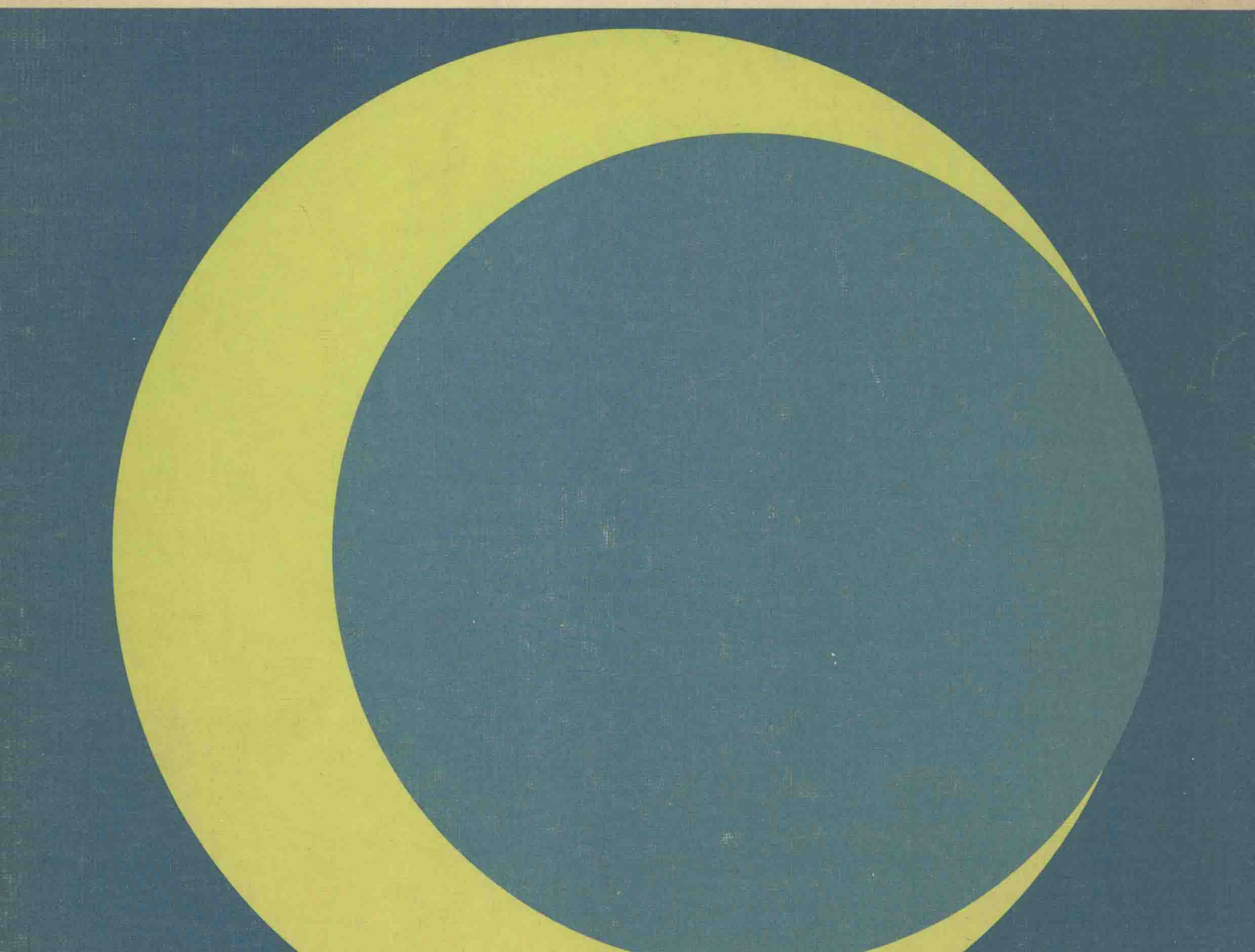
Atlas of continental displacement, 200 million years to the present

CAMBRIDGE EARTH SCIENCE SERIES

H.G. OWEN



CAMBRIDGE UNIVERSITY PRESS

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CAMBRIDGE UNIVERSITY PRESS
Cambridge
London New York New Rochelle
Melbourne Sydney

Published by the Press Syndicate of the University of Cambridge
The Pitt Building, Trumpington Street, Cambridge CB2 1RP
32 East 57th Street, New York, NY 10022, USA
296 Beaconsfield Parade, Middle Park, Melbourne 3206, Australia

First published 1983

Printed in Great Britain at the University Press, Cambridge

Library of Congress catalogue card number: 83-67083

British Library cataloguing in publication data

Owen, H. G.
Atlas of continental displacement, 200 million years to the present

1. Continental drift – Maps
I. Title
912'.1551136 G1046.C55

ISBN 0 521 25817 0

UP

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ATLAS OF CONTINENTAL DISPLACEMENT
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H. G. Owen

