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EDITED BY
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Preface

During the early 1970s a series of climate-related disasters – droughts in the Sahel and Ethiopia, failure of the Indian monsoon in several successive years, bad harvests in the USSR, floods in Brazil and so on – helped to focus attention on the possibility that climate can and does change rapidly enough and to a large enough extent to affect the activities of our global society. In particular, it became clear that at a time of rapidly growing population with only slender reserves of food there now exists a greater danger than ever before that a small shift in, say, rainfall distribution, could have widespread and devastating implications. Having trained as an astrophysicist, my own interest in these problems was as a journalist, reporting and interpreting the relevant specialist work in different climate-related disciplines to a wide audience of scientists, chiefly through the pages of *Nature*. To do so effectively, I needed to develop some understanding of the basics of climatic change, and I sought unsuccessfully for a 'standard text' that would encapsulate up-to-date thinking on the subject and provide the necessary background. The failure to find such a book led directly to the idea of the present volume as an overview of the basics of climatic change, intended for any scientifically literate person with an interest in climate. In essence, this is the book I needed in 1973, with the bonus that more recent developments are now also included.

With the benefit of the knowledge I have gained through editing the book, it seems clear to me that our understanding of climatic change is likely to improve rapidly over the next few years, partly through the development of better computer models, partly through the availability of better data from instruments flown above the atmosphere in artificial satellites, and partly through the synthesis of ideas from different disciplines which are all relevant to the climate problem – or problems. Although the analogy is not exact, it seems that the study of climatic change is in some ways developing as the 1970s' 'revolution in the Earth sciences', following the revolution in our understanding of the solid Earth brought about in the 1960s through the development of the concepts of plate tectonics. I am grateful to all the researchers who agreed so readily to contribute to this volume and have provided me with an inside view of the development of this new revolution in our understanding of Planet Earth. The importance of the subject is now beyond doubt, and I hope that in this book we have retained also some flavour of the excitement of working in such a field as a comprehensive overall picture begins to emerge. There is still room for a great deal more development, from many disciplines, and I hope that this volume will help to stimulate some of that development.

March 1977 John Gribbin

Contents

SECTION 1 **Studying the climates of the past**

I

The geological—geophysical framework of ice ages

D. H. TARLING

Perhaps the most well-known evidence for the reality of climatic change is that for the successive advances and retreats of immense ice sheets over temperate latitudes during the past million years or so. The occurrence of this Late Cenozoic Ice Age at the same time as Man's discovery of tools, fire and so on may be no coincidence, since the drastic changes in climatic zonation, with associated changes in flora and fauna, resulted in a strong evolutionary bias towards any organisms which could adapt quickly to such changes and which could modify their effects.

Direct records of climatic change are only available for the past few hundred years (Lamb, 1972) and it is difficult to isolate 'natural' climatic trends from those due to other influences. In any case, the recognition of climatic cycles does not necessarily indicate their cause because of the strong interactive nature of most climatic controls. The most fundamental need is, of course, to fill the gap in knowledge between climatic changes over geological time-scales and meteorological records (Lamb, 1975). However, geologically controlled climatic changes are still occurring and their effects must be isolated from other factors if any understanding of climatic change is to result. It is probable, for example, that a much better evaluation of the effects of increased dust and carbon dioxide in the atmosphere or the diversion of freshwater rivers away from the Arctic, can be made from studying the past effect of similar situations (Gates & Imbrie, 1975) than from computer simulations (Barry, 1975) – at least for some years to come. Even more significant is the possibility that certain geological factors may operate much more rapidly than previously thought. If ice sheets disappear rapidly, as is indicated by the geological record, then major ice surges from Antarctica may be possible and almost instantaneous (Hughes, 1975) with resultant rapid rise in sea-level in days rather than over several thousand years. Similarly, it is possible that the unstable ice sheets which covered much of northern Europe and North America grew rapidly to a significant extent and quickly gave rise to surrounding periglacial conditions – even though it took several thousand years for them to reach their maximum development. The evidence for or against the reality of such mechanisms must lie within the geological records and a knowledge of the development and recession of past ice sheets may then provide clues by which relatively minor, microclimatic controls could be used to prevent or reduce their speed of development. Indeed, the geological dictum 'the present is the key to the past' could well be converted, for climatology, into 'the past is the key to the present and future'. After all, weather forecasting still depends largely on comparison of past and present atmospheric conditions in order to predict over only a few days.

