4	9.28 9.29 9.30 9.32 9.33 10.09 10.10
Africa	2	61S 81E	..	81S 203E	..	10.15 9/40
India	3	10S 118E	..	85S 52E	..	9.44 8/60 and one other (Note 3a)
Antarctica	4	56S 218E	..	82S 229E	..	9.37 9.38 9.56 and one other (Note 3b)
South America	2	80S 54E	..	73S 110E	..	9.35 11/41
Europe	2	78S 341E	..	61S 267E	..	(10.05–06) 8/51
North America	11	65S 9E	5·9	84S 297E	5·9	10.12 10.17 8/48 8/52 9/36 9/42 9/43 11/35 11/36 11/37 11/39
Total and means	31	76S 106E	12·7	89S 345E	5·0	

3a. Rajmahal Traps (McDougall and McElhinny 1970).
3b. Dolerites. Enderby Land (Gusev 1967).

Source region	*Number of studies*	*Relative to present coordinates*	a_{95} (*Note 1*)	*Relative to map* (*Note 2*)	a_{95} (*Note 1*)	*Reference numbers* (*Note 3*)
MAP 3. 'JURASSIC'						
Australia	7	48S 146E	7·4	79S 58E	7·4	As for Cretaceous
Africa	2	61S 81E	..	79S 234E	..	,,
India	3	10S 118E	..	85S 344E	..	,,
Antarctica	4	57S 218E	..	78S 254E	..	,,
South America	2	80S 54E	..	78S 117E	..	,,
North America	2	76S 322E	..	80S 241E	..	9.47 8/61
Total and means	20	67S 142E	15·2	South pole	5·3	

Source region	*Number of studies*	*Relative to present coordinates*	a_{95} (*Note 1*)	*Relative to map* (*Note 2*)	a_{95} (*Note 1*)	*Reference numbers* (*Note 3*)
MAP 4. 'TRIASSIC'						
Australia	3	46S 160E	..	77S 96E	..	8.28 8.29 8/80
Africa	7	66S 81E	6·4	80S 194E	6·4	9.50 8/63 8/67 8/72 10/77 and two others (Note 3c)
India	4	13S 127E	..	84S 168E	..	9/66 11/43 11/45 11/57
South America	6	81S 242E	7·1	84S 135E	7·1	11/56 11/60 11/61 12/105 and two others (Note 3d)
Western Europe	2	44S 313E	..	63S 325E	..	8.06 8.07
Northern Asia	2	50S 341E	..	71S 16E	..	10/92 10/93
North America	6	60S 283E	10·3	84S 302E	10·3	8/51 9/52 9/53 10/96 11/58 11/59
Spain	2	59S 8E	..	73S 328E	..	9/61 11/54
Total and means	32	86S 101E	13·8	89S 283E	5·2	

3c. Two combined poles from Karroo igneous rocks, numbered 2.35 and 2.48 (McElhinny *et al.* 1968).
3d. Mendoza–Uspallata (Valencio 1969); Cuesta dos Tencros (Vilas 1969).

TABLE 1 (*cont.*)

Source region	Number of studies	Mean palaeomagnetic South pole: Relative to present coordinates	a_{95} (Note 1)	Relative to map (Note 2)	a_{95} (Note 1)	Reference numbers (Note 3)
MAP 5. 'PERMIAN'						
Australia	6	46S 133E	7·3	69S 119E	7·3	7.42 7.43 8/79 8/103 8/104 8/105
Africa	1	27S 89E	..	53S 130E	..	8/91
India	2	27S 132E	..	42S 134E	..	10/114 11/64
South America	4	60S 345E	..	78S 70E	..	12/116 12/117 12/118 12/124
Europe	10	44S 338E	4·7	80S 299E	4·7	7.05 7.11 7.13 7.54 8/83 8/87 8/94 9/89 9/90 and one other (Note 3e)
North America	4	44S 300E	..	81S 296E	..	8/88 10/105 10/106 11/65 11/66 11/67
Total and means (M_1)	27	71S 356E	20·3	84S 116E	7·2	
Northern Asia	3	8N 130E	..	38S 318E	..	8/70 8/76 8/78
Spain	4	42S 29E	..	88S 4E	..	9/80 11/72 11/73 11/74
Corsica	2	45S 39E	..	88S 152E	..	9/88 11/75
Turkey	1	18S 102E	..	64S 138E	..	8/84
Total and means (M_2)	37	67S 34E	19·1	88S 68E	7·4	

3e. Permian sediments, Devon (Cornwell 1967).

Source region	Number of studies	Relative to present coordinates	a_{95} (Note 1)	Relative to map (Note 2)	a_{95} (Note 1)	Reference numbers (Note 3)
MAP 6. 'LOWER CARBONIFEROUS'						
Australia	3	76S 308E	..	84S 272E	..	5.36 6.60 8/127
Africa	1	26S 26E	..	74S 85E	..	9/117
North America	7	30S 302E	..	83S 194E	9·7	8/117 8/120 8/121 8/123 9/120 9/125 10/126
Europe	4	20S 342E	..	85S 1E	..	6.11 8/124 10/129 12/134
Total and means	15	38S 322E	15·8	88S 205E	11·9	
MAP 7. 'LOWER DEVONIAN'						
Australia, Africa, and North America		All data as for Lower Carboniferous map				
Europe	5	3S 315E	..	South pole	..	8/126 9/124 12/137 12/138 12/139
Northern Asia	2	30S 340E	..	South pole	..	10/127 10/128
Total and means excluding North America (M_1)	11	31S 316E	14·6	South pole	7·8	
Total and means for all data (M_2)	18	31S 315E	6·5	76S 99E	10·0	
MAP 8. 'CAMBRIAN/LOWER ORDOVICIAN'						
Australia	2	14S 4E	..	75S 328E	..	12/143 12/148
India	1	28S 32E	..	66S 178E	..	11/85
Antarctica	1	28S 10E	..	68S 93E	..	10/140
Africa	3	31N 342E	..	79S 305E	..	4.09 9/132 9/137
South America	4	10N 325E	..	83S 133E	..	12/140 12/141 12/144 and one other (Note 3f)
North America	3	7S 320E	..	78S 285E	..	8/147 8/148 10/148
Europe	6	7S 0E	10·3	80S 280E	10·3	9/131 and five others (Note 3g)
Northern Asia	8	38N 309E	4·0	South pole	4·0	10/138 10/139 10/141 10/142 10/143 10/144 10/145 11/81
Korea	2	11N 317E	..	62S 112E	..	10/146 10/147
Total and means	30	12N 336E	11·9	89S 284E	5·8	

3f. Urucum Formation (Creer 1970).
3g. One pole from the European Ordovician (Murthy and Deutsch 1971), four unpublished poles of J. C. Briden, J. D. A. Piper, and W. A. Morris.

TABLE 2. Euler poles and angles for maps

MAP 1. 'TERTIARY' (EOCENE)

Fragments rotated	*Lat.*	*Long.*	*Angle*	*References and notes*
New Zealand to Antarctica	70 N	298 E	21	Le Pichon (1968)
Australia to Antarctica	3·6S	40 E	−31	Smith and Hallam (1970)
Antarctica to South America	74·9S	194 E	15·8	McKenzie and Sclater (1971). Pole and angle for 36 m.y. map. Map 1 omits small arbitrary rotation needed for their 45 m.y. map
South America to Africa	58 N	323 E	17·1	Le Pichon (1968)
India to Africa	26 N	21 E	17	,,
Africa to North America	79·1N	344·3E	−17·1	Le Pichon and Fox (1971). Assumes fixed pole and uniform spreading during this phase
Arabia and Iran to Africa	36·9N	18 E	−6	Smith and Hallam (1970). McKenzie *et al.* (1970) give another estimate of this pole and angle
Eurasia (including all fragments in Alpine-Himalayan belt) to North America	88·4N	27·7E	−11	Pole assumed to be that of Bullard *et al.* (1965). Angle estimated from Laughton (1971)
Greenland unmoved relative to North America				Spreading in Labrador Sea had ceased (Laughton 1971)
Mean South pole of reassembly	76·5S	358 E		Pole relative to North America
North America to map	0 N	268 E	−13·5	Euler rotation from mean pole

Reassembly sequence: New Zealand and Australia to Antarctica; Antarctica to South America; South America, India, Arabia, and Iran to Africa; Madagascar unmoved relative to Africa; Africa to North America; Eurasia to North America; Greenland unmoved relative to North America; reassembly rotated relative to North America.

MAP 2. 'CRETACEOUS'

Fragments rotated	*Lat.*	*Long.*	*Angle*	*References and notes*
New Zealand to Antarctica	32·1S	225 E	30·1	Smith and Hallam (1970)
Australia to Antarctica		As in Map 1		,,
Antarctica to Africa	1·3N	324 E	58·4	,,
India to Africa	28·9N	42·2E	−58·9	,,
Madagascar to Africa	9 S	313 E	15	,,
Iran and Arabia to Africa		As in Map 1		
Eurasia (including all fragments in Alpine-Himalayan belt) to Africa	50 N	3·1E	41·3	Smith (1971). Combines rotation of Europe to North America followed by North America to Africa given by Bullard *et al.* (1965) into single rotation
followed by	58·3N	359 E	−36·5	Le Pichon and Fox (1971). Strictly speaking, this pole applies to a different starting position from the one used above, but the differences between the maps drawn using Le Pichon and Fox's initial position and the one above are negligible. The angle assumes a uniform spreading throughout this opening phase
Greenland to Europe	73 N	96·5E	22	Bullard *et al.* (1965)
North America to Africa	67·6N	346 E	74·8	,,
	followed by the second rotation applied above to Eurasia			
South America to Africa	44 N	329·4E	57	Bullard *et al.* (1965)
Mean South pole of reassembly	55·2S	67·6E		Pole relative to Africa
Africa to map	0 N	337·6E	−34·8	Euler rotation from mean pole

Reassembly sequence: New Zealand and Australia to Antarctica; Antarctica, India, Madagascar, Arabia, Iran, and South America to Africa; Greenland to Europe; Eurasia, North America to Africa in two rotations; reassembly rotated relative to Africa.

MAP 3. 'JURASSIC'

New Zealand, Australia, Antarctica, South America, Madagascar, India, Arabia, and Iran all reassembled relative to Africa as in Map 2.

Fragments rotated	*Lat.*	*Long.*	*Angle*	*References and notes*
Yugoslavia, Greece, and Turkey to Europe	47·7N	7·4E	−67·7	Smith (1971). From a speculative reassembly of the Mediterranean region
Italy to Europe	44·4N	7·4E	−87·4	As above
Corsica and Sardinia to Europe	49·2N	2·9E	−33·7	As above
Balearic Islands to Spain	38·6N	0 E	21·3	As above. The combined rotation of the Balearic Islands to Spain followed by Spain to Europe is incorrectly given in Smith (1971, Table 1)
Spain to Europe	43·6N	1 E	−27·8	Equivalent to position in Bullard *et al.* (1965)
Greenland to Europe		As in Map 2		
Europe to North America		,,		
North America to Africa	67·6N	346 E	74·8	Bullard *et al.* (1965)
followed by	58·3N	359 E	−6·6	Le Pichon and Fox (1971). See comment in Map 2 on second rotation of Eurasia. Angle assumes opening of Atlantic Ocean began here about 180 m.y. ago

TABLE 2 (*cont.*)

Fragments rotated	*Lat.*	*Long.*	*Angle*	*References and notes*
Mean South pole of reassembly	51 S	73·4E		Pole relative to Africa
Africa to map	0 N	343·4E	−39	Euler rotation from mean pole

Reassembly sequence: Yugoslavia, Greece, Turkey, Italy, Corsica, Sardinia, Balearic Islands, and Spain all reassembled to Europe. Then reassembly sequence of Map 2. Lastly North America, Greenland, and all pieces attached to Europe rotated away from Africa according to second rotation of North America above.

MAP 4. 'TRIASSIC'

All pieces reassembled as in Map 3, except that second rotation not applied to North America and all pieces attached to it.

Mean South pole of reassembly	60 S	62·5E		Pole relative to Africa
Africa to map	0 N	332·5E	−30	Euler rotation from mean pole

MAP 5. 'PERMIAN'

All pieces reassembled as in Map 4.

Mean South pole of reassembly	40 S	47·5E		Relative to Africa
Africa to map	0 N	317·5E	−50	Euler rotation from mean pole

MAP 6. 'LOWER CARBONIFEROUS'

Three large fragments: 'Gondwanaland', consisting of New Zealand, Australia, Antarctica, South America, Africa, Madagascar, India, Arabia, Iran, Spain, Corsica, Sardinia, Italy, Yugoslavia, Greece, and Turkey; two, Asia east of the Urals; and three, Eurasia west of the Urals, Greenland, and North America.

Mean South pole of Gondwanaland	30 S	8 E		Pole relative to Africa
Gondwanaland to map	0 N	278 E	−60	Euler rotation from mean pole
Mean South pole of Asia east of Urals	47·5S	350·5E		No data available. Uses mean pole of Map 5 rotated to Asia
Asia east of Urals to map	0 N	260·5E	−42·5	Euler rotation from mean pole
Mean South pole of Eurasia west of Urals, Greenland, and North America	24·6S	342·2E		Pole relative to Europe
Eurasia west of Urals, Greenland, and North America to map	0 N	252·2E	−65·4	Euler rotation from mean pole

MAP 7. 'LOWER DEVONIAN'

Same three fragments as in Map 6.

Gondwanaland Mean pole and map pole same as for Map 6.

Mean South pole of Asia east of Urals	30 S	340 E		Pole relative to Asia
Asia east of Urals to map	0 N	250 E	−60	Euler rotation from mean pole
Mean South pole of Eurasia west of Urals, Greenland, and North America	3 S	315 E		Pole relative to Europe
Eurasia west of Urals, Greenland, and North America to map	0 N	225 E	−87	Euler rotation from mean pole

MAP 8. 'CAMBRIAN/LOWER ORDOVICIAN'

Map made by treating world as in Map 7, except that Europe has been split from Greenland and North America along the trend of the Caledonian-Appalachian orogeny. The three continental fragments have been placed in a position indicated by the mean pole of all of them joined as in Map 6 and then moved apart an arbitrary amount along lines of constant palaeolatitude.

Mean South pole of Gondwanaland	23·5N	352 E		Pole relative to Africa
Gondwanaland to map	0 N	262 E	−113·5	Euler rotation from mean pole
Mean South pole of Asia east of Urals	38 N	309 E		Pole relative to Asia
Asia east of Urals to map	0 N	219 E	−128	Euler rotation from mean pole
Mean South pole of Asia west of Urals, Greenland, and North America	9 S	10 E		Pole relative to Europe
Asia west of Urals, Greenland, and North America	0 N	280 E	−81	Euler rotation from mean pole

SIGNS OF ROTATIONS: Positive rotations are anticlockwise rotations about the Euler pole when viewed from outside the Earth. Negative rotations are clockwise with respect to an observer in space.

reassembly. If the mean palaeomagnetic South pole has a latitude (λ) and a longitude ϕ relative to the reassembly (measuring from 0° eastwards around the globe), then a rotation about the point on the equator of the reassembly at longitude $(270+\phi)$ through an angle of $-(\lambda+90)$ will bring the geographic South pole and the palaeomagnetic South pole into coincidence (see Table 2).

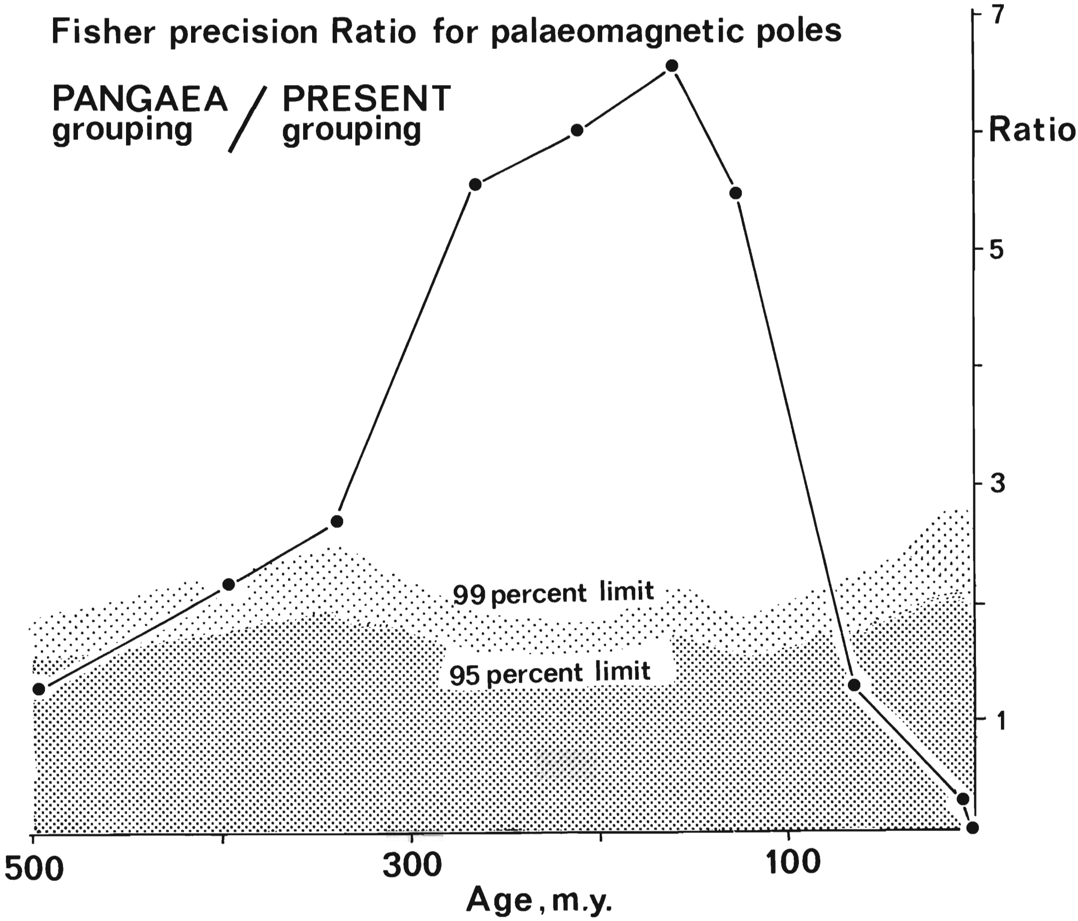
The validity of this procedure depends on the extent to which two conditions are satisfied: one, the accuracy with which the observed remanence directions in rocks record the ancient geomagnetic field; and two, the accuracy with which these directions may be projected into estimates of the ancient geographic pole.

To ensure that only the most reliable data have been used we have insisted on four conditions: one, positive geological evidence for the age of the remanence; two, evidence that the remanence resides, in part at least, in magnetic domains whose relaxation times are likely to exceed the age of the rock; three, sufficient data to minimize small-sample bias; and four, adequate knowledge of the age of the host rock. The data we have used is summarized in Table 1. Our compilation is not comprehensive, but we do not believe the inclusion of other valid data would materially alter the maps. The most important omissions known to us are the Russian data summarized by Khramov and Sholpo (1967), which came into our possession after all the maps had been prepared.

To satisfy the second ideal we have to ensure that the poles calculated from palaeomagnetism are good estimates of the geographic pole. This is the geocentric axial dipole model that is accepted as a standard in palaeomagnetic work. The history of the most recent field suggests that it will average to a geocentric axial dipole provided the time-span of the sampling extends over a period greater than 10^5 years. This condition imposes further limits on the number of samples that make up a study acceptable for the making of maps.

The extent to which the field model is justified may be roughly assessed by inspection of the maps. a_{95} is the circle of 95 per cent confidence (in degrees) about the calculated mean, and is plotted, where known, on the South pole stereographic maps. Declinations should be aligned along the meridians, and inclinations should match the scale marked alongside the latitudes on the Mercator maps. This scale is calculated from the centred dipole relation between magnetic inclination (I) and latitude (λ): $\tan I = 2 \tan \lambda$. The assessment may also be made statistically. For example, the Triassic maps show that all the continents belong to a single crustal plate. The grouping of palaeomagnetic poles on the Triassic reconstruction (text-figs. 9, 17) may be quantified by Fisher's (1953) statistics to give a precision estimate of $k \sim 25$. A high value of k implies a tight grouping of the points. On present-day coordinates the same data give a $k \sim 4$. Thus the reassembly is much more appropriate to Triassic times than is the present distribution of continental areas. This feature is illustrated in text-fig. 4, which shows, not surprisingly, that the Pangaea reconstruction becomes progressively less satisfactory in recent time.