Preface

This volume is intended as the first of a two-part work designed to provide maps of the distribution of continental and oceanic crust during the last 700 million years of the Earth's history from the late Pre-Cambrian to the present day. It is, however, only for the last 200 million years that ocean-floor spreading information is available to indicate the chronology and mode of ocean basin development and accompanying continental displacement. When this information is plotted onto maps which assume that the Earth has been of modern dimensions throughout the last 200 million years, spherical triangular gaps (gores) appear progressively back in time from the present day. The fit of the continents together in a single supercontinent, the Pangaea recognized by Alfred Wegener, lasted until the middle Jurassic, albeit that rift valley formation had occurred earlier. However, it is only in the central 'hub' of the refit, that is, the fit of the north-west African margin into the American East Coast embayment, that the fit is perfect on a globe of modern dimensions. Radiating from this hub are gores separating regions known on geological evidence to have been in direct contact with each other at this time.

Some decades before the general acceptance of the continental displacement hypothesis, a few workers such as Hilgenberg (1933), Jordan (e.g. 1966), Egyed (1957) and Halm (1935) had speculated that such displacement might have occurred upon an Earth which was expanding its dimensions. Professor Warren Carey, during a symposium on 'continental drift' held in Hobart, Tasmania, in 1956 (Carey 1958) demonstrated that the fit of the continents together was much improved if the Earth's diameter was less than its modern value at the time of Pangaea. He referred to the earlier work on this notion carried out in Germany by Otto Hilgenberg, who published a series of reconstructions in 1933. However, neither Carey nor Hilgenberg had the benefit of ocean-floor spreading data to test their ideas and, indeed, Carey was fighting for the recognition of continental displacement at a time when most geologists considered the idea to be absurd.

The discovery that the oldest oceanic crust in the World's oceans was not older than the middle Jurassic, led Carey (1970, 1975, 1976) to advocate that all Earth expansion had occurred since then. This has become known as the 'fast expansion hypothesis' and is not supported by the available data on crustal development. By 1970, however, the so-called revolution in the Earth sciences was well under way with the general acceptance of the hypotheses of continental displacement and the development of rigid oceanic crustal plates. The latter hypothesis, together with contemporary – and current – palaeomagnetic theory, precluded the possibility of Earth expansion during Phanerozoic time.

In 1976, I presented a spherical geometric analysis of the bulk of the ocean-floor spreading evidence made available up to 1974. During this task, it was found that the continents would only fit together to form Pangaea, according to the geological evidence, when the Earth's diameter was 80% of its modern mean value. Below that figure, Pangaea could not be reformed without intra-continental dislocations. Above that figure, gores appeared in the reconstructions. Pangaea existed as a complete supercontinent until the middle Jurassic when it commenced to break up. The subsequent ocean-floor spreading patterns in the passive-margined oceans, in which the full history of continental splitting and subsequent displacement of continents apart is preserved, was found to support a near-linear increase in diameter up to the present day, consistent with the nearly straight limb of an exponential curve of increasing diameter. Despite its firm base in field data, this 'slow expansion hypothesis' is widely discounted by many geologists and geophysicists at present, although by perhaps fewer than in 1976.

A substantial increase in the amount and geographical coverage of ocean-floor spreading data since those previously analysed (Owen 1976) has prompted a new analysis of the spherical geometric implications. At the same time, the opportunity has been taken to plot the data onto maps which assume an Earth of constant modern dimensions throughout the same period of time. The conventional cartographic processes take time and the data used are those made available up to June 1980. The present atlas provides, therefore, two series of maps. The first series assumes an Earth of constant modern dimensions, while the second series assumes an Earth expanding from a diameter of 80% of its modern mean value 180–200 million years ago to its modern size. The atlas provides, therefore, a test of the validity of the two conflicting hypotheses on maps which can be tested for cartographic integrity. This is the first time that such a test has been attempted.

The second intention of this atlas is to provide base maps to facilitate studies in palaeogeography, palaeoclimatology and palaeogeophysics. In order to assist in the plotting of such data, the outline of the Earth's modern continental geography is superimposed on the reconstructions of the past. However, the actual distribution of land and sea was very different in the past. The maps given here merely represent the distributions at selected points in time of the crustal units, both continental (sialic) and oceanic (simatic), which formed the complete crust at the time of the reconstruction.

Throughout history, cartographers of the modern Earth have had to rely on numerous travellers and surveyors to provide the basic data for their maps. This atlas is no exception to that rule. The geophysical data used here are those made available up to June 1980 by the efforts of the people given in the list of references to sources and their team colleagues. However, the projection of the maps and their degree of accuracy, together with the plotting of the data, are purely the responsibility of the author.