In the following sections an attempt is made to identify some of the characteristics of previous ice ages and thus to evaluate the significance of various geological and geophysical factors that have influenced past climatic changes and may be responsible for current change. It is clear, however, that no one factor alone is responsible and it is only by comparison of the past records that it becomes more evident how these different climatic controls interact with each other.

Table 1.1 gives a summary of the radiometric

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age of Palaeozoic stages involved in glacial episodes for readers unfamiliar with these.

Table 1.1. *Approximate radiometric age of Palaeozoic stratigraphic stages involved in glacial episodes*

	Stages	$\times 10^6$ yr ago
Permian		245
	Kazanian	
		250
	Kungarian	
		255
	Artinskian	
		270
	Sakmarian	
		280
Carboniferous	Stephanian	
		290
	Westphalian	
		310
	Namurian	
		325
	Visean	
		335
	Tournasean	
		345
Ordovician		480
	Caradocian	
		450
	Llandeilo	
		465
	Llanvirn	
		475
	Arenig	

Previous Ice Ages

For well over 200 yr, the sediments and morphological features bordering the Alps have been recognised as indicating the former extent of glaciation in Europe. Subsequent studies and bibliographies for such sediments and morphological features in Europe and North America, in particular, are now extensive (Embleton & King, 1968; Péwé, 1969; Flint, 1971; Washburn, 1973) and key papers have recently been collected into one volume (Goldthwait, 1975). But although such features undoubtedly accompanied earlier glaciations, most of them are likely to have been eroded subsequently, particularly where mountain glaciation was involved, and it is the detritus from such later glaciation that is most likely to be preserved. Even so, most deposits are likely to have been reworked by river action which would have been stronger following the melting of the ice sheets. Nonetheless, certain characteristics can be recognised (Flint, 1961, 1975) as strongly indicative of a glacial origin, although each of these features can be created by other means (Schermerhorn, 1975), particularly by deposition from turbidity currents (Carter, 1975). It is, therefore, the morphological features of striated surfaces, roches moutonnées and so on that are usually considered the most diagnostic. Although even these rarely preserved features can be created by other means, such as landslips, if several such glacial features can be discovered over an extensive area, with associated periglacial sediments and low fauna and floral speciation, then the evidence becomes very convincing. To be climatically significant, however, such evidence must indicate the presence of ice sheet activity, rather than highland glaciation which, though locally important, may not be diagnostic of the regional climate. The occurrence of such indicators over a very wide area of low relief and elevation can, therefore, unambiguously indicate the presence of an ice sheet with the concomitant implications of major climatic changes.

Precambrian Glaciations

At least four major ice ages have been recognised within Precambrian times (Fig. 1.1), although rocks older than 2800 Myr tend to be metamorphosed to the extent that identification of an original glacial origin is now unlikely. The most striking of these is the youngest, the Varangian, which occurred some 660 to 680 Myr ago; glacial deposits of this age have been recognised in North America, Greenland, Spitsbergen, Scandinavia, the British Isles, France, USSR, China, India, Australia, Africa and South America (Harland, 1972; Harland & Herod, 1975). The most detailed and thorough studies so far available are for the deposits in Scotland (Spencer, 1971, 1975) where most glacial features, other than striated pavements, are present. Striated pavements of this age are, in fact, only known in northern Norway and Sweden. It has been suggested that many of these deposits are not truly glacial, but owe their glacial characteristics to other causes, such as turbidite deposition in active tectonic environments (Schermerhorn, 1975). Palaeomagnetic evidence seems to indicate that these deposits in Greenland, Spitsbergen and Britain did not form in high latitudes (Girdler, 1964; Tarling, 1974) as is also indicated by the presence in most areas of interbedded, well-developed limestones, dolomites and stromatolites. Nonetheless the glaciogenic features of these sediments are extremely striking and it seems probable that some of these are indeed of glacial origin, but further research is still necessary before final conclusions can be drawn.