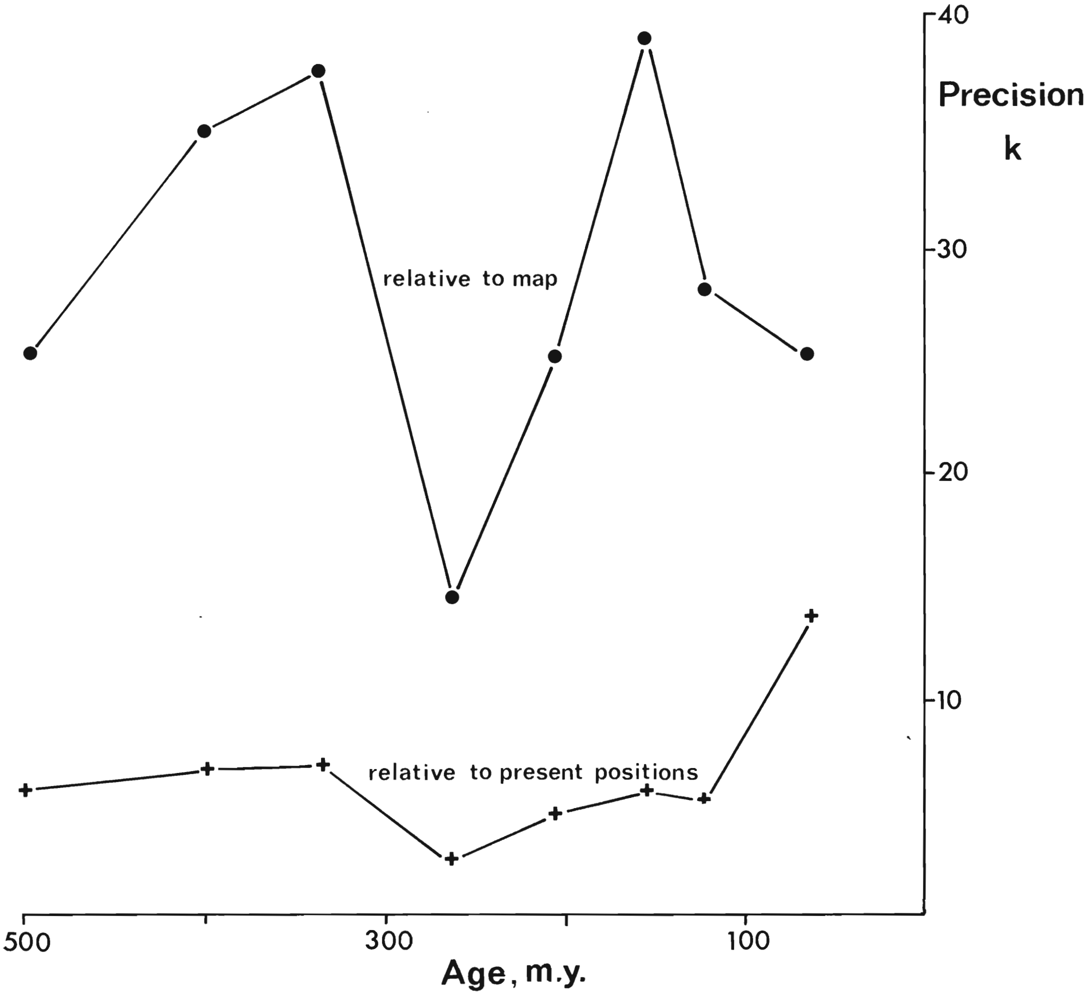
The Fisher precision estimate associated with all the maps may also be compared with the corresponding scatter on the modern grid. Text-fig. 5 shows how precision relative to present coordinates progressively decreases as one retreats through time. This decrease is a reflection of crustal drift. But the reconstructions all appear to be of comparable quality, bearing in mind that by their very nature the present-day



TEXT-FIG. 4. The precision estimate k (see text), for the Pangaea reconstruction of text-fig. 3 is divided by its value on present-day maps. The high confidence limits for Permian to Cretaceous time shows how much better a Pangaea reconstruction is for this interval than is the present-day continental distribution. The lower confidence limits for most of the other maps suggests that Pangaea is as poor an estimate of relative continental positions in the earlier Palaeozoic as it is of the present-day world. In other words, the earlier Palaeozoic continents had a distribution markedly different from Pangaea.

data yield very high precision. Similarly, since the mean pole for each pre-Permian crustal fragment anchors that fragment to the pole of the map projection, the associated precision is merely a measure of the average scatter *within* each fragment. Because the data from each fragment is comparable with present-day data, the maps are certainly oriented in the magnetic latitude appropriate to a geocentric dipole field. If this field was also axial, that is, aligned with the Earth's spin (geographic) axis, then the grid on the maps is also the palaeogeographic grid.

Direct palaeomagnetic evidence of its axial character exists only as far back in time as crustal drift has been negligible; that is, only so far back in time that the errors associated with individual palaeomagnetic pole determinations are greater than those due to plate movements. The plate motions over the past 10 m.y. are



TEXT-FIG. 5. The precision estimate k (see text) is plotted against age for all palaeomagnetic poles for two cases: one, relative to map; two, relative to present-day positions. A high value of k indicates a high precision for the map. The value of k relative to the map is about the same except for the Permian (text-figs. 10, 18), where it is low. The value of k for the continents in their present-day positions is low, and the precision is very poor, except for the Tertiary (Eocene) map (text-figs. 6, 14).

certainly smaller than the average palaeomagnetic errors, and the palaeomagnetic data in this interval support a geocentric axial dipole field. Farther back in time it is necessary to appeal to the palaeoclimatic evidence provided by fossils and sediments. The pertinent test is whether distributions of latitude-dependent features are parallel or oblique to the latitude lines on the maps. Various contributions in this volume discuss such evidence, and we find in them no convincing evidence for discrepancies that exceed the angular errors involved in orienting the maps from the data selected (see a_{95} in Table 1).

THE MAPS

The choice of a geographic pole fixes the palaeolatitude and palaeolongitude grid over the whole reassembly, thus providing a world map. Latitudes are defined absolutely, but longitudes, like present-day longitudes, have an arbitrary datum. In this way we have drawn the Tertiary, Cretaceous, Jurassic, Triassic, and Permian maps. The Tertiary and Jurassic maps differ slightly from the maps in the remainder of this volume because we have been able to incorporate some new data into them. The scatter of the palaeomagnetic poles (text-figs. 14A–21A, and a_{95} in Table 1) gives a measure of uncertainty in orientation of the maps. Any difference between the over-all mean palaeomagnetic pole and the chosen pole of projection for any particular map reflects the addition of new palaeomagnetic data to our calculations after the maps themselves had been drawn. Such differences are small; less than the associated 95 per cent confidence limits.

The existence of some Carboniferous orogenic belts, such as the Urals and the Appalachian–Hercynian chain, that cut across Pangaea is itself evidence that Pangaea had not formed until at least early Permian time. The formation of Pangaea in Late Palaeozoic time is also supported by the progressively greater scatter of palaeomagnetic poles older than the Permian relative to Pangaea (text-fig. 4). As discussed above, in pre-Permian time Pangaea must be divided into a number of fragments bounded by orogenic belts. Each of these fragments behaves as a rigid mass, that is, each belongs to a plate. In the Carboniferous period, it is quite clear that there were at least three large plates, of which the continental parts consisted of the southern continents (Gondwanaland), Asia east of the Urals, and North America–Greenland–Eurasia west of the Urals. Further back in time the number of fragments may increase, but it is not clear whether they all belonged to separate plates or whether some of them belonged to the same plate, such as India and Australia do today or, indeed, whether some of the fragments were joined together into a single continent. Because there is no sufficiently accurate method for reorientating plates that are now separated from one another by orogenic belts, and because it is not known how many plates existed in the earlier Palaeozoic, each of the continental fragments should be treated separately.

The mean palaeomagnetic pole for each fragment is taken as the pole of the projection. In this way absolute palaeolatitudes are still defined, but relative longitudes can only be prescribed within a fragment. There is as yet no sufficiently precise method for defining relative longitudes among different crustal fragments in pre-Permian time. The pre-Permian maps (text-figs. 11–13, 19–21) have been made by superposing each crustal fragment in its correct orientation on a world palaeolatitude/palaeolongitude grid. They simulate world maps but are really composites instead. We acknowledge this fact by the strips of ornament around each fragment (text-figs. 11–13). Compositing proves useful because the finite size of the earth places limits on the uncertainties in relative longitude separation. We do not have any rigorous method for determining the sequential positions of the continents. For example, if there were three continents A, B, and C, all straddling a particular latitude line, we have no rigorous method of deciding whether they lay in the sequence A–B–C or A–C–B. But there are some constraints: the continents cannot overlap;

during their passage from an earlier Palaeozoic position to a later position two continents may approach one another and are likely to give rise to an orogenic belt during their period of approach, though the approach could also be made along suitably oriented transform faults. The overlap problem is obviously accommodated in the way we have drawn the maps, but we have not given sufficient consideration to the second constraint.

In the older Palaeozoic some large continental areas for which palaeomagnetic data are lacking were separated from the principal fragments. For example, China is now joined to Siberia via a Hercynian orogenic belt. It was presumably separated from Siberia in pre-Hercynian time by an ocean, but we have not discovered any palaeomagnetic data that would allow us to reposition China in pre-Hercynian time. Without such data China can be repositioned only by using geological data, which we have deliberately not used (except to estimate the outlines of each fragment). Thus the position of China on the Carboniferous and older maps is not only uncertain, but it is probably incorrect. It has been drawn in its present-day position relative to Siberia merely for convenience. The uncertainty is indicated by a query on the maps. Similar uncertainties apply to other stable parts of the world for which there is no local palaeomagnetic control. Queries have been placed on these areas.

Mercator and equal-angle stereographic maps are presented. Both sets show the outlines of continents and both use the mean palaeomagnetic poles as the pole of the projection. The Mercator maps show the palaeomagnetic directions and sampling areas, the positions of orogenic belts that were active at the time concerned or later, and the stable areas for which no palaeomagnetic data exists. The stereographic maps show the palaeomagnetic poles, the over-all mean palaeomagnetic pole, and its 95 per cent confidence circle.

The Mercator projection was chosen for the larger maps (text-figs. 6–13) for several reasons. Firstly, it shows the entire circumference of the globe at the equator and extends to 70° N. and S. Latitude lines are straight, so that latitudinally controlled distributions will show up as horizontal belts across the map. The projection highlights the tropical regions where faunas and floras are commonly prolific and diverse. Their distributions might therefore show some symmetry about the middle of the map (the palaeoequator). Shapes of continents do not change along latitude lines; this is especially useful for the Palaeozoic maps, because the continental fragments can be moved into any relative longitude merely by sliding them along latitude lines, as if on an abacus, without having to redraw their shapes each time. Of course, if new data suggest a different orientation for the fragment concerned then the shape of the fragment on the map will change. Palaeomagnetic declinations should parallel the palaeolongitude lines, that is, they should be aligned north–south. Anomalous declinations can therefore be readily detected. Likewise, inclinations should correspond to the scale at the side of the map, and any anomalies can easily be seen. The only disadvantage is that the Mercator projection distorts the higher latitudes and cannot show the poles themselves.

These disadvantages are compensated by the provision of the stereographic maps (text-figs. 14–21). These each show a hemisphere whose circumference is the palaeoequator and whose centre is the palaeopole. They therefore highlight the polar regions.

The most appropriate geological time intervals that could be used to draw world maps are, naturally, those for which geometric, palaeomagnetic, and tectonic uncertainties are minimum. However, the prime purpose of these maps was to enable the plotting of the distributions of fossils of various ages by the contributors to this symposium. This has meant that some of the maps are based on quite inadequate data. For example, we have aggregated the 100 m.y. or more time-span of the Cambrian to Lower Ordovician interval into a single map. This may be analogous to trying to draw one map for all the changes that have taken place since the middle of the Cretaceous. Nevertheless, we must emphasize that the maps are based almost entirely on geometrical and geophysical information, and are independent of any sedimentologic, palaeontologic, or palaeoclimatic evidence.

The Euler rotation poles and rotation angles used are given in Table 2. The Eocene maps (text-fig. 6) show the only reassembly based entirely on ocean-floor spreading data, though the orientation has of course been found by continental palaeomagnetic evidence. Text-figs. 7 and 8, which are intended to refer to Early Cretaceous and Mid-Jurassic times respectively, use the topographic fits of the southern continents

TEXT-FIGS. 6–21. The data used to make the maps are given in Tables 1 and 2. There are three series of figs.: 6–13, Mercator; 14A–21A, southern hemisphere stereographic; 14B–21B, northern hemisphere stereographic. Each series consists of eight maps: 6, 14, 'Tertiary' (Eocene); 7, 15, 'Cretaceous'; 8, 16, 'Jurassic'; 9, 17, 'Triassic'; 10, 18, 'Permian'; 11, 19, 'Lower Carboniferous'; 12, 20, 'Lower Devonian'; 13, 21, 'Cambrian/Lower Ordovician'. The edge of the continents is shown either as a dashed line (the present-day 1000-metre or 500-fathom line) or as a dotted line (an arbitrary line of separation of one continent from another).

The palaeogeographic pole for the three series is the mean palaeomagnetic pole for continental reassemblies or for particular continental groupings (see text).

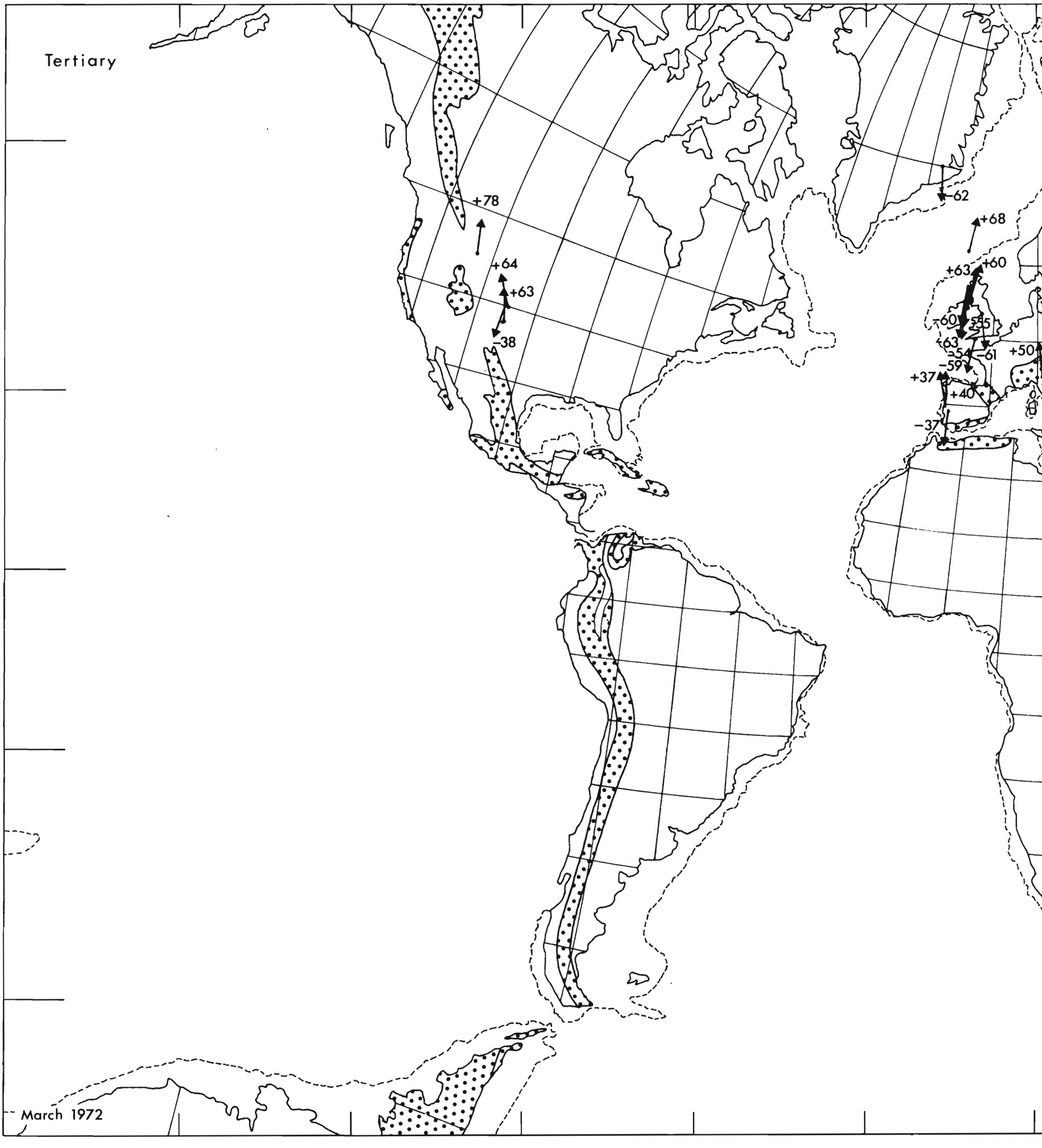
(*a*) Mercator maps 6–13: These extend around the world at the inferred palaeoequator and show areas up to palaeolatitudes 70° N. and 70° S. The latitude and inclination scales are related by the relationship tan (inclination) = 2 tan (latitude). Declination directions are shown by the trends of the arrows, inclination values by the numbers at the ends of the arrows.

Present-day outcrop areas affected by Phanerozoic orogenies are shown schematically as follows: dark cross-hatching = Lower Palaeozoic (Caledonides, etc.); dark stipple = Upper Palaeozoic (Hercynian, etc.); medium stipple = Mesozoic; large stipple = Tertiary. The relative positions of all these areas, together with areas subsequently covered by younger deposits, are not known during or before the time of the orogeny concerned. The positions of small stable areas attached to larger areas via an orogenic belt is also generally indeterminate. The longitudinal separations of the continental groupings during Lower Carboniferous and earlier time (Maps 11–13) is also indeterminate. Strips of horizontally ruled material diagrammatically indicate the lateral boundaries of these groupings.

(*b*) Stereographic maps 14–21: These are equal angle stereographic projections with the palaeogeographic pole in the centre and the palaeoequator at the edge. Orogenic belts and magnetic data shown in series (*a*) maps have been omitted. Mean magnetic poles and their circles of confidence (when known) have been plotted. The larger the circle the greater the uncertainty in pole position (see text). Longitudes are arbitrary.

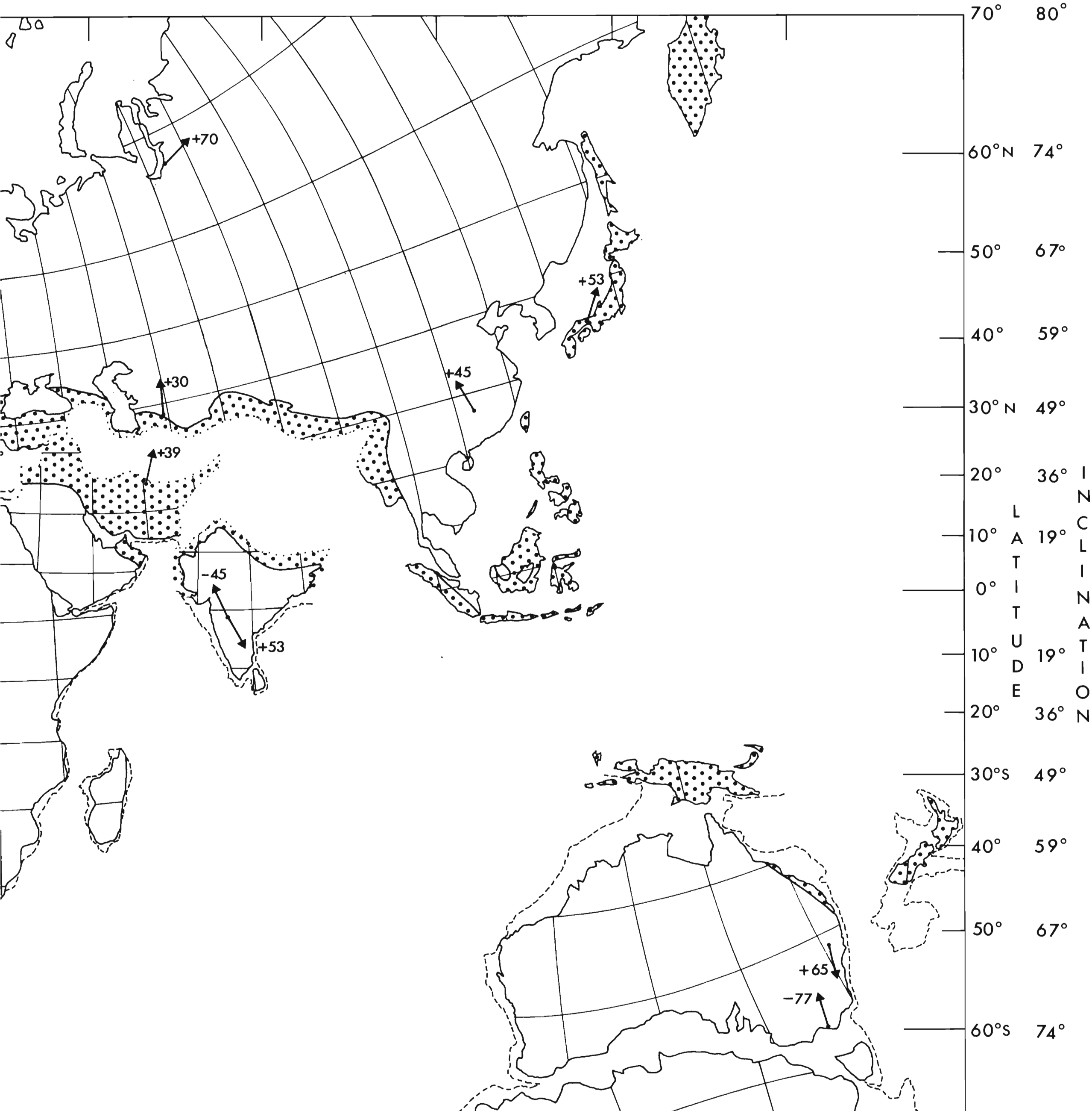
The following abbreviations have been used: Af = Africa; Ant = Antarctica; Aus = Australia; C = Corsica; Ch = China; Eur = Europe; F = Faeroes; G = Greenland; Ind = India; It = Italy; J = Japan; K = Korea; M, M_1, M_2 = various mean poles (see Table 1); N Am = North America; N As = North Asia; N Pac = North Pacific; S Am = South America; Sib = Siberia; Sp = Spain; T = Turkey; W Eur = western Europe.