My personal thanks are due to Mr W. B. Harland, Gonville and Caius College, Cambridge, whose original suggestion and encouragement has resulted in this atlas; to Dr H. W. Ball and Dr C. G. Adams of the Department of Palaeontology, British Museum (Natural History), without whose fundamental support this volume could not have been completed in such a relatively short period of time; and to others of my colleagues in the British Museum (Natural History) and in particular Dr G. F. Elliott, Dr M. K. Howarth and Dr R. P. S. Jefferies, for their encouragement.

Contents

Part 1
THE TEXT

Introduction

The so-called 'revolution in the Earth sciences' which has occurred during the last two decades, has been well documented in numerous books and papers. In its centenary year, the British Museum (Natural History) in conjunction with the Cambridge University Press published a two-volume work under the general title *Chance, Change and Challenge*. The first volume, called *The Evolving Earth* (Cocks, L. R. M. (Ed.) 1981), contains a series of essays on various aspects of the geological evolution of the Earth. Some of these essays review many of the present ideas and hypotheses concerning the development of the World's ocean basins and associated displacement of the continental (sialic) crustal masses. I would recommend *The Evolving Earth* as background reading for the non-specialist.

It is readily apparent from the various essay chapters in *The Evolving Earth* that the bulk of current scientific opinion favours the concept of an Earth which has possessed its modern dimensions throughout much of geological time. However, in one chapter, I have questioned whether the ocean-floor spreading evidence, which indicates how the ocean basins have developed and during what periods of time, actually supports the concept of a constant modern dimensions Earth. Although outline maps are used to illustrate the discussion, they are too small to have plotted on them the detailed ocean-floor spreading data now to hand.

In 1976, I discussed the probability of global expansion on the basis of the geological and geophysical data made available up to the early part of 1974 (Owen 1976). The field evidence to support that hypothesis could be divided into two principal categories; the first being the evidence of geological fit together at now separated continental margins, and the second being the spherical geometric implications of the growth of the ocean-floor spreading patterns.

The evidence of geological fit at continental margins had led Carey to consider the possibility of global expansion at a time when no ocean-floor spreading data were available to determine the detailed history of the splitting apart of the continents formerly grouped together as Pangaea (Carey 1958). His views were influenced by the work of Hilgenberg (1933) who, on theoretical grounds, considered that the Earth's continental crust had once formed a continuous sialic shell at the lithosphere surface of an Earth some 55% of its modern diameter. This idea was speculated upon during the 1960s by workers such as Barnett (1962) and Creer (1965) and by others since. When ocean-floor spreading patterns showed that the ocean basins, including the Pacific, were not older than middle Jurassic, Carey took the extreme view that all global expansion had taken place since then and that no subduction had occurred at the Pacific margins, a requirement of the constant modern dimensions hypothesis (Carey 1970, 1975, 1976). However, such an interpretation of the field evidence requires that the Earth was shaped like a rugby football at the time of Pangaea.

In 'passive-margined' oceans such as the Atlantic, Arctic and much of the Indian, a full history of development from the initial, tensional, splitting of the continents up to the present day, is preserved. A critical examination of the evidence of fit at the common margins of these oceans indicated that the diameter of the Earth at the time of Pangaea, immediately before its break-up, was 80% of its modern value (Owen 1976). This corresponded with a short interval of time between 180 and 200 Ma which includes the late Triassic and the lower Jurassic. At diameters above the value of 80%, the continents will not fit together according to the geological data, spherical triangular gaps ('gores') appearing progressively in extent away from the centre of re-assembly of Pangaea as the diameter is increased. The fit together of the continental margins and of subsequent isochronous regions of ocean floor is affected by changing values of surface curvature. This can be illustrated by the fits of South America against Africa on two curved surfaces and one flat surface shown in figure 1 and in detail on maps 24–33. If one reduces the diameter of the Earth below a value 80% of its modern length, the continents will not fit together without increasing intra-continental displacement along major wrench fault zones which, as it happens, exist.

The analysis of the ocean-floor spreading patterns attempted in my 1976 paper was based on the passive-margined oceans, the area of which is sufficient to permit the spherical geometry of a globe and its dimensions to be determined. The spreading patterns indicate that a near-linear increase of the Earth's diameter has occurred during the last 200 million years of its history. If the sialic (continental) crust of the modern Earth once formed a complete outer crustal shell, the diameter of the Earth in the late Proterozoic would have been 55% of its modern mean value, which is not consistent with an exponential expansion during the last 700 million years (figure 2). However, there has been a substantial increment of continental crust since the Proterozoic, particularly within the Palaeozoic, which could account for part of the discrepancy.

The reconstructions given by the author in 1976 precluded the fast expansion concept advocated at that time by Carey. Moreover, the spherical geometry of the Earth at the time of Pangaea, determined by the geological evidence, showed the presence of a substantial area of earlier (Palaeozoic) oceanic crust called the Eo-Pacific. None of this crust is present today and it is logical to assume that it has been subducted. The geological evidence from the various Pacific marginal orogens, together with the ocean-floor spreading patterns within the area of the Pacific itself, indicate that marginal subduction zones were active throughout the Mesozoic and Cenozoic, in direct contradiction of Carey's view that no subduction had occurred.