The Sturtian Ice Age (Harland & Herod, 1975) has been recognised some 750 Myr ago in Australia, China, southwest Africa and Scandinavia, and the Gnejsö Ice Age occurred some 950 Myr ago in Greenland, Spitzbergen and Norway. The Huronian Ice Age, some 2300 Myr ago, is strongly indicated by sedimentary (Gowgandan Tillite) and morphological evidence in Canada and may correlate with other, possibly glacial, debris in South Africa and India (Harland & Herod, 1975). The Canadian deposits seem to have accumulated at high latitudes (Symons, 1975) and therefore are probably derived from a polar ice-cap. It seems probable that the reality of these ancient ice ages will be confirmed by further study and it may eventually be possible to establish their palaeogeographical situation. At this stage, however, the data available are inadequate to throw significant light on the factors associated with the occurrence of glaciation, other than their possible chronological relationship with galactic rotations and so on (see Chapter 7).

Lower Palaeozoic Glaciations

The most striking and well-known glacial deposits of this age are in Ordovician rocks in the Sahara (Fairbridge, 1974; Allen, 1975). These occur through much of North Africa (Fig. 1.2) where they have mainly been researched by Beuf and his colleagues (Beuf, Biju-Duval, Mauvier & Legrand, 1968*a*; Beuf *et al.*, 1968*b*; Gariel, de Charpal & Beenacef, 1968; Rognon, de Charpal, Biju-Duval & Gariel, 1968). In some areas, U-shaped palaeo-valleys are present with polished and striated floors overlain by tills, some of which are water-laden and include dropstones. Graded sediments and outwash sediments are also present with marginal permafrost characteristics bordering them which include polygons, kettle-hole structures and so on. The age of these deposits is not known precisely but they are overlain by Silurian

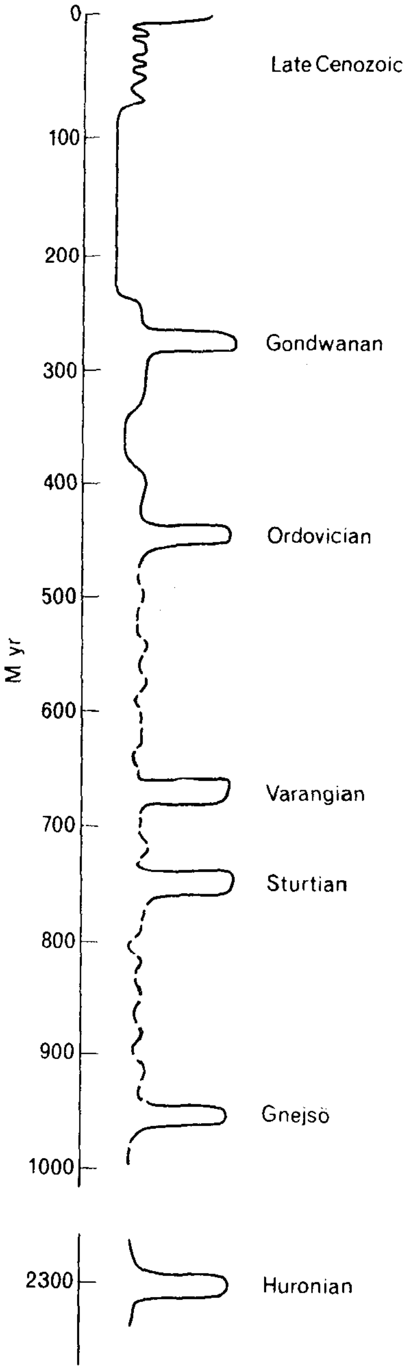

Fig. 1.1 Ice ages through geological time. The right hand side of the curve corresponds to periods of major ice sheet formation with each period including several glacial and interglacial stages. The left hand side of the graph corresponds to periods with no known glaciation, with intermediate position indicating the possible extent of mountain glaciation.