Mean poles for Tertiary to Permian time (Maps 14A–18A) are shown either as small filled-in circles or as large open circles. Mean poles for continents belonging to the same fragment in the Lower Carboniferous and older maps are shown by the same symbol, but the symbol varies from fragment to fragment (19A–21A).

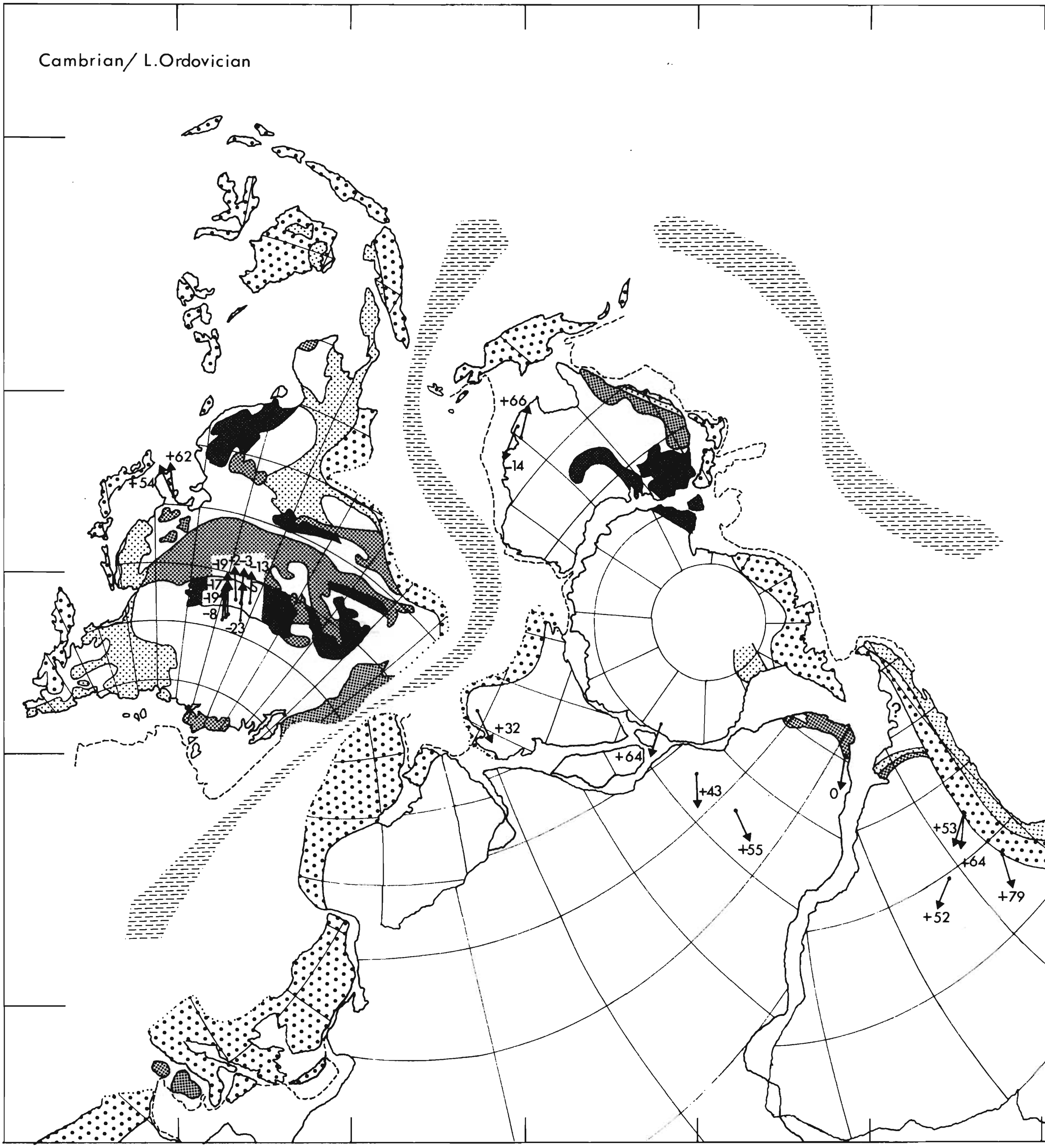


TEXT-FIG. 6. Map 1, 'Tertiary' (Eocen

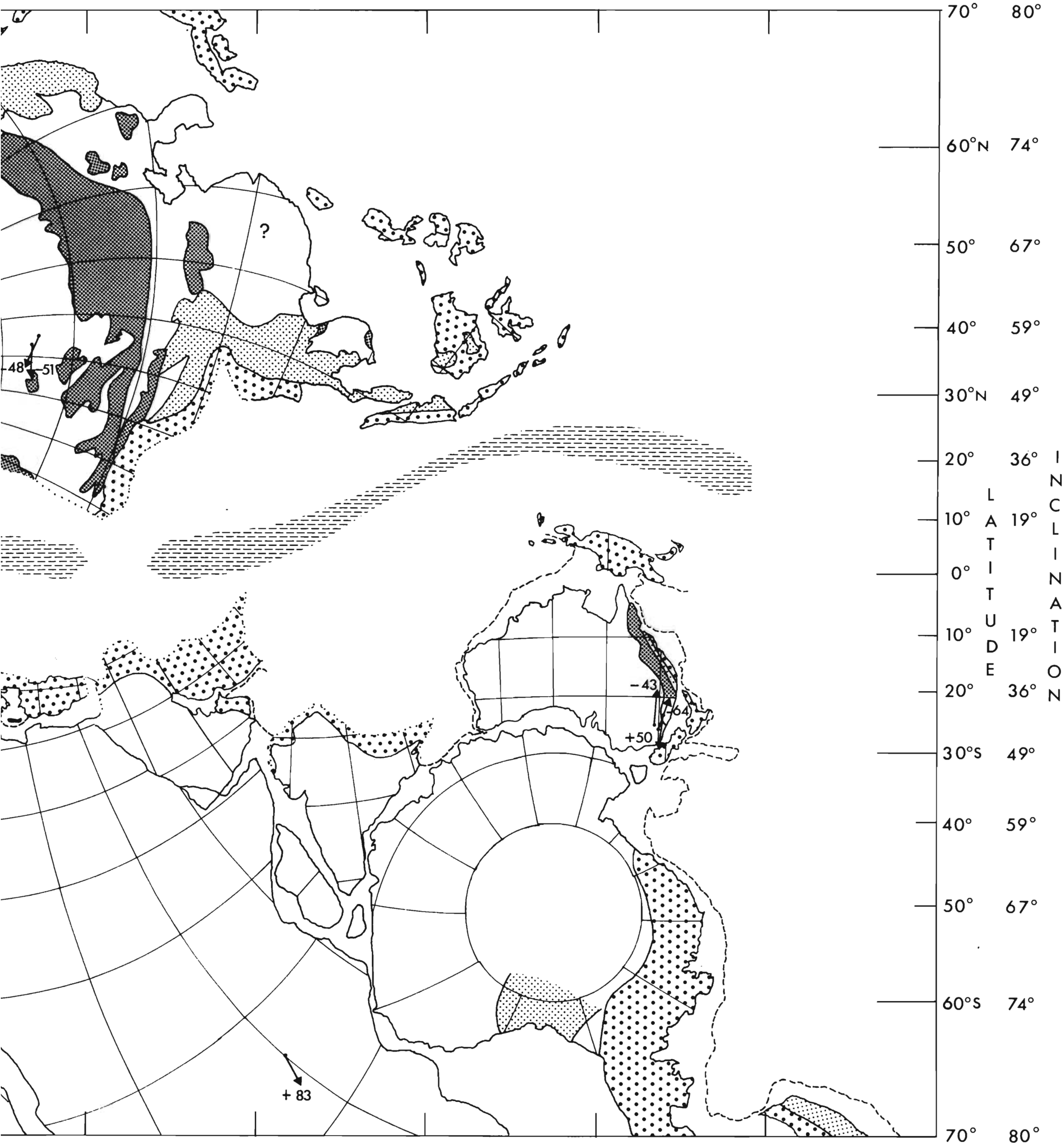
Text-figs. 6–13 between pp. 18 and 19.



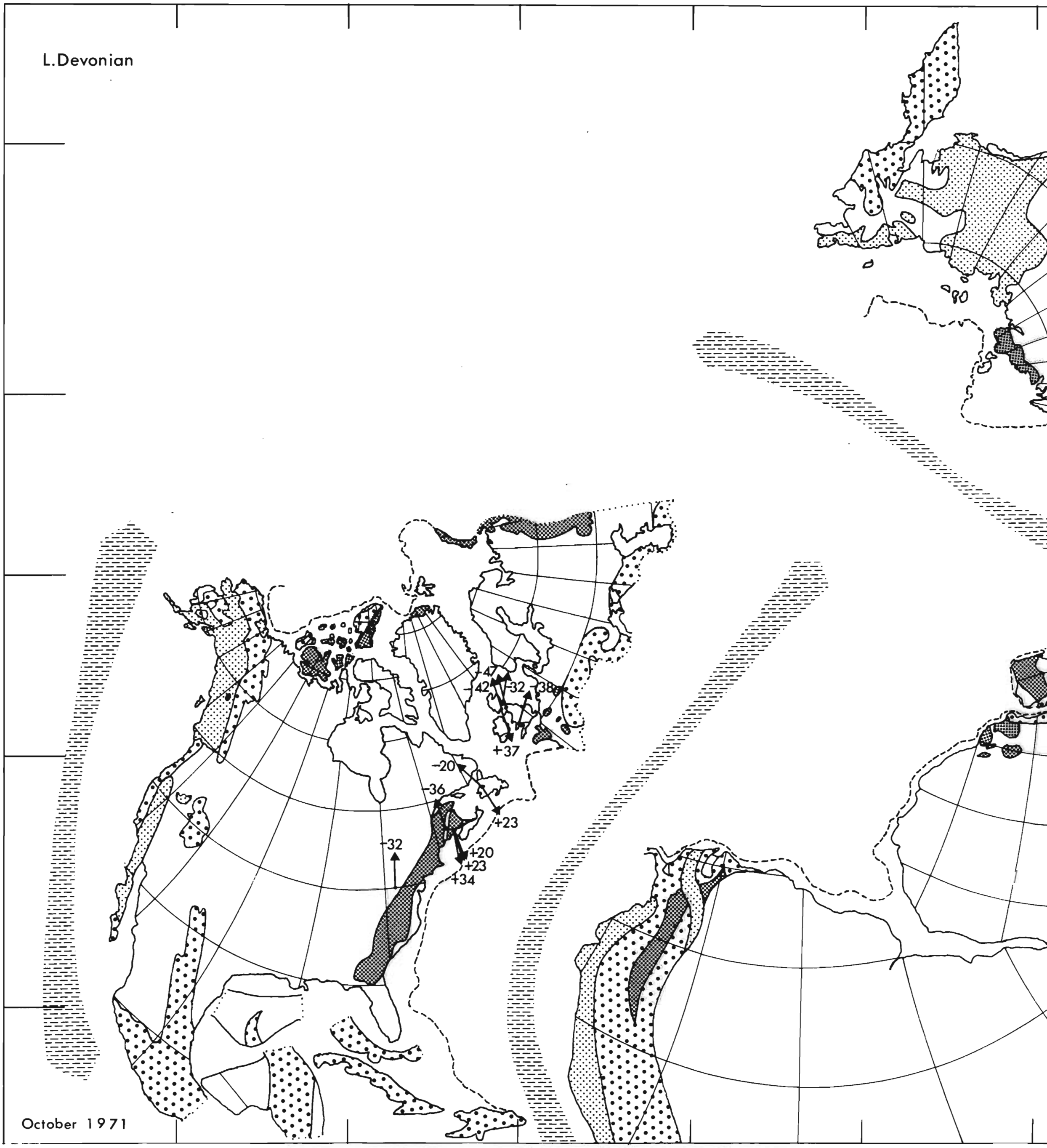
t 50±5 m.y.b.p.; Mercator projection.



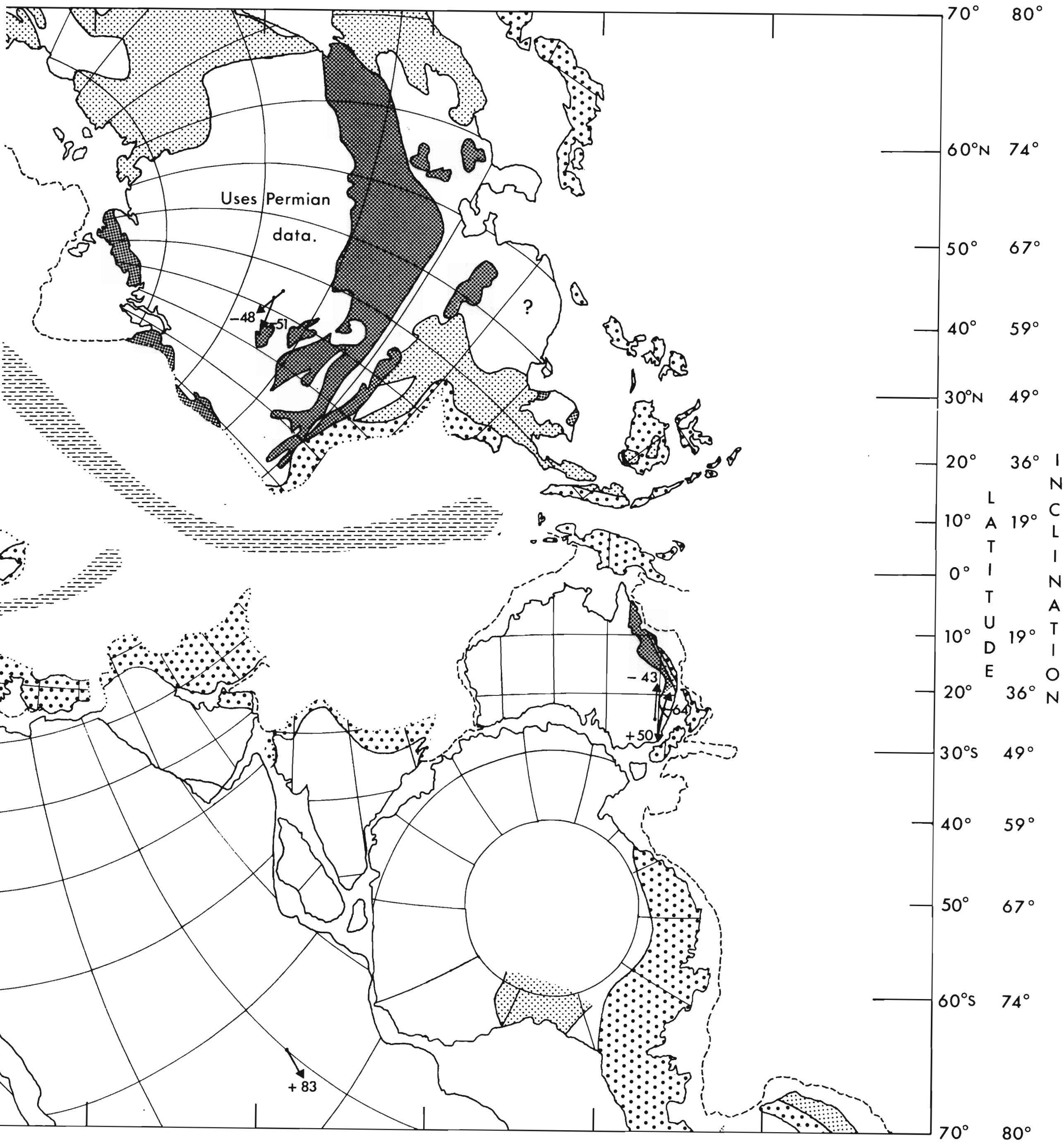
TEXT-FIG. 13. Map 8, 'Cambrian/Lower Or



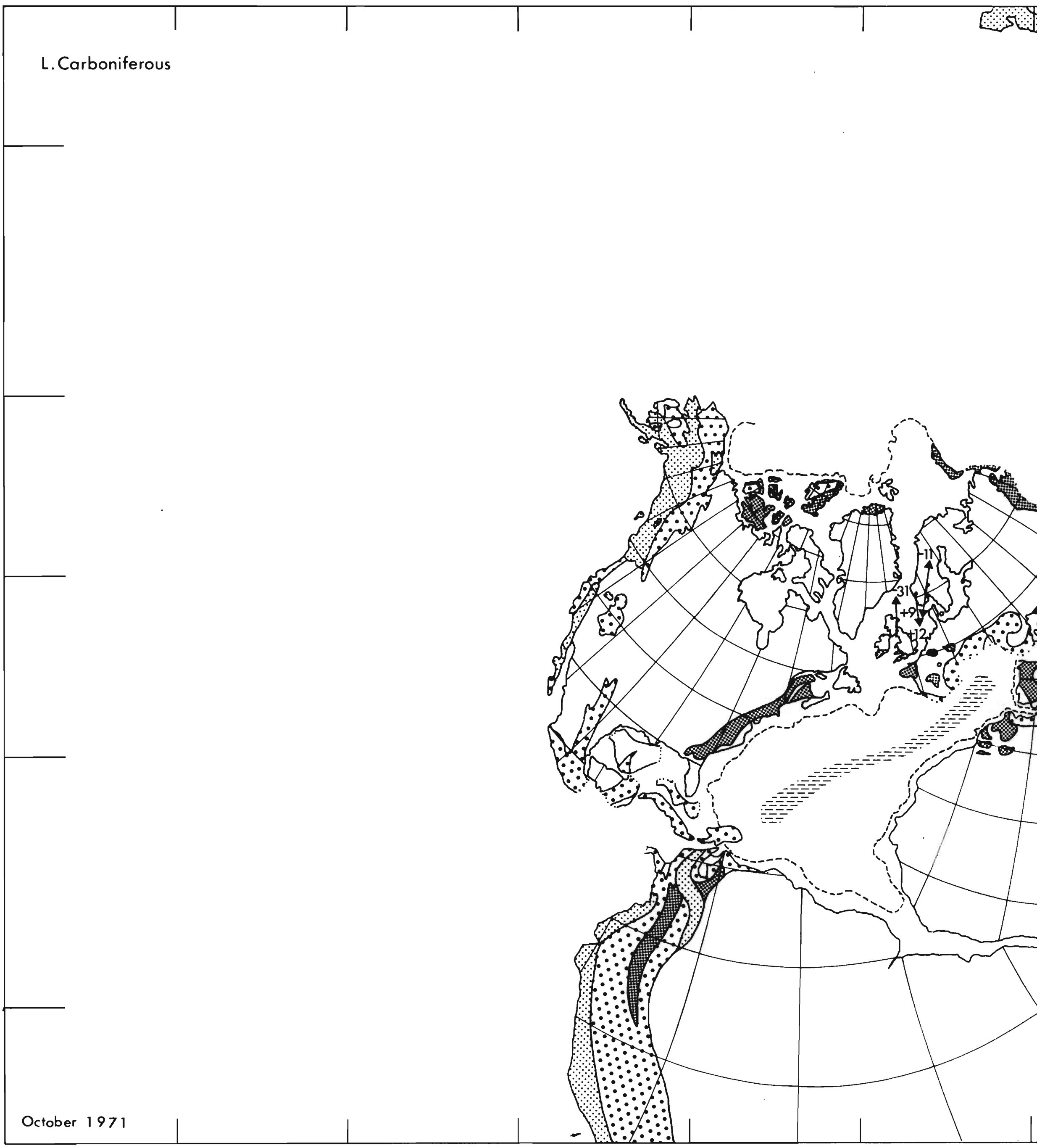
±3 m.y.b.p.; Mercator projection (see p. 36 for
of 'Euramerica').