In 1976, I did not provide corresponding maps of stages of continental displacement which assumed a constant modern dimensions Earth to accompany those which assumed an expanding Earth. This was a mistake, rectified here, and the opportunity was missed to provide a test of the two conflicting hypotheses at an earlier date. Predictably, the 1976 paper was the subject of substantial criticism, having transgressed elements of current geophysical theory. However, a detailed rebuttal of it has not yet been attempted on a global scale using the available ocean-floor spreading data. A number of reconstructions of the development of individual ocean basins have been published which assume a constant dimensions Earth. Most assess the field data objectively, discussing, or at least recording, the inconsistencies of fit which occur within the region concerned. Some transfer the problems of fit to regions adjacent to that described, while a few others have produced fits which are, apparently, convincing but which are, in reality, artefacts of faulty map projection. Examples of these are described in 'Some errors in reconstructions' below.

Since 1974, a substantial amount of new magnetic traverse information has become available. There are now few oceanic areas of which the basic history of development is not known and there are large areas in

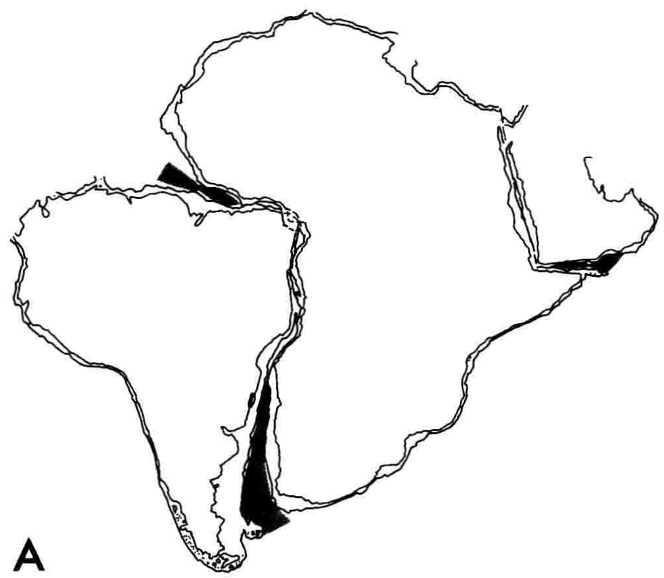
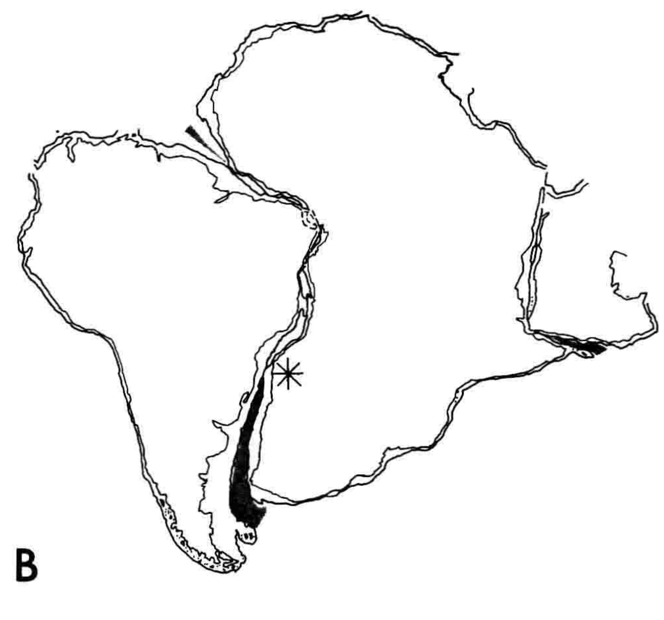
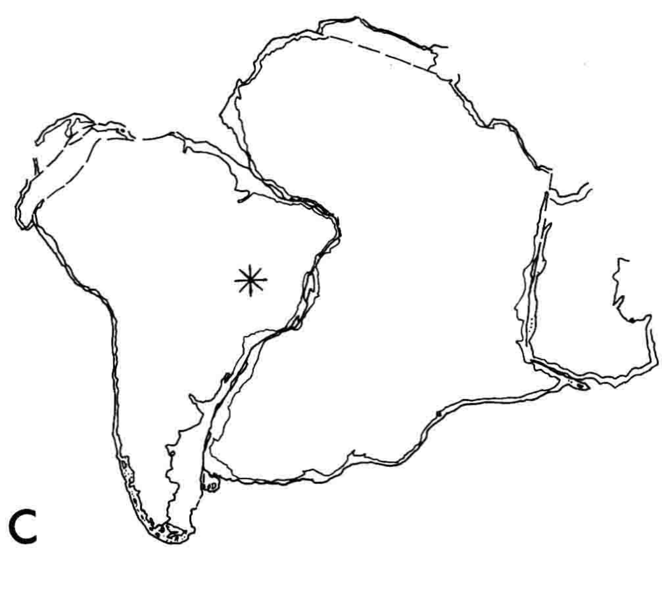