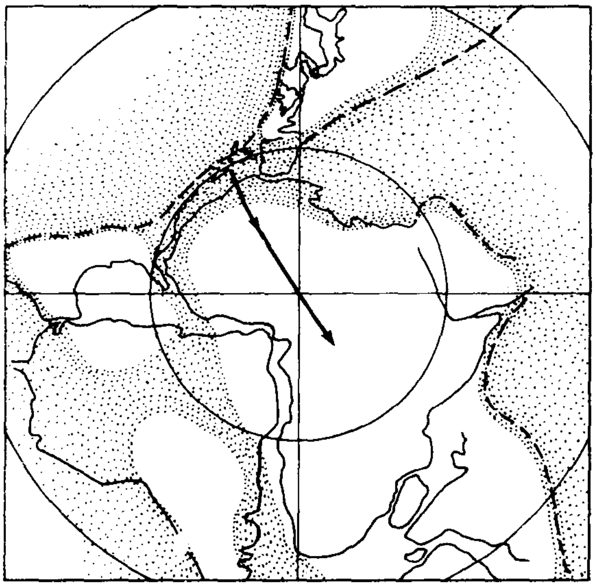

Fig. 1.2. The palaeogeography of the Ordovician (Saharan) glaciation. The continental boundaries at this time are very uncertain – and present-day coastlines are only indicated for general location purposes. The polar movement relative to the continent for this period (broad arrow) is still badly defined, that is, it is uncertain within some 20° of its indicated position, but must travel from the top left hand side of the map to the bottom right hand side during the Lower Palaeozoic.

deposits and one of the tillites includes Upper Ordovician fauna; it seems probable that most of the glaciation was during the Caradocian, with some activity during the Llandeilian. Attempts to determine directly the palaeomagnetic latitude of these sediments have been largely unsuccessful (Abou-Deeb, 1976) but it is clear from studies of younger and older rocks from the North African platform that the area was in high latitudes during the Ordovician (Fig. 1.2) and that these deposits are of polar ice-cap origin. The presence of marine sediments within some of the deposits shows that the ice was at or close to sea-level, although most of the deposits were laid down in unfossiliferous waters. Glacial deposits of Ordovician age have also been recognised in various parts of South America, South Africa (although these may be Cambrian), West Africa, Newfoundland and possibly Britain (Harland & Herod, 1975) but the glacial origin and age of most of these deposits are uncertain.

Upper Palaeozoic Glaciations

With the obvious exception of those of the Late Cenozoic Ice Age, the glacial deposits of Permo-Carboniferous age (Fig. 1.3) in all of the Gondwana continents (South America, Africa, India, Australia and Antarctica) are the best documented and studied of all glaciations (Crowell & Frakes, 1970, 1975). Most of the discoveries, except in Antarctica, were made in the nineteenth century and were possibly the major factor influencing geologists from these areas in accepting the concept of continental drift during times when most 'northern' geologists were unwilling to consider the theory.

(a) South America

Late Palaeozoic glacial rocks were not reported from South America until the beginning of this century (White, 1907) but have now been found over some 1 500 000 km^2 in the Parana Basin alone. Although much of the glacial material is reworked, particularly in the outcrops along the edge of the Andes, all of the classical features of glacial activity have been recognised, including tills, striated platforms, glacially cut and filled valleys, dropstones, faceted pebbles, roches moutonnées, eskers and other features, and it seems certain that the deposits of the Parana Basin are of ice sheet derivation, although those of the Andes and further south may be associated with mountain or piedmont glaciation (Frakes & Crowell, 1969). The oldest glacial deposits of this Gondwanan sequence have been found in the Paganzo Basin where the flora indicate a probable pre-Westphalian age (Kemp, 1975), and glacial deposits in the Rio Blanco basin are thought to be of Early Carboniferous age (Frakes & Crowell, 1969). Glacials deposits of Middle and Upper Carboniferous age are also known, although the maximum glacial extent appears to have been confined to the very latest Carboniferous and earliest Permian (Fig. 1.2). Glaciation, possibly mountainous and on a very local scale, seems to have persisted locally in Brazil until the Artinskian or possibly slightly later (McClung, 1975). This record of glaciation is the longest for all of the Gondwanan continents for this period and it may be significant that the estimate of a minimum of 17 advance/