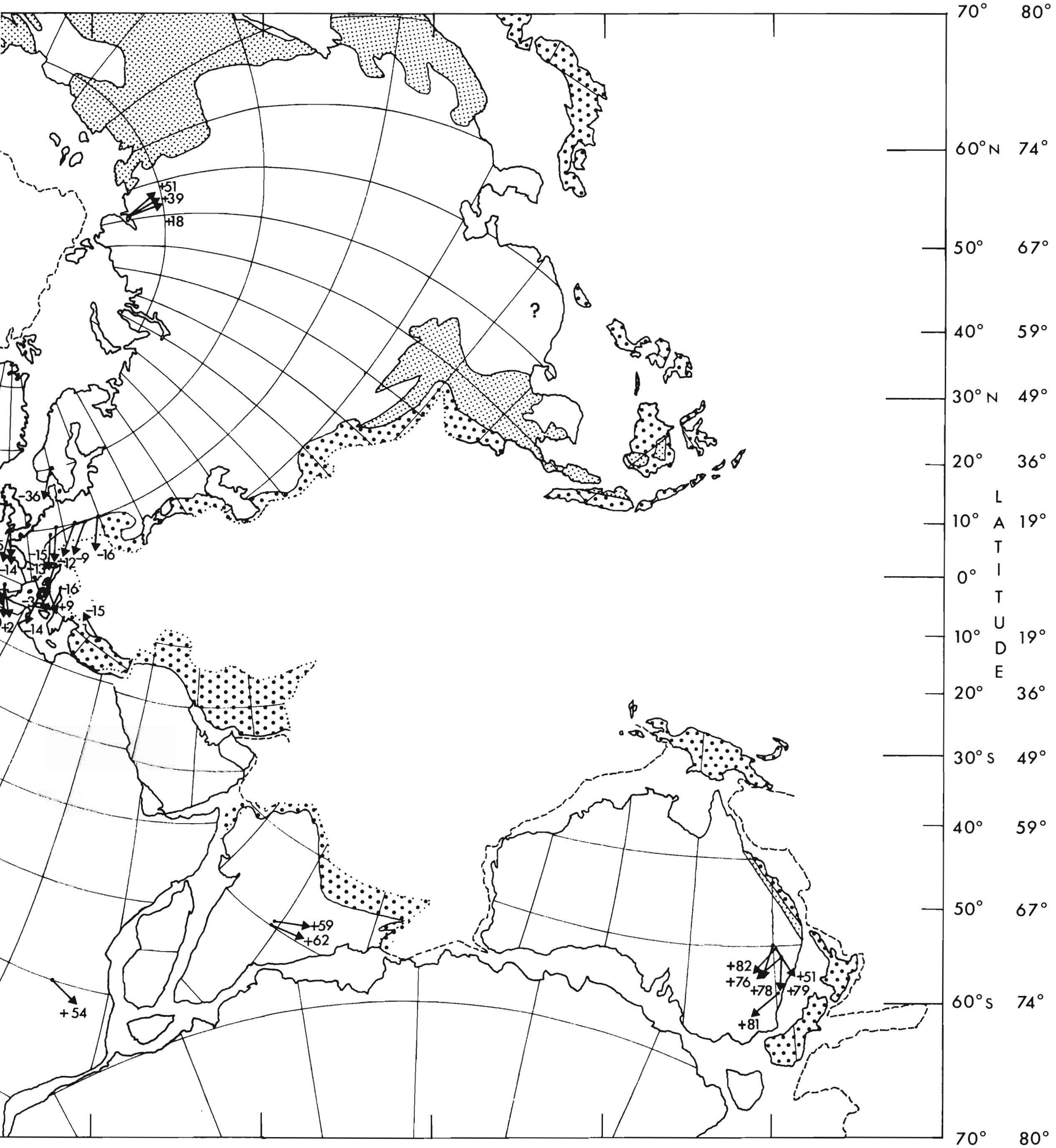
TEXT-FIG. 12. Map 7, 'Lower Devonian', ab
comments on



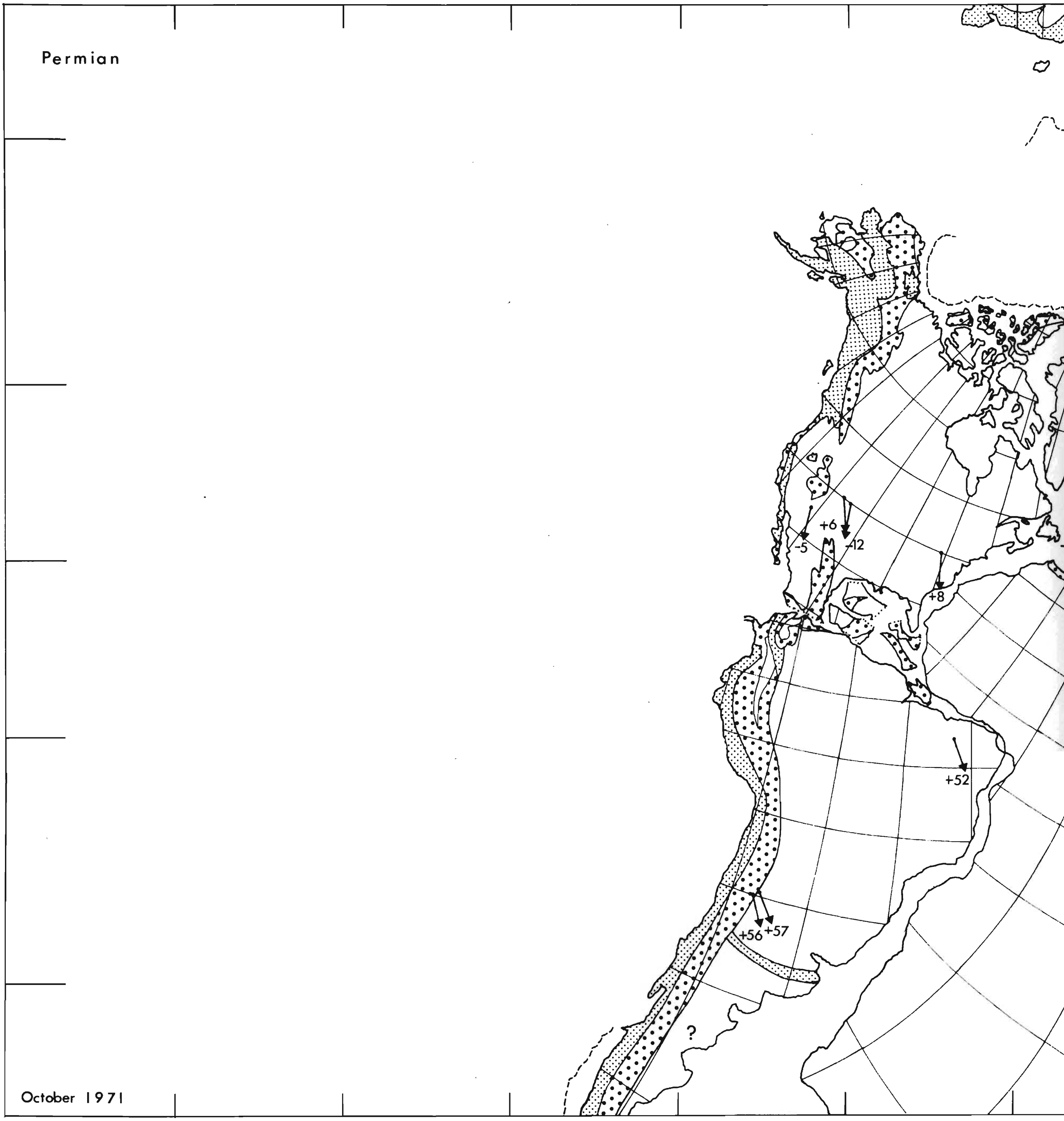
out 340 ± 30 m.y.b.p.; Mercator projection.



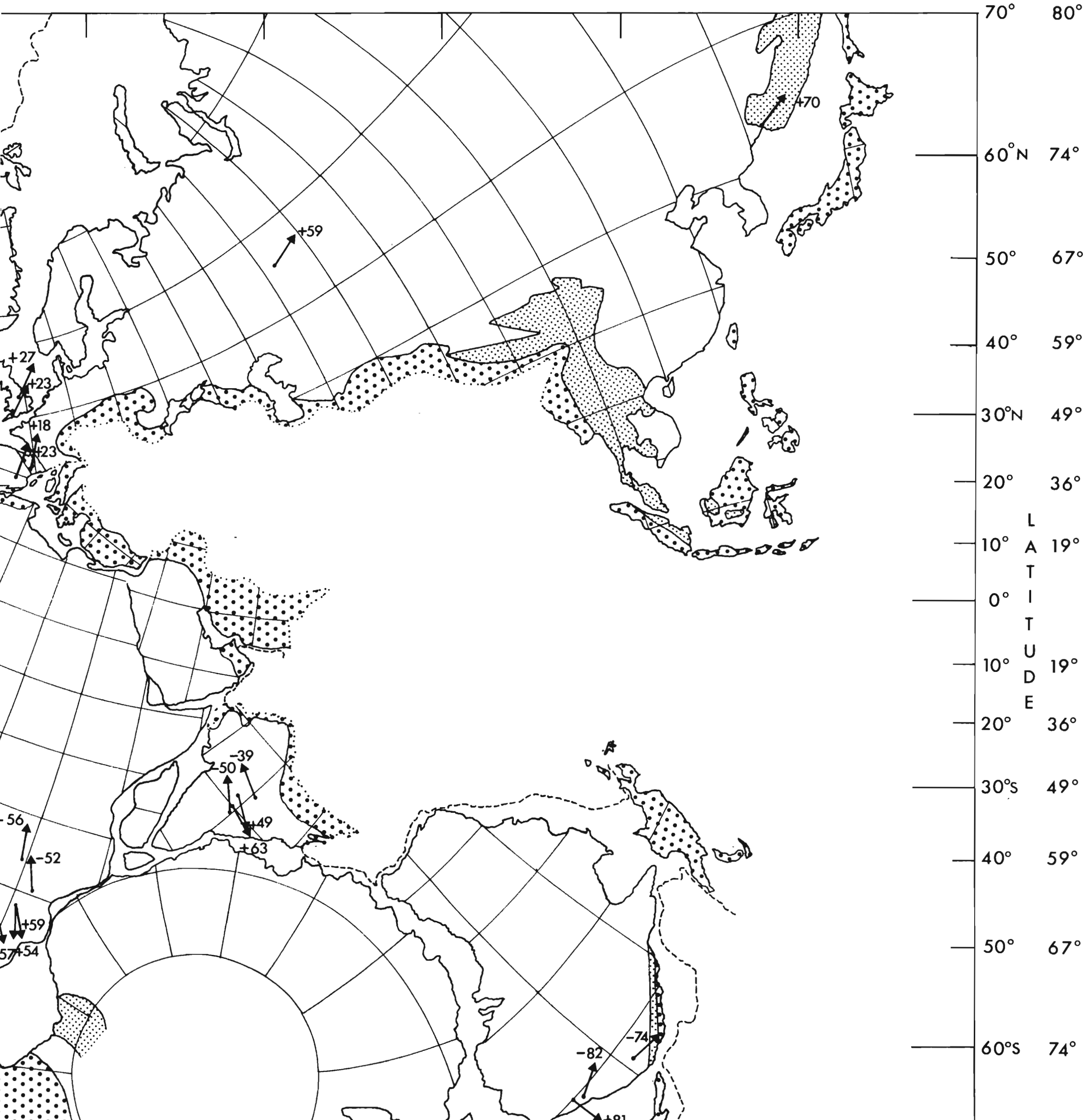
TEXT-FIG. 11. Map 6, 'Lower Carbonife



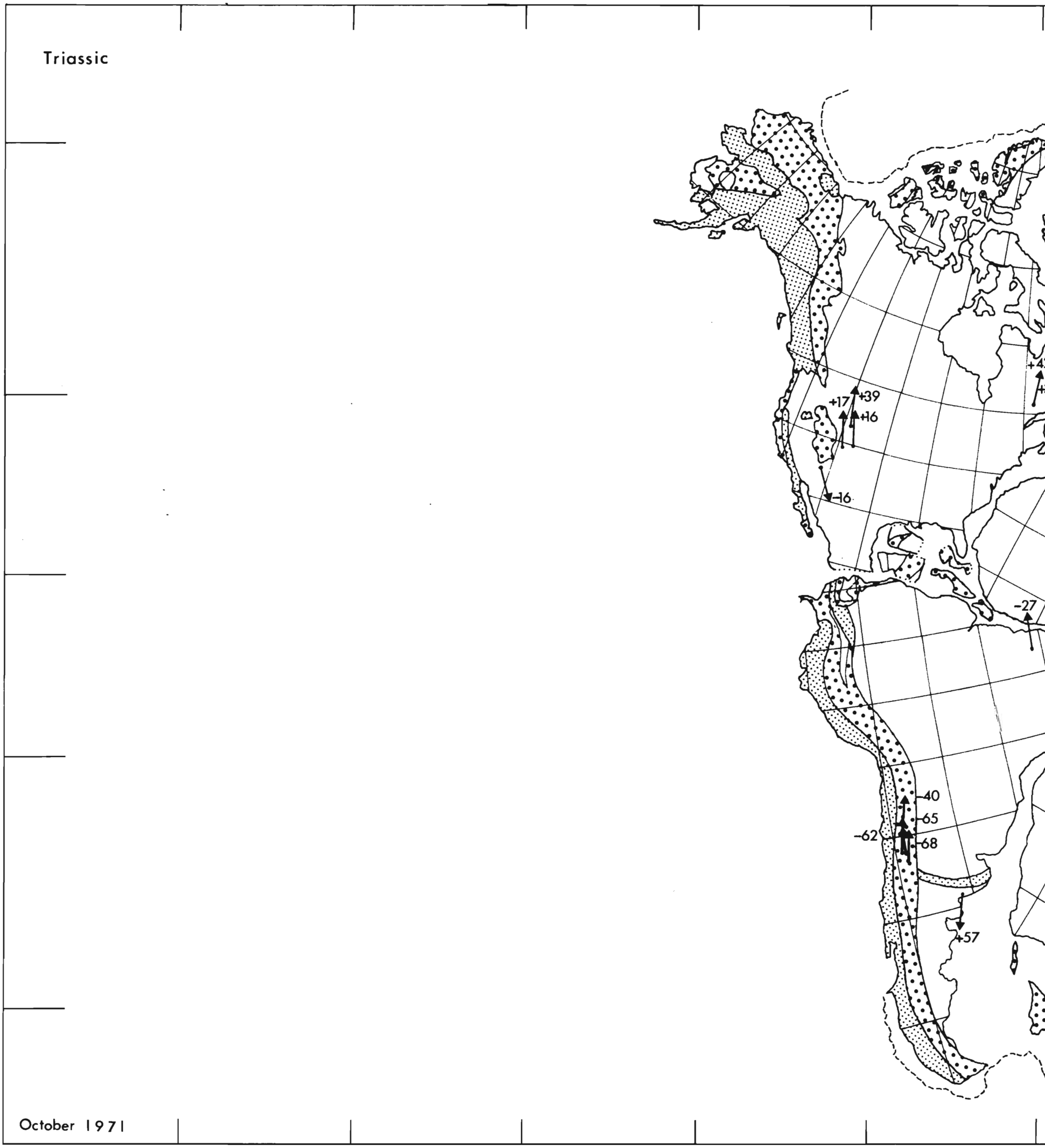
0 $\pm$ 25 m.y.b.p.; Mercator projection.



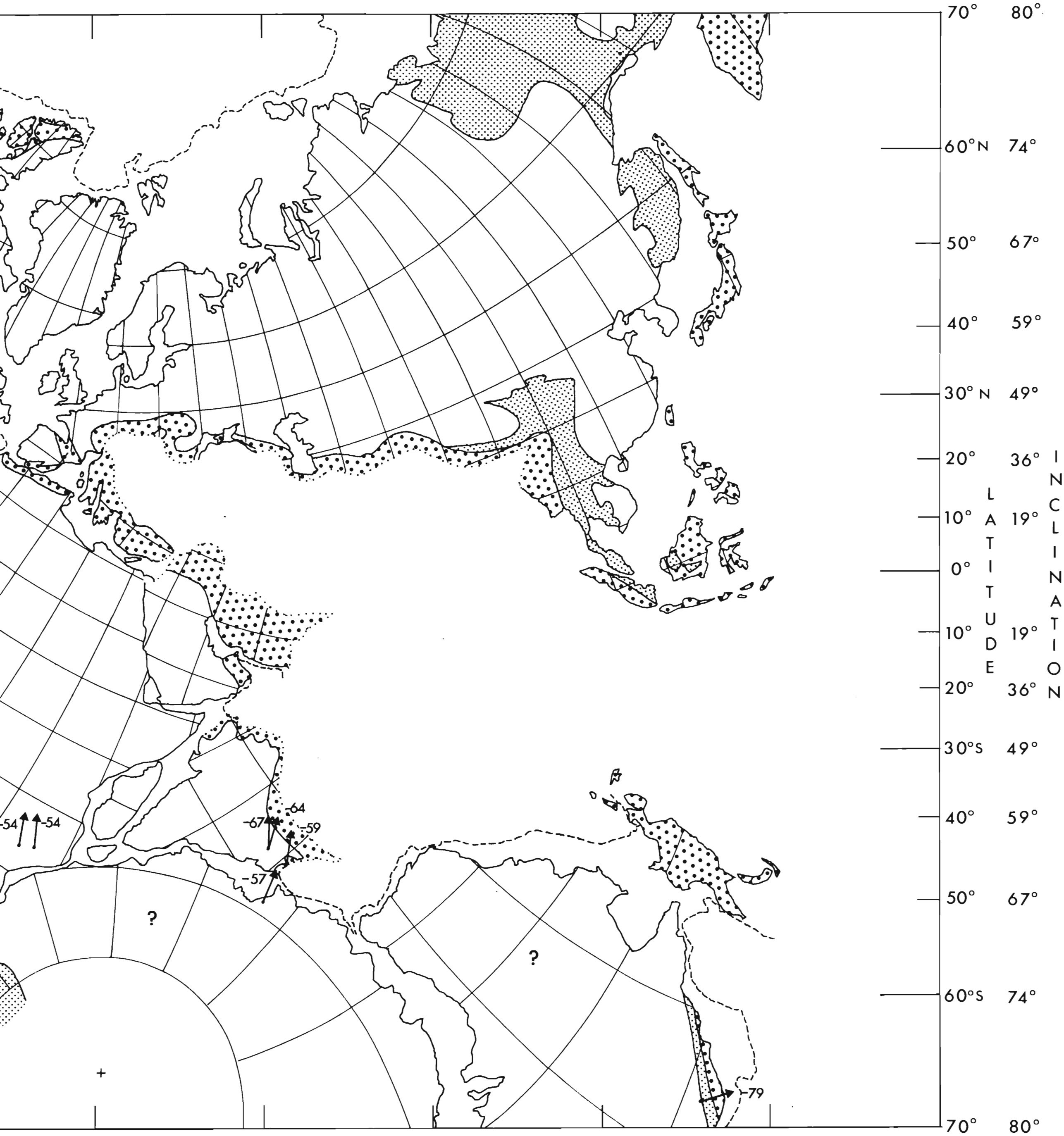
TEXT-FIG. 10. Map 5, 'Permian', about



±20 m.y.b.p.; Mercator projection.