Figure 1. The effect of changing values of surface curvature on the fit of the continents together. (A) South America and Africa with Arabia are projected separately using an azimuthal equidistant projection and then fitted together on a flat surface. Although distortions are inevitable in such a practice, the demonstration of marked V-shaped gores (shown shaded) is valid. (B) The fit of South America and Africa together, assuming an Earth of modern dimensions (diameter = 12752 km); azimuthal equidistant projection with pole indicated ∗. The V-shaped gores are greatly reduced in area, but are still present. (C) The fit of the continents together assuming an Earth with a diameter 80% of its modern mean value (10202 km); azimuthal equidistant projection with pole indicated ∗.





which the growth patterns are known in some detail. The development of certain areas of high deformation such as the Mediterranean region, the Alpine–Himalaya belt, South East Asia and the Philippines and the West Antarctic Peninsula, remain to be resolved in detail. In this atlas, the reconstructions which assume a constant modern dimensions Earth retain the modern configuration of these deformed areas, to conform with similar series published by other authors (e.g. Smith, Hurley & Briden 1981, see Appendix Note 1). In the reconstructions assuming an expanding Earth, the broad outline of regional deformation which is consistent with the adjacent ocean-floor spreading evidence is given, but it is grossly over-simplified. The fact that palaeomagnetic evidence indicates that certain zones in Japan were widely separated along a major wrench fault zone at a particular time, while they are shown here in their modern relationship, does not invalidate the reconstructions based on the ocean-floor spreading data. It merely reflects that the author has concentrated his efforts and capacity in assimilating the spreading data and assessing its spherical geometric implications and that his capacity to include detailed additional data is limited.

This Atlas provides a test of the ocean-floor spreading information on two conflicting models; one which assumes that the Earth's dimensions have been constant during the last 200 million years, the other which assumes an increase in diameter from 80% of its modern mean value 180–200 million years ago to its present value. This is the first attempt at such a test of the basic field data upon which the determination of the mode and chronology of ocean basin development depends.

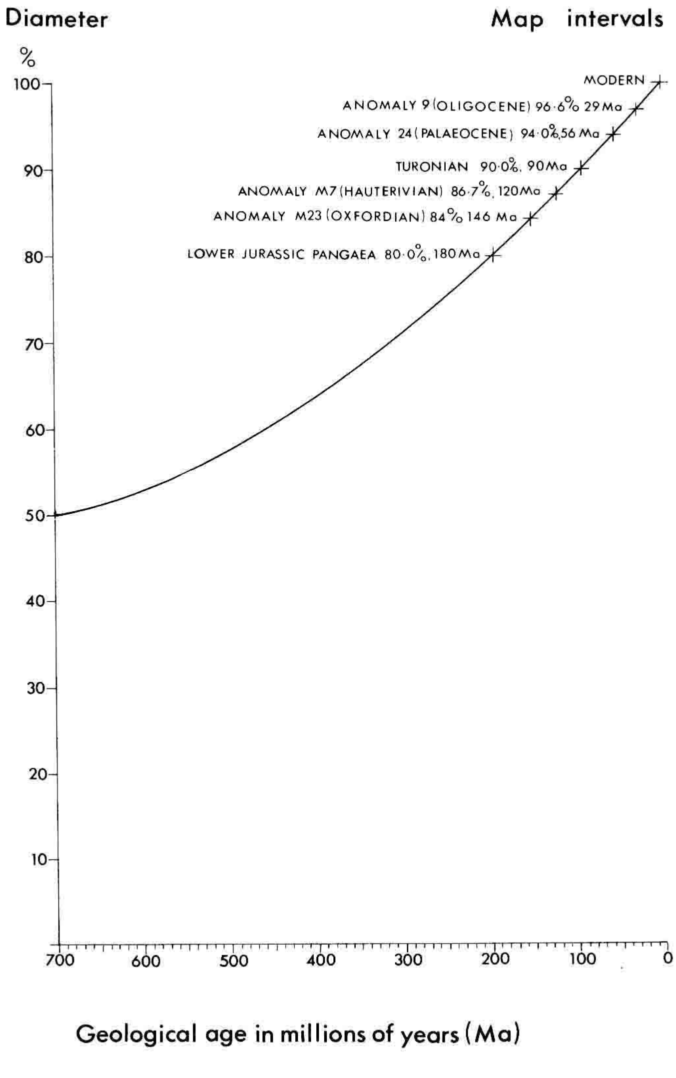
Data sources, handling methods and limits

All global cartographers rely on the work of countless surveyors to provide the basic information from which their maps are constructed. This is true equally of the great map-makers of the past, such as Ptolomy, Contarini, Mercator and Jodocus Hondius among many others, right up to the present day. Today, the primary surveyor is being partly replaced by the optical/electronic systems in high-flying aircraft and orbital satellites. Even the conventional cartographer might one day be replaced by the skillful use of the computer (e.g. Monmonier 1982).