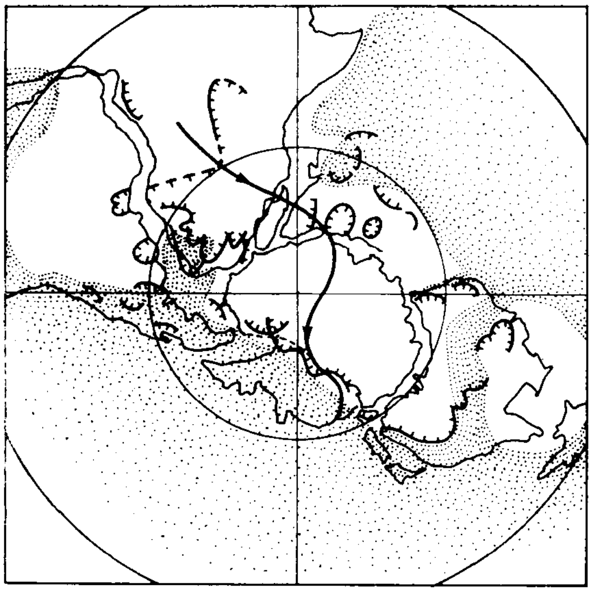

Fig. 1.3. The Gondwanan glaciation. The distribution of ice sheets at this time is indicated by the barbed line. Although there is some doubt about the exact synchroneity, it seems probable that most of these ice sheets were active simultaneously in the very Early Permian and disappeared almost simultaneously from all of these continents as soon as the Gondwanan continent had drifted so that the pole was approaching the 'Pacific' Ocean. The polar path, although better defined than for the Ordovician (Fig. 1.2), can only be broadly indicated by the arrowed line with a probable uncertainty of some 10° as it moves from its Lower Carboniferous to Middle Permian position.

retreat cycles (Rocha-Campos, 1967) is by far the largest determination of the number of glacial fluctuations.

(b) Southern Africa

Since the original description of glacial deposits of Late Palaeozoic age (Sutherland, 1870), there has been little doubt about the glacial origin of the Dwyka tillite with its associated striated pavements, glacial valleys infilled with glacial debris and other features. Most geologists who have visited outcrops have been convinced of its glacial origin (Frakes & Crowell, 1970*a*; Crowell & Frakes, 1972), although there is increasing recognition of the extent of fluvial reworking (Elliott, 1975). Several ice lobes have been recognised, some deriving from the south-east of the continent and others passing from the continent onto the then adjacent South American continent (Fig. 1.3). It has often been assumed that these lobes are of very similar age, with different directions of motion indicating the local effect of topography (Matthews, 1970; Rust, 1975) but at least four major advance/retreat cycles have been recognised (Theron & Blignault, 1975). The flora within the various outcrops indicate glaciation spanning much of the Carboniferous and Early Permian (Plumstead, 1973), although recent studies indicate that the maximum glaciation was largely confined to the uppermost Carboniferous and earliest Permian (Kemp, 1975). This age seems to be confirmed by the Early Permian marine fauna near the top of the glacial sequence in the Karroo Basin (McLachlan & Anderson, 1975) which also suggests that much of the glaciation occurred at low levels and was of a polar ice-cap form, although undoubted mountain glacial features can be recognised on a local scale. The youngest glacial deposits seem to be those of probable highland glaciation in the Congo, where an Artinskian age is suggested (McClung, 1975).

(c) The Indian subcontinent

The Talchir glaciation was the first of the Late Palaeozoic Gondwanan glaciations to be recognised (Blandford, Blandford & Theobald, 1859) and was of critical significance in persuading Earth scientists about the reality of continental drift, since these glacial deposits implied that the Gondwanan glaciation extended well past the equator and therefore implied world-wide glaciation if the continents were then in their present-day positions. The fact that the remaining northern continents were mostly characterised by equatorial conditions at this time therefore provided very strong evidence for the continents being in different positions relative both to the rotation poles and to each other at this time. Glacial beds have been recognised in many areas (Frakes, Kemp & Crowell, 1975) and include diamictites, tills, glaciated pavements, etc. (Fig. 1.3). The flora generally indicate a Westphalian to Sakmarian age (Frakes *et al.*, 1975) although there is increasing floral and faunal evidence for glaciation being mostly restricted to latest Carboniferous and earliest Permian, mainly Sakmarian (McClung, 1975; Kemp, 1975; Shah & Sastry, 1975). The glaciation, which includes at least three major episodes (Casshyap & Qidwai, 1974), was during a time of low relief and close to sea-level, as indicated by the series of extensive marine transgressions in various places. The final ice recession, accompanied by minor fluctuations, appears to have been very rapid (Ghosh & Mitra, 1970).