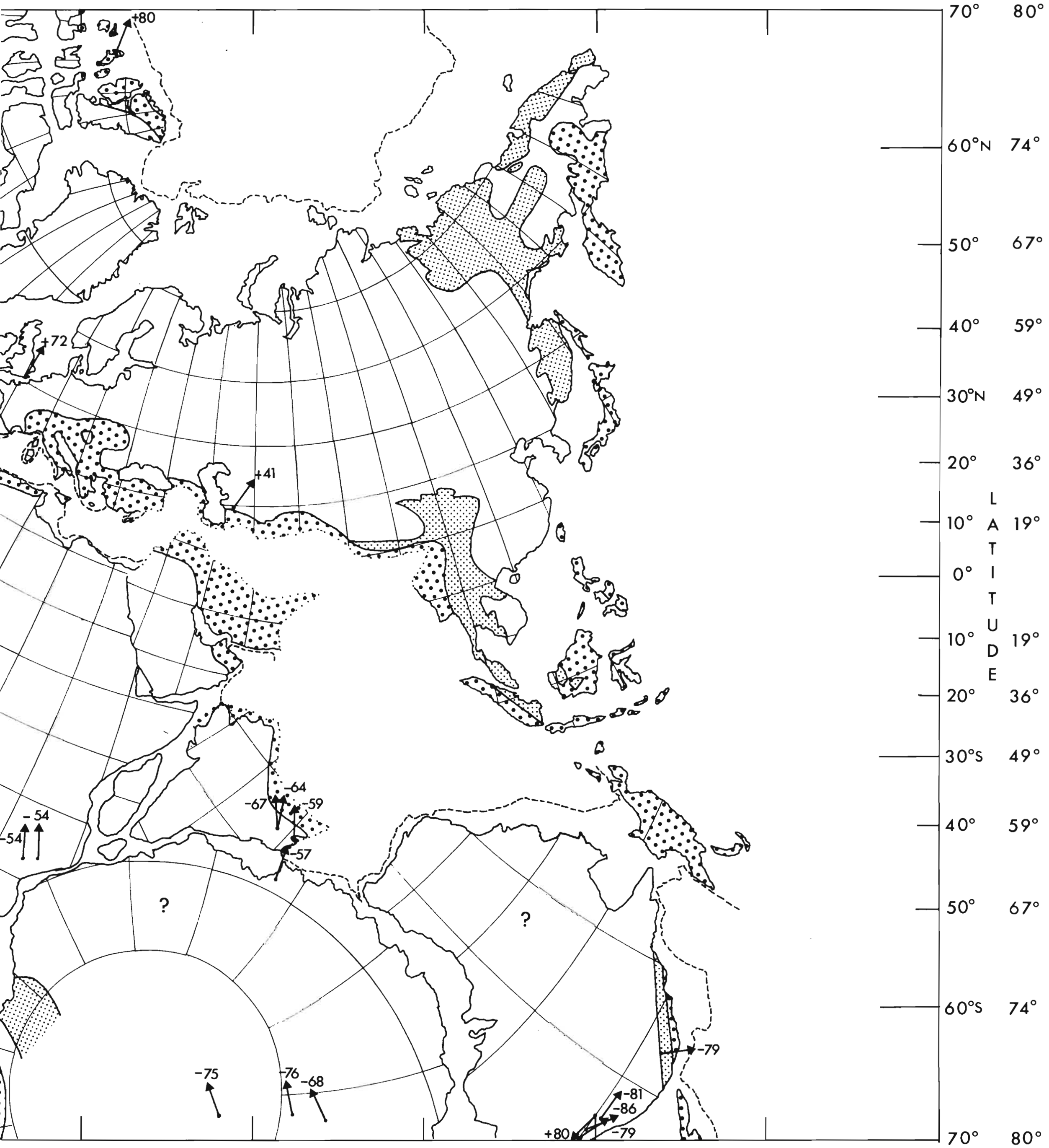


TEXT-FIG. 9. Map 4, 'Triassic', al

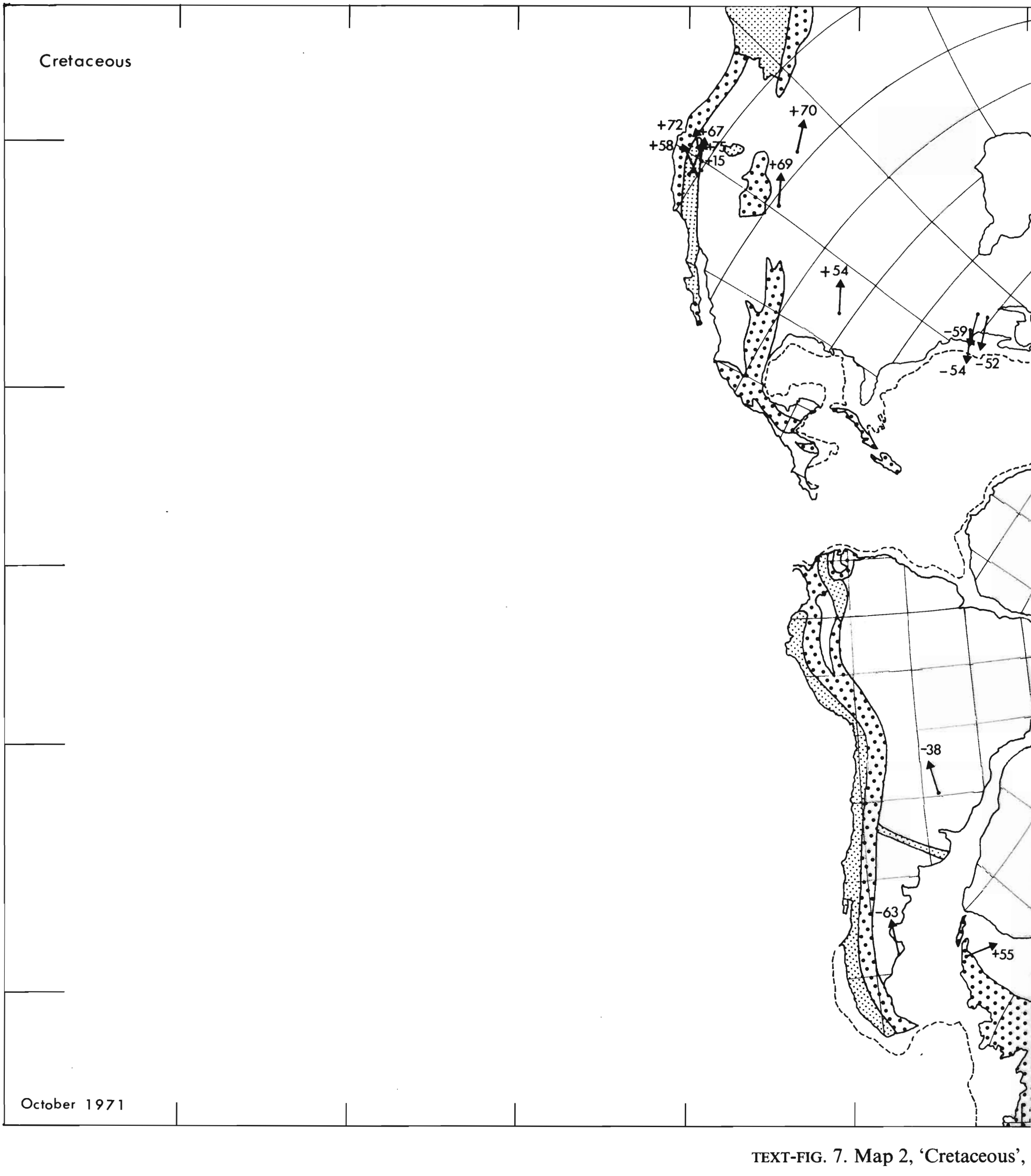


0±15 m.y.b.p.; Mercator projection.

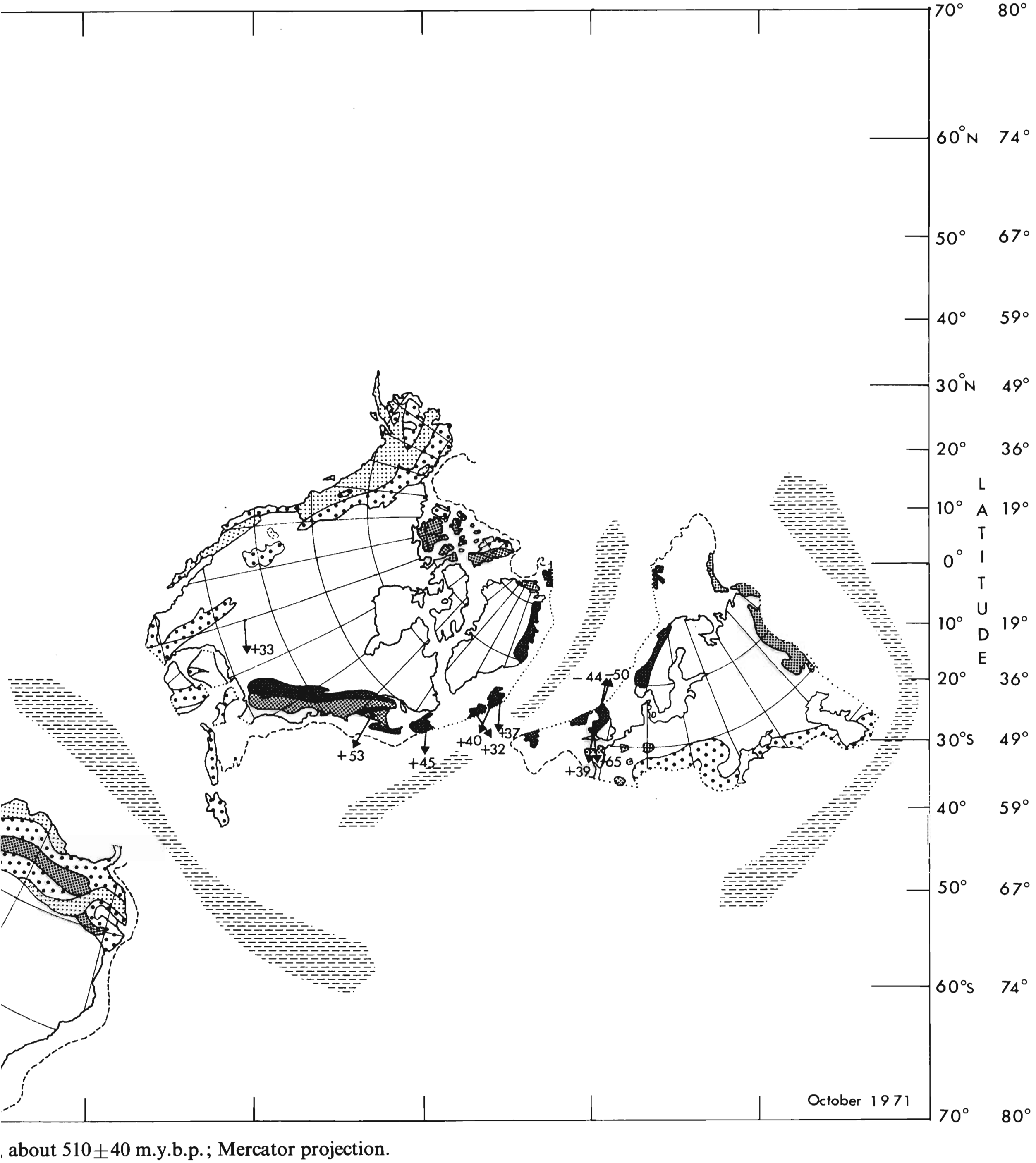
TEXT-FIG. 8. Map 3, 'Jurassic', ab



)±10 m.y.b.p.; Mercator projection.



TEXT-FIG. 7. Map 2, 'Cretaceous',



, about 510±40 m.y.b.p.; Mercator projection.

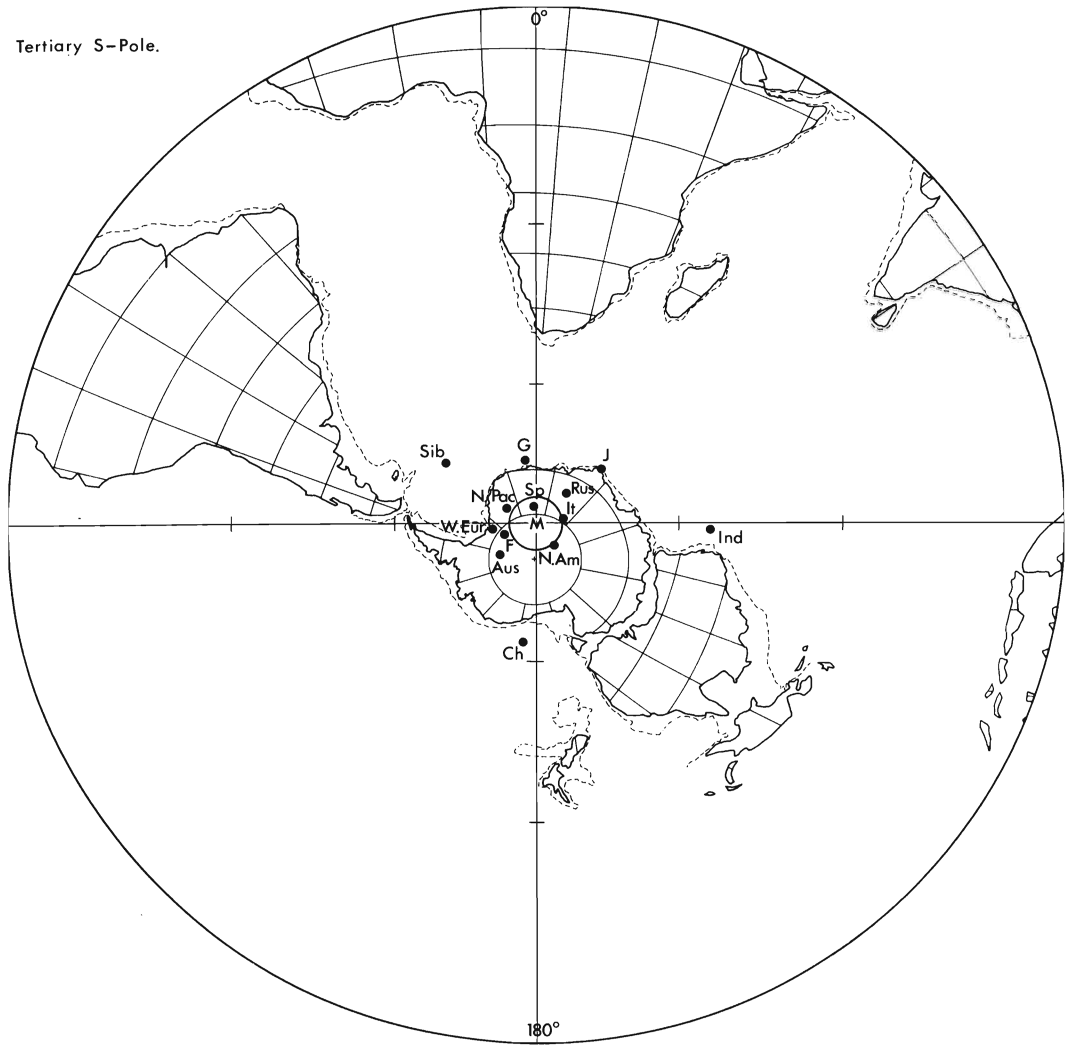
(Smith and Hallam 1970), and of the north and south Atlantic (Bullard *et al.* 1965), together with ocean-floor spreading data from the central Atlantic (Le Pichon and Fox 1971).

The fit of the southern continents has been criticized on a number of grounds. For instance, it has been pointed out that the Antarctic peninsula and the southern part of South America should be 'straightened out' because the present curvature has been imposed since the break-up of Gondwanaland. Nevertheless, it seems preferable to us to retain the present-day shapes, while at the same time realizing that they were different in the past, rather than attempting to portray the original shape, which is quite unknown. The same comments apply to any regions involved in a Phanerozoic orogenic episode. A more serious contention is that the fit is wrong; this is an opinion for which there is as yet no persuasive supporting evidence. The topographic fit adopted here satisfies two criteria: it links together truncated orogenic belts and other geological features; it also reassembles all the southern continents into a single mass without any gaps between the pieces. In principle, the correctness or otherwise of this fit will be established when the older parts of the Indian Ocean have been surveyed. The present data allow reassemblies based on ocean-floor spreading anomalies to be made as far back as 75 m.y. (McKenzie and Sclater 1971) which are not incompatible with the older maps drawn here.

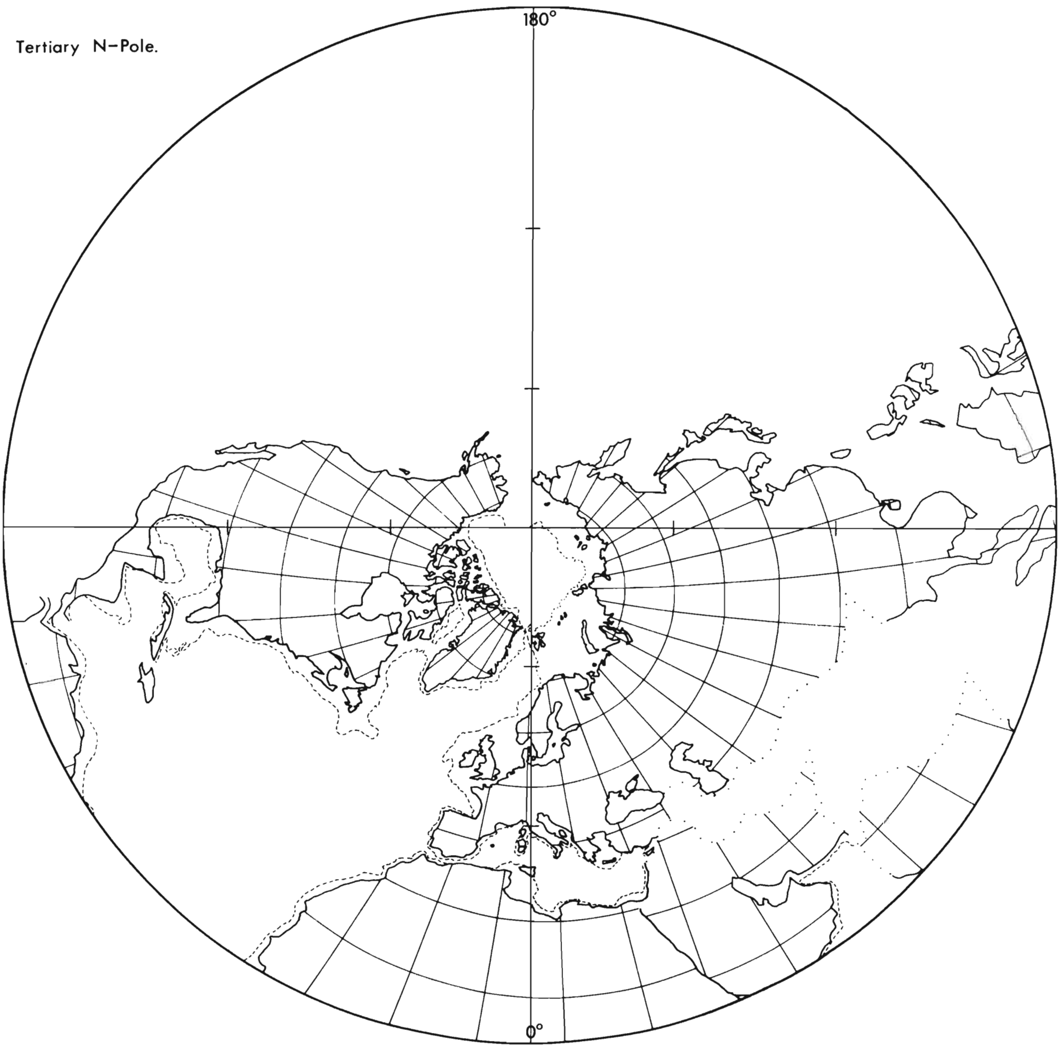
The main uncertainties in the Cretaceous and Jurassic maps are the times of break-up of Gondwanaland. We have assumed that neither the South Atlantic nor the Indian oceans had spread significantly before Mid-Cretaceous time. Extrapolation of the known spreading history of the South Atlantic over the last 80 m.y. to the time when South America and Africa were joined together suggests that significant spreading began in Early Cretaceous time (Hsü and Andrews 1970). Similarly, some palaeomagnetic data support a separation of the two continents before Mid-Cretaceous time (Valencio and Vilas 1970). However, the stratigraphic sequences observed on the margins of the two continents (Allard and Hurst 1969) strongly support the view that parts of the two continents were not significantly separated until at least Late Cretaceous time. We have given this stratigraphic evidence greater weight than the extrapolation of the spreading anomalies or of the palaeomagnetic data.

The time of significant dispersal of Australia from Antarctica is well known from ocean-floor spreading evidence (Le Pichon 1968). The time of significant separation of India, Madagascar, Africa, and Antarctica is not known from this evidence. Smith and Hallam (1970) argued on the basis of the distribution of igneous rocks, sediments and faunas that these parts of Gondwanaland began to break up mostly in Jurassic and Early Cretaceous time. Isotopic ages and the distribution of faulting in Africa support this view (Sowerbutts 1972). However, we believe that it may be erroneous to interpret these features as indicating significant dispersal, particularly in the light of Morgan's (1972) speculations that many of these igneous sequences represent 'hot-spots' established on the edges of continents long before significant spreading occurred. In other words, the time of break-up is well known, but the time of significant dispersal is not. We have assumed that significant dispersal did not occur until after Early Cretaceous time.