The present atlas is no exception to this rule. The basic data have been collected by numerous individuals operating ship-borne and air-borne towed magnetometers, supported by crews keeping vessels and aircraft on accurately positioned traverses. Others have interpreted the magnetometer traces and checked the data against the information obtained from deep ocean borehole core sequences. The result of all this effort and expense, is a widespread coverage of magnetic anomaly data over the World's oceanic crust which, in some areas, is very detailed. If one adds to this the wealth of geological and geophysical survey information from the continental margins, a very good picture of the development and age of the ocean basins can be obtained (e.g. Nairn, Stehli *et al.* (Eds.) 1973–81).

The ocean-floor spreading data used in this atlas are those made available up to July 1980. Some of the more recent principal papers published after the preparation of the global reconstructions mapped here, are referred to in the Appendix. In order that the plotting of the information may be checked, it is shown here on three maps employing the conventional Mercator's projection (Maps 1–3). Map 1 shows the North and South Atlantic Oceans, the spreading data being derived from the following sources: Barker (1970, 1972a, b), Barrett & Keen (1976), Bergh (1977), Bergh & Barrett (1980), Cande & Kristoffersen (1977), Dickson, Pitman & Heirtzler (1968), Hayes & Rabinowitz (1975), Herron & Tucholke (1976), Johnson & Vogt (1973), Keen, Hall & Sullivan (1977), Kristoffersen (1978), Kristoffersen & Talwani (1977), Kumar & Embley (1977), La Brecque & Hayes (1979), Ladd, Dickson & Pitman (1973) Larson & Hilde (1975), Larson & Ladd (1973), Larson & Pitman (1972), Lattimore, Rona & De Wald (1974), Laughton (1971, 1972), Le Pichon & Fox (1971), Le Pichon & Hayes (1971), Mascle & Phillips (1972), Olivet, Le Pichon, Monti & Sichler (1974), Peter, Lattimore, De Wald & Merrill

Figure 2. Exponential curve of the value of the Earth's mean diameter through time, assuming today's value, a value of 80 % of the modern diameter 180–200 Ma B.P., and the amount of sialic crust known, or thought, to have been formed by the late Proterozoic, which it is assumed formed a complete sialic shell. The curve also assumes that the Earth has retained its shape as a sphere of rotation throughout this period, and that the radioactive decay rate used in the dating has been constant.



(1973), Phillips, Fleming, Feden, King & Perry (1975), Pitman, Larson & Herron (1974), Pitman, Talwani & Heirtzler (1971), Purdy & Rohr (1979), Rabinowitz, Cande & Hayes (1979), Rabinowitz & La Brecque (1979), Rabinowitz & Purdy (1976), Ramberg, Gray & Raynolds (1977), Sclater, Bowin, Hey, Hoskins, Peirce, Phillips & Tapscott (1976), Steiner (1977), Storetvedt (1972), Talwani & Eldholm (1977), Taylor & Greenwalt (1976), Van Andel, Rea, Von Herzen & Hoskins (1973), Vogt, Anderson & Bracey (1971), Vogt & Avery (1974), Vogt & Einwich (1979), Vogt & Johnson (1971), Vogt & Ostenso (1970), Williams & McKenzie (1971). Map 2 shows the Indian Ocean, the spreading data being derived from the following sources: Bergh (1977), Bergh & Norton (1976), Bowin, Purdy, Johnston, Shor, Lawver, Hartano & Jezek (1980), Hayes (1972), Hayes & Ringis (1973), Heirtzler, Cameron, Cook, Powell, Roeser, Sukardi & Veevers (1978), Larson (1975, 1977), Larson, Carpenter & Diebold (1978), McKenzie & Sclater (1971), Markl (1974, 1978), Norton & Sclater (1979), Schlich (1974), Sclater & Fisher (1974), Sclater, Luyendyk & Meinke (1976), Ségoufin (1978), Simpson in Norton & Sclater (1979), Weissel & Hayes (1972). Map 3 shows the Pacific Ocean, the spreading data being derived from the following sources: Anderson, Clague, Klitgord, Marshall & Nishimori (1975), Anderson, Moore, Schilt, Cardwell, Tréhu & Vacquier (1976), Atwater & Menard (1970), Ben-Avraham, Bowin & Segawa (1972), Ben-Avraham & Uyeda (1973), Bowin, Purdy, Johnston, Shor, Lawver, Hartano & Jezek (1980), Bracey (1975), Christoffel & Falconer (1972), Christoffel & Ross (1970), Cooper, Scholl & Marlow (1976), Elvers, Srivastava, Potter, Morley & Sdidel (1973), Falconer (1972), Handschumacher (1976), Hayes & Pitman (1970), Hayes & Ringis (1973), Hayes & Taylor (1978), Herron (1971, 1972), Herron & Tucholke (1976), Hey (1977), Hey, Johnson & Lowrie (1977), Hilde, Isezaki & Wageman (1976), Hussong, Wipperman & Kroenke (1979), Kobayashi & Isezaki (1976), Larson & Chase (1972), Larson & Pitman (1972), Lonsdale & Klitgord (1978), Louden (1976, 1977), Luyendyk, Bryan & Jezek (1974), Luyendyk, MacDonald & Bryan (1973), Malahoff & Handschumacher (1971), Mammerickx, Anderson, Menard & Smith (1975), Molnar, Atwater, Mammerickx & Smith (1975), Murakami, Tamaki & Nishimura (1977), Sclater & Klitgord (1973), Tamaki, Joshima & Larson (1979), Truchan & Larson (1973), Vogt & Byerly (1976), Vogt & De Boer (1976), Watts & Weissel (1975), Weissel & Hayes (1972, 1977), Weissel & Watts (1975, 1979).