(d) Australia

Palaeozoic glacial deposits were recognised (Selwyn, 1859) near Adelaide at almost the same time as the first glacial deposits of similar age in India and these have subsequently been identified over most of the Australian continent (Crowell & Frakes, 1971). These deposits include all features associated with both mountain and ice-cap glaciation. The glaciation seems to have commenced by at least Westphalian time within mountains bordering the Tasman geosyncline and remained active until the end of the Carboniferous, by which time the mountains were largely eroded. Faunal and sedimentological evidence strongly indicates drastic climatic change which commenced in the earliest Namurian, marked by a strong decrease in the diversity of floras (Morris, 1975), changes in marine faunas and the disappearance of true reefs and the subsequent paucity of significant limestone development (Runnegar & Campbell, 1976). Mountain glaciation probably ceased before the formation of ice sheets, in southeastern Australia, in Sakmarian times, although ice sheets may have been present in western areas towards the end of Stephanian times. The ice sheets largely disappeared at the end of the Sakmarian, but some areas retained some glaciers, possibly as late as Kazanian, as evidenced by rafted debris of this age in Queensland, and possibly Tasmania. Marine levels are quite common and it is thought that a direct marine connection existed between northwestern Australia and the Tasman geosyncline for much of the glacial period. At least three phases of glaciation can be recognised, but this is probably a gross underestimate of the number of glacial episodes during this period.

(e) Antarctica

Although Palaeozoic glaciation had long been suspected in this continent by proponents of continental drift, it was not until 1960 that evidence was first found (Long, 1962) and deposits are now known along most of the length of the Transantarctic Mountains of eastern Antarctica and the Ellsworth Mountains of western Antarctica (Frakes, Matthews & Crowell, 1971; Elliot, 1975). However, difficulties of access and exposure have continued to restrict knowledge of these deposits and their terrestrial nature and, with a lack of diagnostic fossils, means that they are still only known to be post-Devonian and to be overlain by Permian deposits laid down when glaciation had ceased in these regions. Frakes *et al.* (1971) suggested that the glaciation was of different ages in different localities, on the basis that Antarctica drifted through polar regions during the Carboniferous and Lower Permian, but an uppermost Carboniferous–earliest Permian age now seems likely (Barrett & Kyle, 1975; Kemp, 1975), although not proved. For palaeogeographic considerations (Fig. 1.3) it is important to note that there is evidence for a Jurassic–Cretaceous strike-slip motion of Antarctica relative to East Antarctica so that at this time cratonic blocks lay alongside the Transantarctic Mountains (Barrett & Kohn, 1975; Elliot, 1975;) and much of West Antarctica was the site of geosynclinal accumulations.

(f) Elsewhere

Only two other localities are considered to show evidence for glacial activity at or about the same time as the glaciation of the Gondwanan continents, as the Wajid Sandstones of Saudi Arabia are now known to be neither of glacial origin nor of Permo-Carboniferous age (Hadley & Schmidt, 1975).

(i) The North American Permo-Carboniferous Squantum 'tillite' of Massachusetts seems to be a very localised deposit (Newell, 1957; Dott, 1961); and it has been argued that it may not even be glacial (Frakes *et al.*, 1975), although a glacial origin would be consistent with its grain textures (Rehmer & Hepburn, 1974). It certainly does not seem to be associated with ice-cap glaciation, if only because of its restricted extent, and is not therefore considered a major indication of the palaeoclimate of North America which was almost certainly equatorial to tropical from the studies of fauna, flora and nature of sediments of this period (such as those of Chaloner & Meyen, 1973 and Milner & Panchen, 1973) and from palaeomagnetic studies (Turner & Tarling, 1975).