The Permian and Triassic maps have been obtained by joining together the best-fits of the Atlantic continents (Bullard *et al.* 1965) and the southern continents

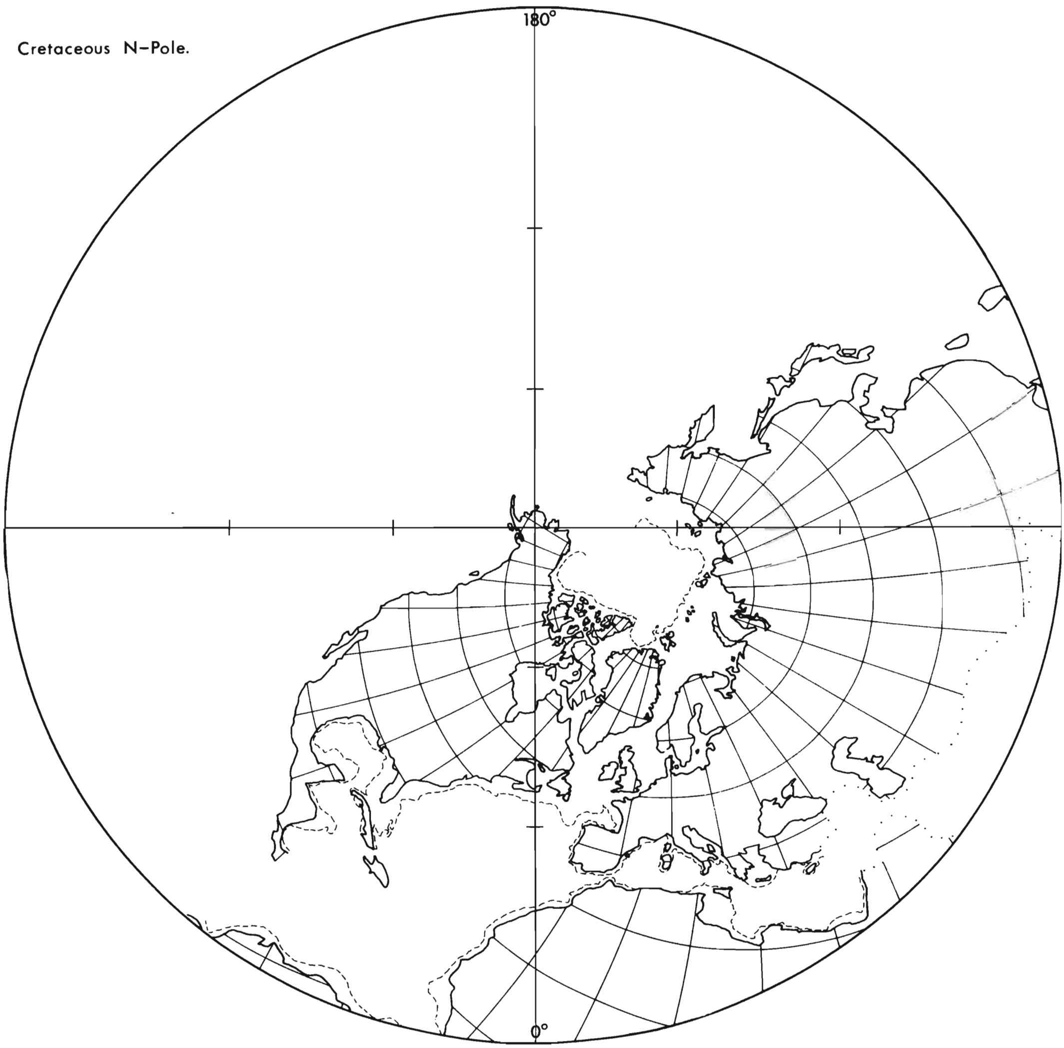


TEXT-FIG. 14A. Map 1, 'Tertiary' (Eocene), about 50±5 m.y.b.p.; S-pole stereographic projection.

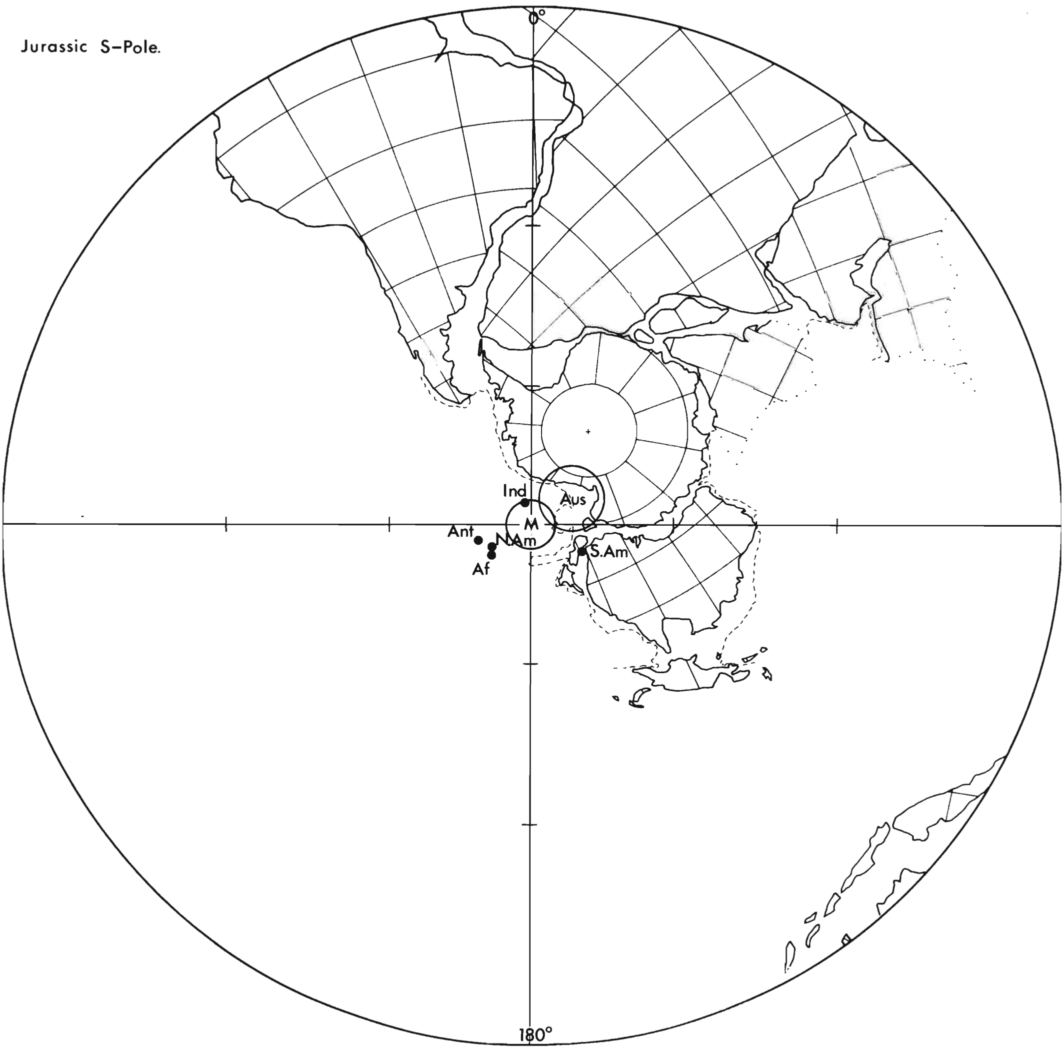


TEXT-FIG. 14B. Map 1, 'Tertiary' (Eocene), about 50±5 m.y.b.p.; N-pole stereographic projection.

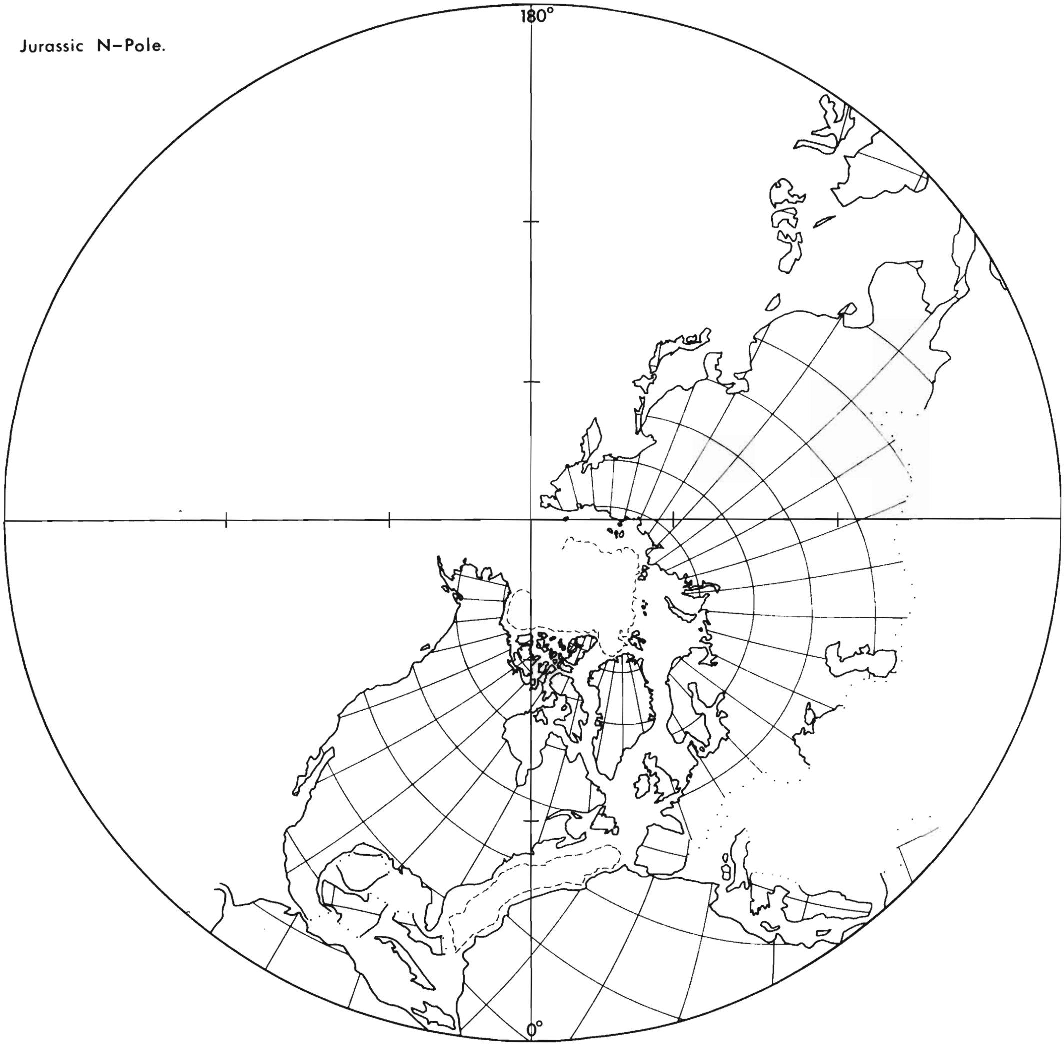
TEXT-FIG. 15A. Map 2, 'Cretaceous', about 100±10 m.y.b.p.; S-pole stereographic projection.



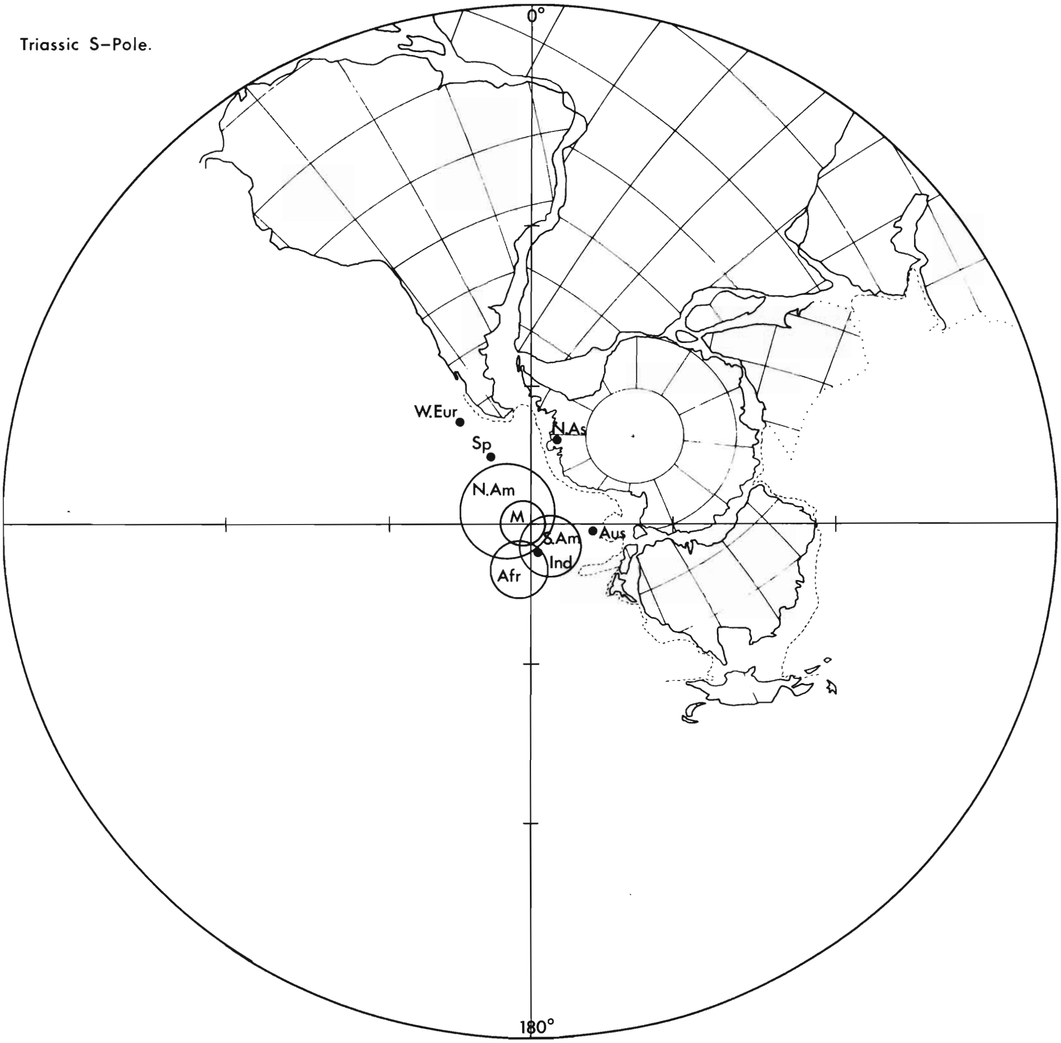
TEXT-FIG. 15B. Map 2, 'Cretaceous', about 100±10 m.y.b.p.; N-pole stereographic projection.



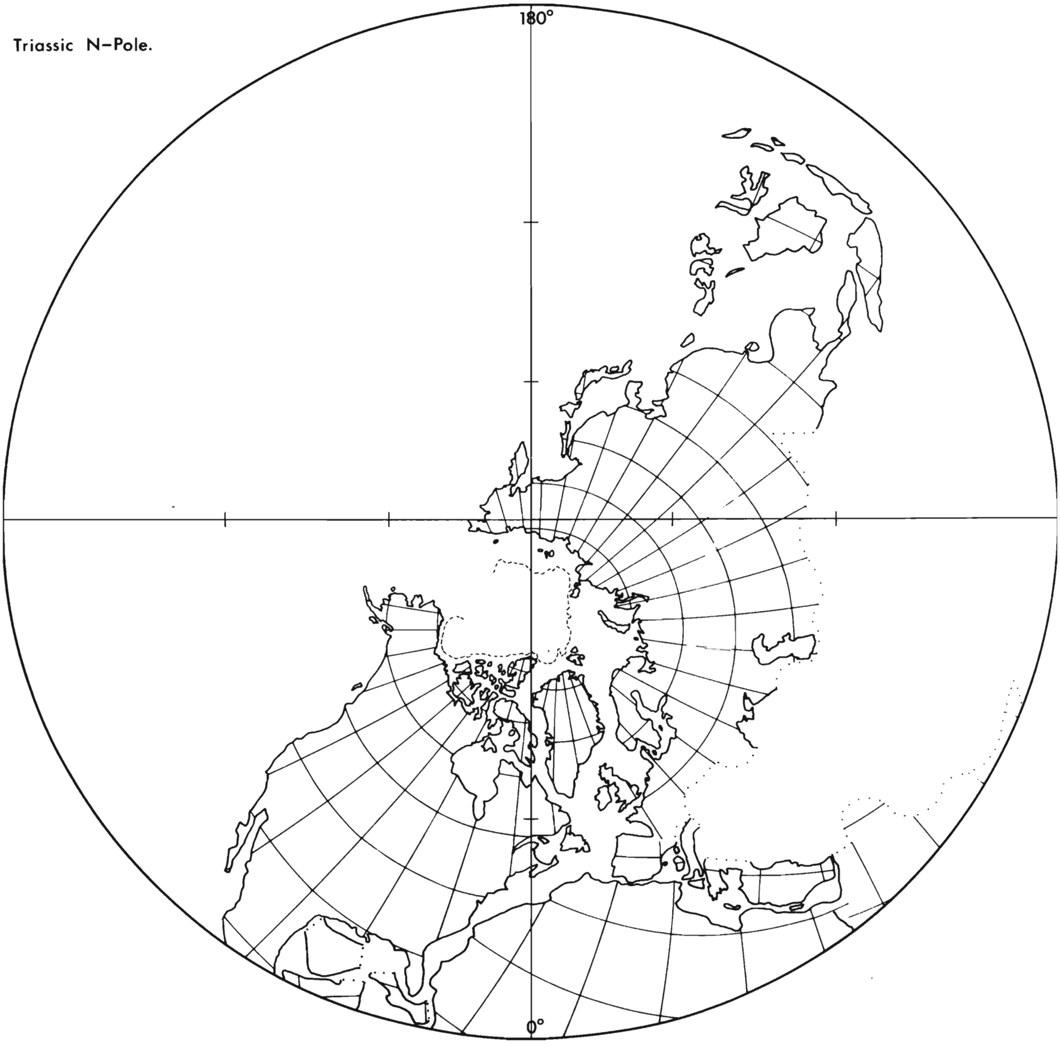
TEXT-FIG. 16A. Map 3, 'Jurassic', about 170 ± 15 m.y.b.p.; S-pole stereographic projection.



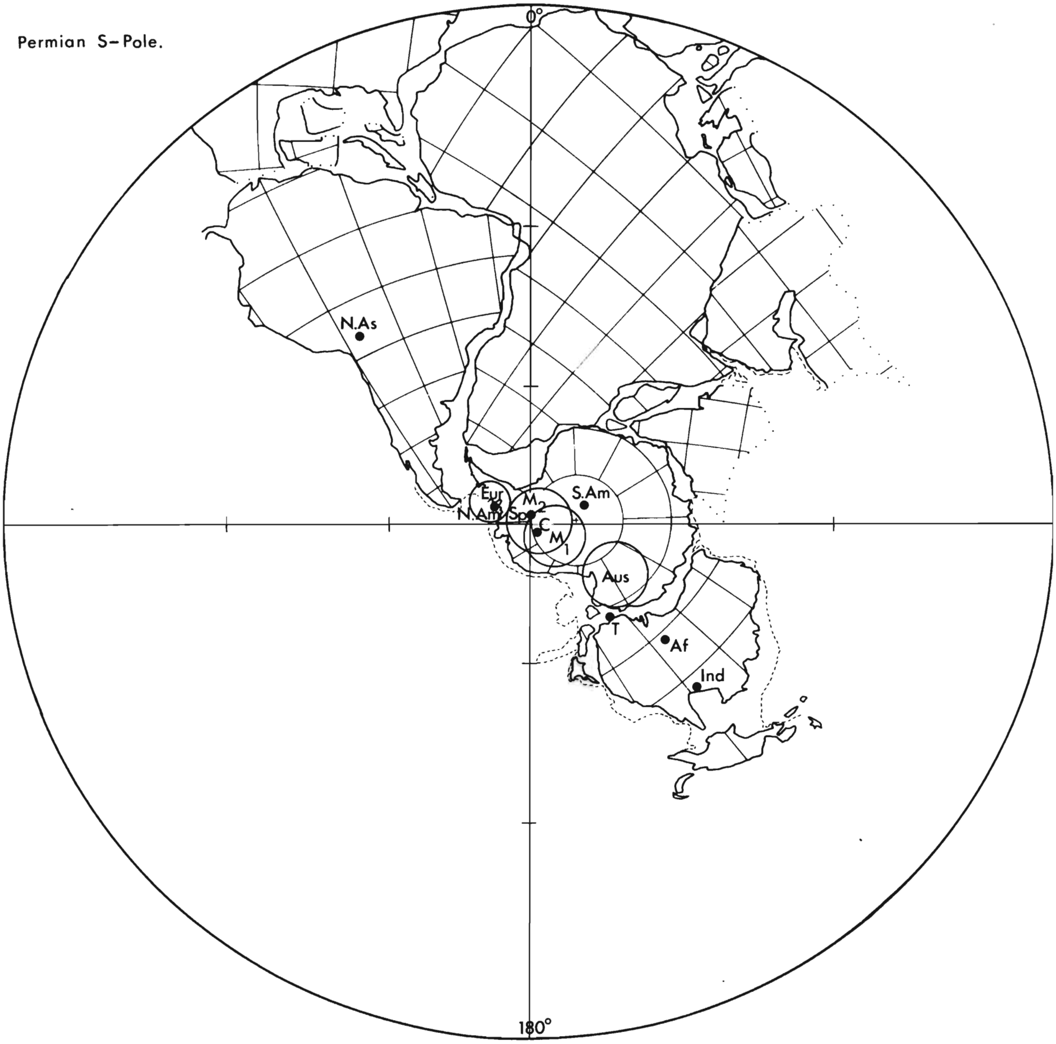
TEXT-FIG. 16B. Map 3, 'Jurassic', about 170±15 m.y.b.p.; N-pole stereographic projection.