The Arctic Ocean cannot be displayed using Mercator's projection and the following additional sources are used in the modern Arctic map (Map 4): Jackson, Keen & Falconer (1979), Johnson & Vogt (1973), Vogt, Taylor, Kovacs & Johnson (1979).

Conventional cartographic methods have been employed in the projection of the maps given in this atlas. Although the computer is used extensively nowadays in the production of ocean-floor spreading maps which illustrate the data, it has been employed successfully only in those maps which portray the modern Earth. In map reconstructions of stages of continental displacement which assume a constant modern dimensions Earth, errors are apparent in the projections which indicate imperfect programming. The employment of the computer in the production of detailed ocean-floor spreading maps which assume an expanding Earth, is not a time-effective proposition at present, in terms of programme writing and the costly employment of the software and hardware facilities.

The handling of the data using conventional cartographic methods is quite simple. The information is plotted onto individual grid units with dimensions of 10° of latitude and 10° of longitude coinciding with the Earth's conventional co-ordinate net. Each unit is projected separately using an azimuthal equidistant projection with the pole situated at the centre of each unit. The amount of distortion at the margins of each unit assuming a scale globe of 380 mm diameter is negligible. These units can be used to transfer data to the surface of a globe of any given dimensions in order to test the fit of crustal units together, or they can be used as the basis of maps employing the equidistant projection. The method also lends itself to easy conversion to computer raster data, once accurate programmes have been developed. Because one is dealing with segments of almost true scale surface area, it is possible to build up a mosaic accounting for all the surface area of the Earth at a given point in time. However, once this mosaic is completed it is necessary to transform the reconstruction to a readable map form by re-projection as described in the 'Notes on the cartographic projections' below.

The limits of accuracy in data handling fall into three main categories. In the first instance one can ask the questions; how accurate are the magnetometer records and the course navigation; are the patterns of course tracks sufficient to indicate trends and are the profiles correctly interpreted in terms of the vectors of the anomaly lineations and of their dating? It so happens that when a critical examination of the spreading patterns is made, such as in this atlas, remarkably few problems have arisen which could be put down to major technical or interpretive errors, although some exist. In so far as the dating of magnetic anomalies is concerned (Table 1), it is desirable to have corroborative Deep Sea Drilling Project (DSDP) borehole information at salient points in order to check the magnetic anomaly sequence. Obviously, there are geographical and economical limits to such drilling. At the scale employed here, most of the errors are not of sufficient magnitude to affect the reconstructions.

The second category of accuracy in handling the data concerns the theoretical basis upon which the reconstructions are made. Can we be sure that there is no form of discrete crustal subduction in passive-margined oceans which has not yet been detected? Even had this occurred, it would not explain the gores which are a feature of the constant modern dimensions Earth reconstructions. The assumption of the 1000 m isobath as the effective edge of the continental crust has been questioned by some (e.g. Hallam 1976). However, in passive-margined oceans, the position of the crustal transition zone (the zone between deep-faulted continental crust and oceanic crust) and the commencement of the magnetic anomaly sequences *can be measured from the existing modern coastline.* The argument whether or not the 1000 m isobath represents the edge of the continents world-wide, is irrelevant even in the reconstructions of Pangaea. Apart from facilitating the reading of the maps showing the dotted modern coastline as a guide, the practice allows, also, a check to be made on the accuracy of the plotting of the oceanic crustal information in the reconstructions.