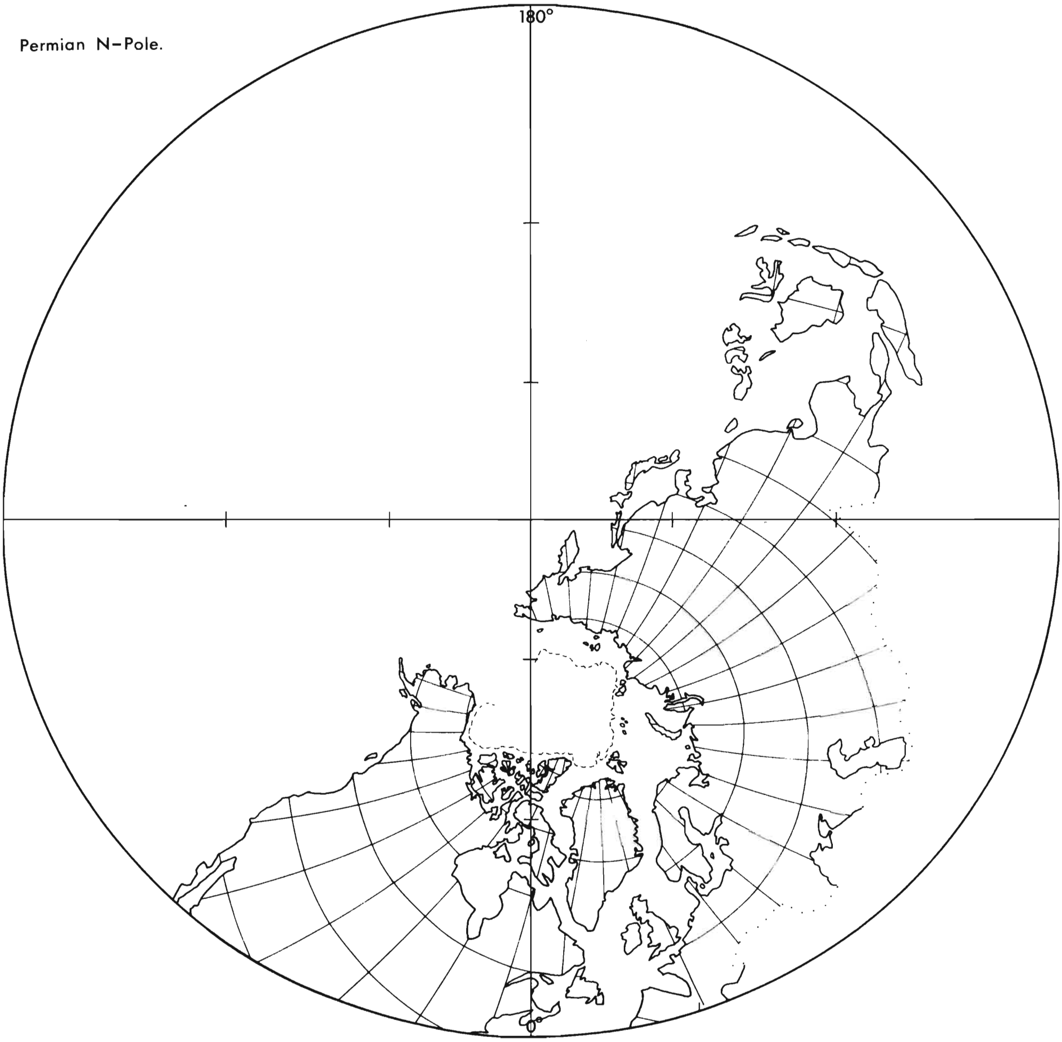
TEXT-FIG. 17A. Map 4, 'Triassic', about 220±20 m.y.b.p.; S-pole stereographic projection.



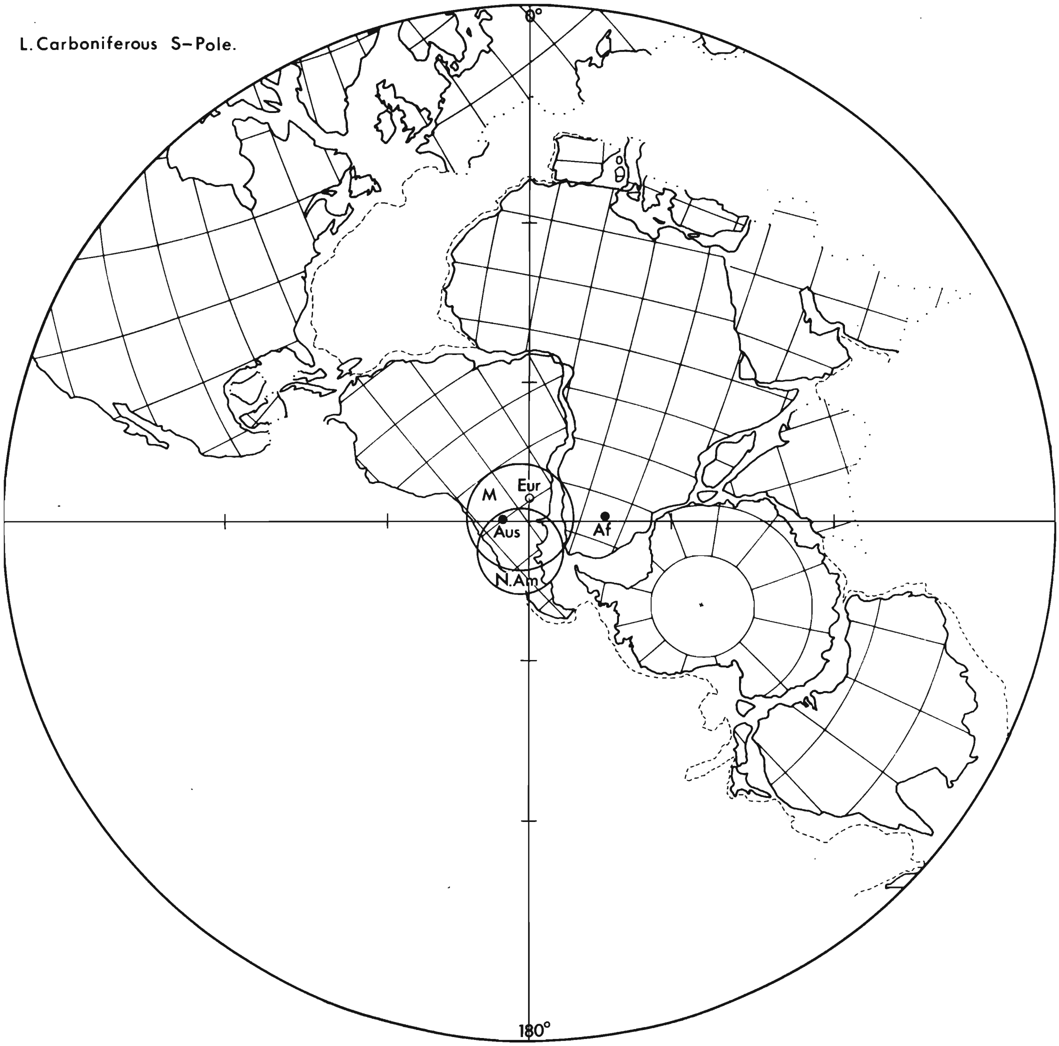
TEXT-FIG. 17B. Map 4, 'Triassic', about 220±20 m.y.b.p.; N-pole stereographic projection.



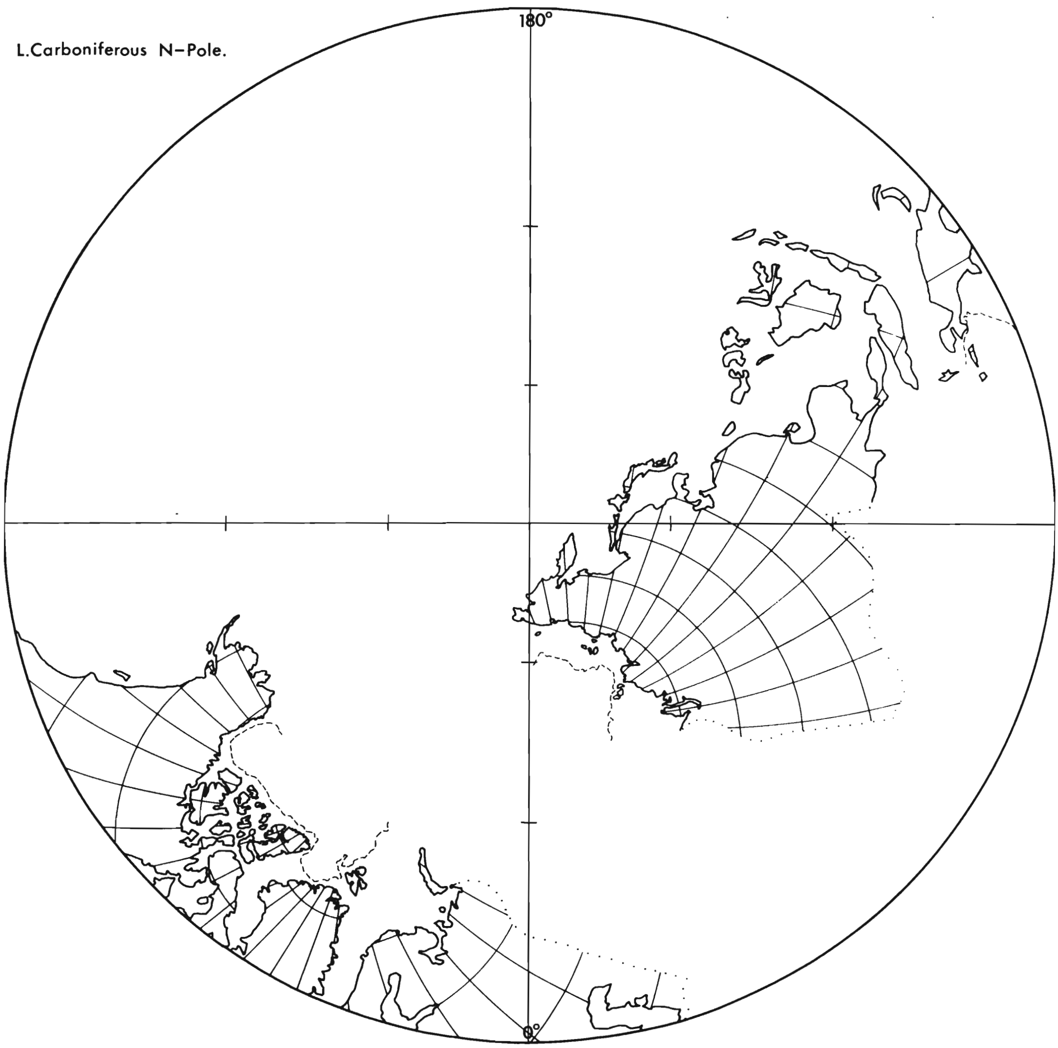
TEXT-FIG. 18A. Map 5, 'Permian', about 250±25 m.y.b.p.; S-pole stereographic projection.



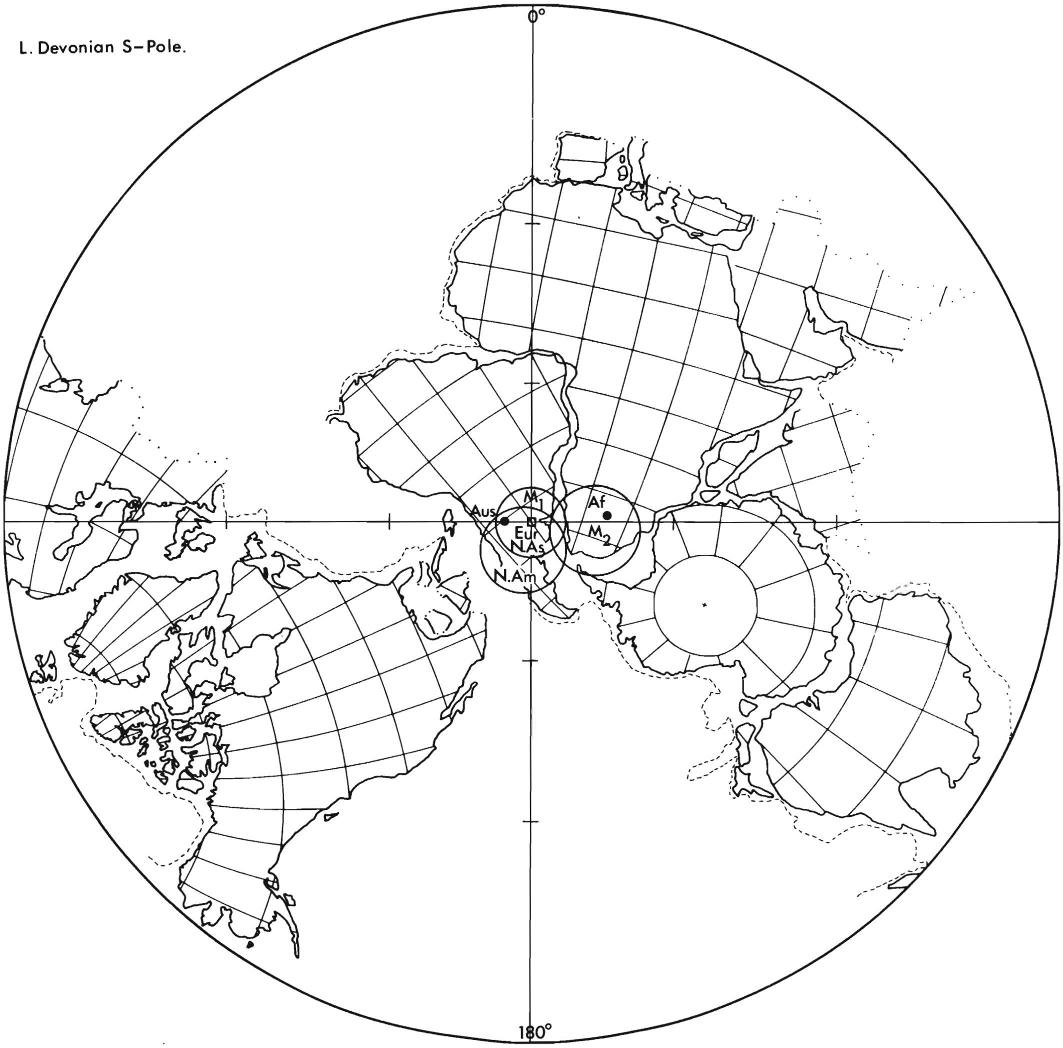
TEXT-FIG. 18B. Map 5, 'Permian', about 250±25 m.y.b.p.; N-pole stereographic projection.



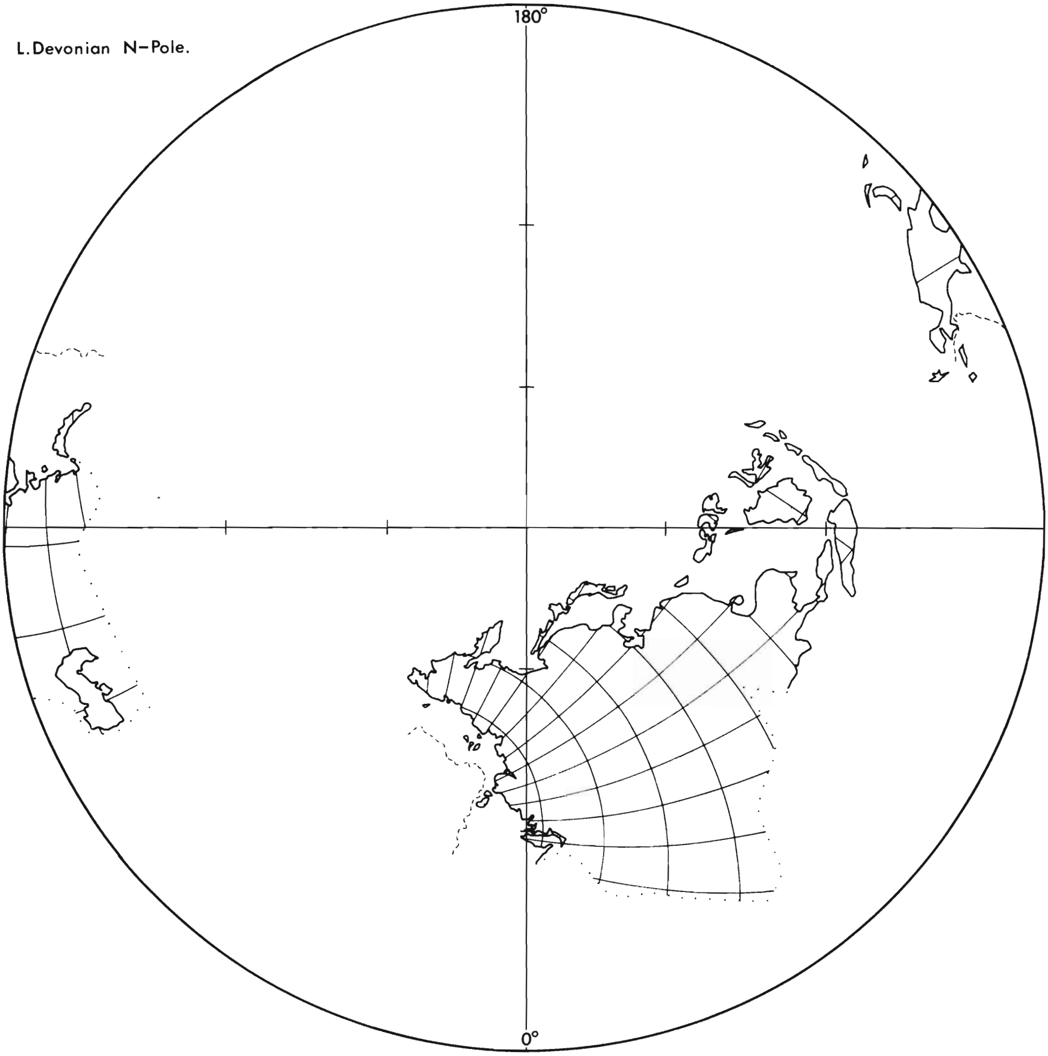
TEXT-FIG. 19A. Map 6, 'Lower Carboniferous', about 340±30 m.y.b.p.; S-pole stereographic projection.



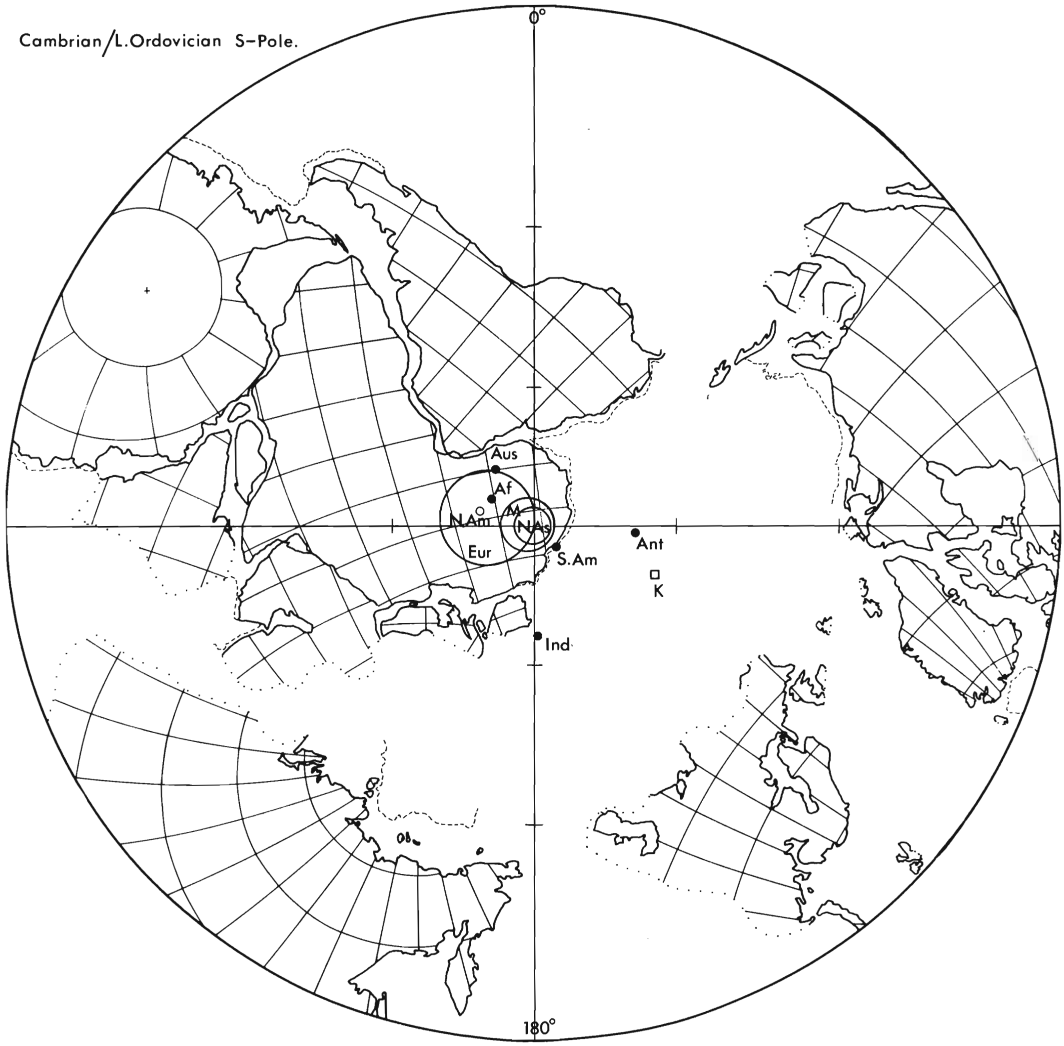
TEXT-FIG. 19B. Map 6, 'Lower Carboniferous', about 340±30 m.y.b.p.; N-pole stereographic projection.



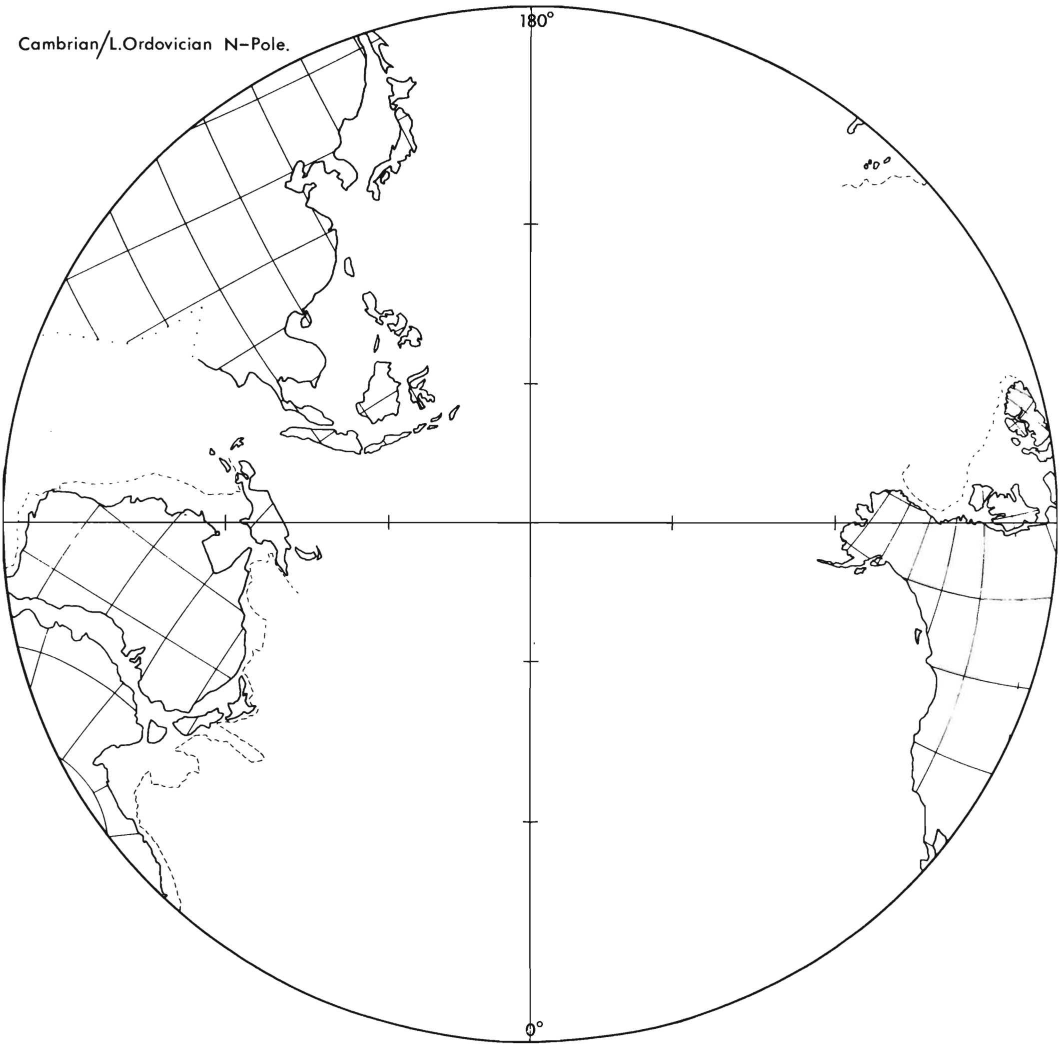
TEXT-FIG. 20A. Map 7, 'Lower Devonian', about 380±35 m.y.b.p.; S-pole stereographic projection. (See p. 36 for comments on position of 'Euramerica'.)



TEXT-FIG. 20B. Map 7, 'Lower Devonian', about 380±35 m.y.b.p.; N-pole stereographic projection.



TEXT-FIG. 21A. Map 8, 'Cambrian/Lower Ordovician', about 510±40 m.y.b.p.; S-pole stereographic projection.



TEXT-FIG. 21B. Map 8, 'Cambrian/Lower Ordovician', about 510±40 m.y.b.p.; N-pole stereographic projection.

(Smith and Hallam 1970). The reassembly forms the 'Pangaea' of Wegener (1924). Because no Permian or Triassic orogenic belts cross this reassembly, except perhaps in Asia, we assume that it existed as an entity throughout Permian and Triassic time. In Carboniferous and earlier time the reassembly must be broken into at least three parts, the lines of separation lying somewhere in the Appalachian-Hercynian and Uralian orogenic belts. We do not know precisely where these lines of separation lie, nor whether some of the areas lying within these orogenic belts formed micro-continents lying between the major pieces. In other words, the particular lines we have chosen are arbitrary though a line or lines must exist in these belts. No reliable Early Carboniferous palaeomagnetic data is known to us from Asia, and we therefore have to choose an arbitrary pole for Asia for Early Carboniferous time. Permian and Devonian poles show that the orientation of Asia is not markedly different during these two periods. We have arbitrarily selected the Permian pole to portray Asia in Early Carboniferous time.

The main uncertainty in the Lower Devonian map is the correct pole for North America-Greenland-Europe. There is no evidence for any plate margin within these continental fragments from Devonian to Triassic time except for minor displacements along the Great Glen and related transform faults. Thus the relative positions of all three continents is given by the reconstruction of Bullard *et al.* (1965). When the maps were drawn we had to choose between the North American and the British data rather than averaging them, since they differ significantly. We selected the British data because of their consistency and good stratigraphic control, and disregarded the North American data. After the maps had been drawn we obtained access to the compilation of Khramov and Sholpo (1967). Their data from the Russian platform are in reasonable agreement with the North American poles but both disagree with the poles from Britain. The reasons for the disagreement are not known. If the North American and Russian poles are used to orientate North America-Greenland-Europe on the map then 'Euramerica' has roughly the same orientation relative to Gondwana as it does on the Pangaea reconstruction.

The main problem with the Cambrian-Lower Ordovician map is that so many parts of it have been involved in more recent orogenies or lack the necessary palaeomagnetic control. The lines of separation of the principal fragments are similar to those that must have existed in Devonian and Carboniferous time, but an additional one must be postulated along the length of the Caledonian-Appalachian chain. These lines represent the positions of one or more former oceans. As in the case of the Devonian and the Carboniferous maps, the precise positions of these oceans is uncertain. In Britain, one of the lines of separation probably lies between the Scottish Highlands and the Southern Uplands (Dewey 1969). The width of the ocean or oceans is not known, but palaeomagnetic and tectonic evidence suggests that it was not wider than about 2000 kilometres (Briden and colleagues, unpublished data).

The orientation of North America, Greenland, and Europe has been found by treating it as an unbroken unit to obtain a mean pole position. The orientated unit has then been broken into two pieces along the Caledonian-Appalachian belt, which have been moved apart along constant palaeolatitude lines to schematically show the position, but not necessarily the width of the Caledonian ocean.

DISCUSSION

The maps and composites show the probable positions of only the major continental fragments. As indicated above, fragments like China that were separated from the major fragments by orogenic belts have not been treated separately. Other parts of the world will also need to be repositioned, such as parts of Asia east of the Verkoyhansk Mountains (McElhinny 1972*b*). Plate tectonic interpretations of parts of eastern Australia involved in Palaeozoic fold belts have been given by Oversby (1971) and are supported by palaeomagnetic data (McElhinny 1972*c*). Many similar interpretations of all the other parts of the world that have been involved in orogenic belts may be anticipated over the next few years.

It is not our purpose to comment at length on the palaeontological relevance of our maps; that is done elsewhere in this volume. But a few brief points are pertinent. One may with fair confidence assign palaeolatitude ranges to floras and faunas that are widespread on the major continents and hence assess their probable palaeoclimatic significance. The post-Carboniferous maps also show the likely migration routes for terrestrial and shelf floras and faunas, and the incidence of provinciality can be assessed. But not even the Eocene map possesses the precision that would enable one to answer such questions as whether there was a tenuous link between two continents at a particular time, and when this link had been made and was broken. We stress that only detailed investigations can hope to tackle such problems.

It is in the improvement of the more speculative Palaeozoic composites that we believe palaeontology will prove of considerable value. In particular, fossil distributions may place constraints on the longitude separations of the composited pieces and may also indicate more precisely their lines of separation. A good example of the value of fossils may exist in the contribution of Cocks and McKerrow (this volume). Their figures change the relative longitude separation of Siberia and western Europe, and moves western Europe somewhat farther south. This more southerly position was chosen to make a simpler interpretation of the brachiopod distribution possible, but it also happens to agree with the most recent palaeomagnetic data (Briden and colleagues, unpublished data). It also suggests a simpler evolution of the Uralide join than is implied by a literal interpretation of text-fig. 12. Thus palaeontological indicators of provinciality, migration routes, and migration barriers can all contribute to the improvement of the Palaeozoic maps. The only constraint on these maps is the approximate latitude and approximate orientation of their components.

The interpretation of distributions of Late Palaeozoic, Mesozoic, and Tertiary fossils and sediments lead originally to the idea of continental drift, and the making of crude world maps. Half a century was to elapse before these notions were confirmed by geophysical evidence. Plate tectonics has not yet advanced the making of Palaeozoic maps much beyond the stage they had reached in 1928, when Van der Gracht (p. 72) speculated: 'It would seem as if in the older Palaeozoic, before the Caledonian diastrophism, America might have moved westward faster than Eurasia, opening a Palaeozoic Atlantic geosyncline, which was partly closed again during the Caledonian diastrophism, on account of the westward drift of Eurasia, which then again became more rapid than that of North America. Thus the former, overtaking the latter, closed the old Atlantic again and folded the Caledonian chains.' In our view, careful interpretation of Palaeozoic fossil and sediment distributions may lead to better Palaeozoic maps some years before they can be confirmed and improved by geophysical methods.

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DISCUSSION

H. G. Owen (British Museum, Natural History). I congratulate the authors on presenting for the first time on a global scale a detailed series of maps showing the possible distribution of continental plates during Phanerozoic time, together with the break-up of Pangaea during the Mesozoic and Tertiary. My remarks are entirely confined to the Mesozoic and Tertiary continental displacement. The authors present their data reconstructed on a global projection representing a diameter between the north and south geographic poles of Modern dimension. This practice produces serious problems when one considers the detailed history of the development of areas such as the Arctic, Caribbean, Mediterranean, South East Asia including the Australian–New Zealand plates, and the Southern Ocean.

If all the available sea-floor spreading data are plotted for the Atlantic on a Mercator projection map a very good picture of the progressive displacement of the African, South American, North American, and European continental plates can be obtained by moving the plates back according to the magnetic reversal anomalies. As Le Pichon and Fox have observed (1971; 6306), if North America and Africa are rotated back into their original pre-Jurassic Mesozoic displacement position against the East Coast area of the United States along the Romanche and Azores fault zone lines, it puts serious constraints upon the original size and development history of the Caribbean area. The development of the Caribbean can be explained by expansion, and reconstructions such as that of Vogt, *et al.* (1971; 4819), which imply northward migration of South America and north–south contraction of the Caribbean area since the Early Jurassic, are not acceptable.

In effect, on a modern diameter globe Pangaea reconstruction, the North American continental plate has to be rotated to a position some 10° further south of its current position. Unfortunately, this has the effect of expanding the area of the Arctic Ocean when proceeding backwards in time into the Late Mesozoic. This apparent opening out of the Arctic Ocean and the continental areas surrounding it is seen in the present authors' maps and in the other excellent map reconstruction drawn by Dr. P. L. Robinson (1971; text-figs. 5, 6) for the Permian and Triassic. There is no other remedy but to open out the Arctic Ocean if a modern diameter globe is used and thus a modern surface curvature for the Earth. However, in fact, the Arctic Ocean is expanding today as a result of sea-floor spreading at the mid-Atlantic ridge, and the bathymetry and movement of Greenland since the Late Cretaceous indicate that this process of expansion has been going on since the Late Mesozoic. The history of the development of part of the Arctic Ocean and its environs given by Harland (1969; 817–851) is apparently correct, but this reconstruction implies expansion and increased oceanic crustal area and not contraction and subvection of oceanic crust in this area from Late Cretaceous to modern times.

Turning south to the fit of South America against Africa, and the relationship of these two continental plates to Antarctica. If South America and South Africa are rotated back together into a pre-displacement configuration on a globe representing a Modern diameter, there is a long wedge-shaped void expanding towards their southern ends. If the diameter is reduced a point is reached where the surface curvature causes this wedge-shaped void to close up, and the fit is extremely good at the 1000 m depth line.

The Southern Ocean provides one of the most important keys to the whole problem of whether the Earth has expanded, or has not, since the Jurassic. This ocean is circum-global except for an island arc connecting the southern tip of South America with Grahamland in the Antarctic. It has no Beniof zone of any length in which marginal oceanic floor can be subvected. The South Sandwich Trench is not of sufficient size and trends in the wrong direction, and its genetic history in my opinion differs entirely from that given by Dalziel and Elliot (1971; 250), it being more analogous to the developmental history of the Caribbean. The mid-oceanic ridge is not itself circum-global. It starts as a continuation of the Mid-Atlantic ridge and connects up with ridges in the Indian Ocean and south Pacific. It is, however, a ridge generating basic igneous rocks around virtually the whole of the Southern Ocean west–east axis. The age of the Ocean deduced from magnetic anomalies and sampling extends from Late Jurassic at the tensional-down faulted margins of South Africa and Australia to Modern at the ridge axis. A reverse chronology is seen from the ridge axis towards Antarctica. Looking at a globe it is apparent that if a Modern diameter is used, and the present latitude position of the fit of Africa into the east coast of North America is maintained, the development of sea-floor spreading in the Southern Ocean would have caused the ballooning out of the Earth's crust south of latitude 55° S. The Earth is indeed slightly pear-shaped today, but not to the extent that it would have been with the development of sea-floor spreading in the Southern Ocean if no increase in radius had occurred since the Jurassic.

When reconstructing Pangaea on a globe representing a Modern diameter, a very large Pacific Ocean is obtained, much larger than the Modern Pacific. Fringing the continental plates of Asia, Australasia, South and North America today are Benioff Zones which can be demonstrated to have a history extending back in time well into the Mesozoic. The sea-floor spreading pattern and the fault zones indicate that in some marginal areas at least, ocean-floor is being over-ridden by the continental plates. However, if the Earth's surface area, and its radius, was not to increase at a quite phenomenal rate, and the Earth to change its shape significantly away from that of a sphere, a certain amount of ocean-floor would have to be subvected at the east and west margins of the Pacific as the continental and oceanic plates are pushed against each other due to the development of sea-floor spreading in the Atlantic, Southern, and Indian oceans.

The Pacific Ocean floor is not itself a simple convecting system with new oceanic crust being generated at a N.-S. trending mid-Ocean ridge, and the oldest crust being subvected at the margins. Some of the oldest crust in the Pacific is situated well out into the more central area, and the sea-floor spreading pattern is complex. Because of this complexity there should be signs in the Pacific sea-floor spreading patterns in the central areas of the wide Tethyan oceanic area which one is forced to construct if in using a globe representative of a Modern diameter, surface curvature and area. There are no signs of this wide, significantly wedge-shaped, Tethyan ocean in the Pacific Ocean floor.

I am convinced that expansion of the Earth has occurred, and although it is not easy, it is possible to produce maps which are based on the concept of an expanding Earth certainly from the Jurassic to the present day. These maps accord better with the sea-floor spreading data and geological data that are now available.

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WILLIAMS, C. A. and MCKENZIE, D. 1971. The evolution of the North-East Atlantic. *Nature, Lond.* **232,** 168–173.

K. G. McKenzie. I understood that an expansion of 5 per cent is acceptable, according to your significance tests, for the Cainozoic. Have you attempted to generate maps for at least this amount of expansion, since you consider greater expansion not acceptable by your tests for significance? Is it difficult to generate maps for, say, a 20 per cent Cainozoic expansion factor?

Laing Ferguson (Mount Allison University, New Brunswick, Canada). The use of the Mercator Projection and its restriction to 70° North and South was particularly unfortunate for the map of the Tertiary as it excluded practically all of the Canadian Arctic Archipelago. This area was strongly affected by Tertiary orogenic movements and perhaps a Polar Projection would have been more appropriate. The Eureka Sound Fold Belt was produced during the Tertiary. Evidence of movement extends along the eastern side of the Mesozoic Sverdrup Basin from Prince Patrick Island in the south-west and up through Axel Heiberg Island and western Ellesmere Island to the Hazen Lake area of north-eastern Ellesmere Island.

The areas affected by Tertiary movements in the Arctic Archipelago are not even indicated as shaded or doubtful areas in the maps of continental distribution during earlier periods, despite the fact that, in these maps, the Arctic Islands are visible in the particular projection and also despite the fact that the other areas of Tertiary orogeny are shaded. This suggests that the writers may have indeed been unaware of these movements and that their exclusion from the Tertiary map might have occurred even if a polar projection had been used.

It is to be hoped that the inclusion of this area of Tertiary orogeny in the maps might help not only in our consideration of Cenozoic plate movements but (as with the other shaded and 'doubtful' areas in the Mesozoic maps) as a caution in the Mesozoic reconstructions.

Should anyone wish to have further data on the Tertiary movements in the Canadian Arctic Archipelago, they could consult the following works by the Canadian Geological Survey:

THORSTEINSSON, R. and TOZER, E. T. 1960. Summary account of structural history of the Canadian Arctic Archipelago since Pre-Cambrian time. *Geol. Surv. Canada, Paper*, **60-67,** 1-25 (see pp. 14-15).

FORTIER, Y. O., *et al.* 1963. Geology of the North-Central part of the Arctic Archipelago, North West Territories (Operation Franklin). *Geol. Surv. Canada Mem.* **320,** 1-671 (see p. 26).

CHRISTIE, R. L. 1964. Geological reconnaissance of Northeastern Ellesmere Island, District of Franklin. *Geol. Surv. Canada Mem.* **331,** 1-79 (see p. 68).

TOZER, E. T. and THORSTEINSSON, R. 1964. Western Queen Elizabeth Islands, Arctic Archipelago. *Geol. Surv. Canada Mem.* **332,** 1-242 (see pp. 188 and 218-219).

Replies to discussion, by J. C. Briden and A. G. Smith

Reply to Dr. Owen. The kind of expansion advocated by Dr. Owen implies that the proportion of the Earth's surface covered by continental crust has decreased with time since the Early Mesozoic. To account for this decrease we must look for a process that affects the interior more than the continental crust. Processes affected by changes in the gravitational constant (G) are likely to affect all terrestrial matter and dimensions equally and therefore to be undetectable. Temperature changes, phase changes, compositional changes, and the like could alter the dimensions of the interior relative to the surface, but are believed to be inadequate to change it by the required amount. However, if we recall the declared impossibility of finding a process that could cause continental drift during debates before 1960, we would be unwise to categorically say that no process could have significantly changed the dimensions of the Earth. In our view the argument is better confined to observational evidence.

Calculations based on palaeomagnetic observations probably give the most reliable estimate of the past size of the Earth. They suggest that no significant changes have occurred since the Palaeozoic. However, these estimates assume that the geocentric dipole model applies with a high precision to the Earth's magnetic field in the past, whereas the detailed validity of this model has been queried by several workers.

A further piece of observational evidence is that the sizes and shapes of parts of the mid-oceanic ridge system closely match those of the continental edges from which they have migrated. These similarities suggest that very little change has taken place in the dimensions of large parts of the Earth's surface during the past 100 m.y.

Arguments based on tectonic features have little weight until it has been shown that plate tectonics on an Earth of the present radius is incapable of accounting for the features concerned. Though the applications of plate tectonics to the regions cited by Dr. Owen have only just begun, we see no reason why they should not successfully account for all those features that in Dr. Owen's view suggest significant Earth expansion. In short, we know of no observational evidence that necessitates Earth expansion on the scale suggested.

Reply to Dr. McKenzie. The problem of drawing maps for a larger (or smaller) Earth would be simple if one knew the appropriate mathematical transformation. This is not known and would depend on how continents adjust to an Earth of which the radius had changed. One could postulate a transformation and draw the corresponding maps, but we have not attempted to do so.

Reply to Dr. Ferguson. We thank Dr. Ferguson for drawing our attention to some omissions from the symposium maps. We believe that the maps now provided in this paper rectify most of the points he raises.