The third limit of accuracy involves the development of certain relatively small, but important, regions for which there was no spreading data available at the commencement of map construction. These regions include the Amerasia Basin of the Arctic Ocean, the Weddell Sea off Antarctica and some of the west Pacific marginal basins. The areal limits in which their development could have occurred, can be determined accurately, however, from the surrounding oceanic regions in which the spreading patterns are known. Nonetheless, the detailed pattern of their development and the chronology, remains conjectural. The reconstructions of the development of these regions given here are possible, but they will have to be revised when definitive

Table 1. *Magnetic polarity time scale for the Mesozoic and Cenozoic*

Anomaly no.	Estimated age Ma B.P.*		System and stage
1	0.0–0.7	QUATERNARY	Pleistocene
2	1.6–1.8		
2A	2.4–3.3	TERTIARY	Pliocene
3	3.7–4.6	(Neogene)	
3A	5.1–5.6		Miocene
4	6.4–7.0		
5	8.3–9.7		
5A	10.9–11.5		
5B	14.3–14.7		
5C	15.7–16.5		
5D	17.1–17.7		
5E	18.1–18.7		
6	19.0–20.0		
6A	20.5–21.4		
6B	22.2–22.6		
6C	23.0–23.9	(Palaeogene)	Oligocene
7	25.2–25.7		
7A	26.1–26.3		
8	26.6–27.5		
9	28.0–29.0		
10	29.6–30.2		
11	31.1–32.0		
12	32.4–32.8		
13	35.3–35.9		
15	37.3–37.7		
16	38.1–39.3		Eocene
17	39.6–41.2		
18	41.4–42.9		
19	43.8–44.2		
20	44.9–46.4		
21	49.0–50.7		
22	52.3–53.0		
23	54.3–55.1		
24	55.6–56.6		Palaeocene
25	58.7–59.2		
26	60.0–60.4		
27	62.3–62.7		
28	63.3–64.0		
29	64.3–64.9		
30	65.4–66.8	CRETACEOUS	Maastrichtian
31	66.8–67.6	(upper)	
32	69.2–71.0		
33	71.6–76.5		Campanian (part)
34	79.6–87.5		Santonian
unnumbered (reversed)†	87.5–88.0		Turonian
35 & 36†	88.0–103.8		Turonian–Albian
unnumbered (reversed)†	103.8–104.0	(lower)	Albian
M0‡	110.9–111.6		Aptian
M1	114.3–114.7		Barremian
M2 (normal)	114.7–115.4		
M3	115.4–117.5		
M4 (normal)	117.5–118.5		
M5	118.5–119.0		Hauterivian
M6	119.2–119.3		
M7	119.5–119.9		
M8	120.2–120.4		
M9	120.7–121.2		
M10	121.5–121.9		
M10N	122.9–123.2		
M11	124.5–124.8		Valanginian
M12	126.0–126.7		
M13	127.7–128.1		
M14	128.3–129.2		
M15	129.8–130.3		
M16	132.1–132.8		Berriasian
M17	133.3–134.9		
M18	135.5–136.0	JURASSIC	Tithonian
M19	137.6–137.9	(upper)	
M20	139.0–139.9		Kimmeridgian
M21	141.2–141.7		
M22	143.7–144.6		
M23 (normal)	145.6–145.7		Oxfordian
M24	147.2–147.4		
M25	148.7–149.0		
	150.0§		Callovian

* Estimated interval in millions of years before present (B.P.) to the nearest 100000 years.

† These include the normal and reversed anomalies mapped in the southern Pacific in the region of New Zealand, and those labelled A–C in the south-western part of the Wharton Basin of the Indian Ocean.

‡ The age calibration of the M series of magnetic anomalies given by Larson & Hilde (1975) has been revised by Vogt & Einwich (1979). However, the ammonite evidence available agrees more closely with the Stage correlations of Larson & Hilde rather than those of Vogt & Einwich. The arguments used by Vogt & Einwich in their revision of Larson & Hilde, illustrate the amount of uncertainty that there is in the dating of magnetic anomalies at fine detail level. This variation does not affect, fundamentally, the reconstructions given in this atlas.

§ Long periods of normal polarity with little reversal activity occur in the Cretaceous, between the Aptian and the Coniacian, and in the lower and middle Jurassic. Crust generated during these intervals is described as being magnetically 'quiet'. Low-amplitude reversals have been detected, however. One example, with a revision of dates, extends the M sequence to M29 (*ca* 157 Ma) within the Callovian (Cande, Larson & La Brecque 1978).

Compiled essentially from La Brecque, Kent & Cande (1977) and, with modifications, from Vogt & Einwich (1979). Anomalies 1–34 are normally oriented although they include minor reversals. Anomalies M0–M26 are reversed unless indicated otherwise.