(ii) Glacial sediments within marine strata have been recorded in the Omolon River, east of the Verkhoyansk Mountains and northeast of the Okhotsh Sea (Mikhazlov, Ustritshii, Chernyak & Yavshits, 1970). These are well dated as Kazanian and therefore later than all of the Gondwanan glaciations, except for isolated deposits in southeast Australia, the Congo (Kemp, 1975) and Brazil (McClung, 1975). These deposits are not on the main Siberian platform and, at that time, this Angaran area was probably isolated from the West Siberian Shield. Although further information on these deposits is needed, it seems probable that they are glacial since the Angaran flora, which were also originally confined to this block (Meyen, 1970; Chaloner & Meyen, 1973), and the close parallism of development of the Angaran and Gondwanan flora, suggest similar climatic environments. It is quite probable that this part of the Siberia Shield lay in high northern latitudes and was not finally welded onto the main Eurasian block until later.

Late Cenozoic Ice Age

More is known about the latest and the maximum phases of the Late Cenozoic Ice Age than about any other, and it is the deposits associated with these and present-day glaciations that provide the diagnostic properties for recognising previous ice ages. The features of these deposits are comprehensively covered in many text books, especially Flint (1971), and such details will not be repeated here. However, there has been a considerable expansion in knowledge about the record for such glaciations from studies of deep-sea sediments, in particular, and it is worth reviewing, briefly, the evidence for the timing of the onset of glaciation changes.

The Late Cenozoic Ice Age was originally labelled the Great Ice Age (Geikie, 1874) and the first appearance of its glacial deposits were used to define the start of the Pleistocene. The Plio-Pleistocene boundary is still defined on the first appearance of cold conditions in the Mediterranean basin (Gignoux, 1913) some 1.7 Myr ago but glaciation was clearly initiated in the northern hemisphere some 3 to 4 Myr ago. (Fig. 1.4) and at least 10 glacial cycles have been recognised in sedimentary sequences in Iceland (Einarsson, Hopkins & Doell, 1967) during the past 3.1 Myr. Much earlier glaciation is indicated in the southern hemisphere (Fig. 1.5 and 1.6). Comparison of the fauna in Australia and South America from Permian times to the present (Colbert, 1973; Cox, 1973, 1974 Denton, Armstrong & Stuiver, 1971; Keast, 1973;) indicates that the climate along the East Antarctic migration route must have been at least mild, probably warm, from Middle Permian times right through to the end of the Cretaceous, at which time it was the formation of new seaways, rather than climatic change, that prevented further migration along this route. Sedimentological studies of rocks in Antarctica and Australia, then still attached to Antarctica, support the evidence for this prolonged equitable climatic situation and indicate that mild climatic conditions persisted in parts of Antarctica through much of the Tertiary period, with drastic faunal and floral changes only commencing in the Miocene, at a similar but probably earlier time than the initiation of glaciation in the northern hemisphere. Examination of the Southern Ocean deep-sea sediments for the presence of glacial sands, cold-water foraminifera, studies of clay mineralogy and palaeotemperatures (Emiliani, 1954; Denton *et al.*, 1971; Margolis & Kennett, 1971; Anon 1973*a*, *b*; Jacobs, 1974; Blank & Margolis, 1975) indicate that glaciation in Antarctica was active in the Late Cretaceous, Early Eocene, late Middle Oecene, Oligocene, Lower Miocene and Late Miocene, with particularly detailed climatic oscillations recorded for the past 5 Myr (Fig. 1.6)

There is no unequivocal evidence for the nature of the Antarctic glaciation during the earlier Tertiary, but it seems probable that the pre-Miocene evidence is largely associated with local, mountain glaciation as the deep-sea data suggest that glacial conditions were not as severe as in the Late Miocene. Furthermore, glaciation in South America only occurred after major oceanic cooling some 3.5 Myr ago (Mercer, Fleck, Mankinen & Sander, 1975) and only this Miocene cooling is strongly marked by floral and faunal changes in Australia. It seems probable that it was only in Late Miocene times that major ice-cap glaciation commenced in the

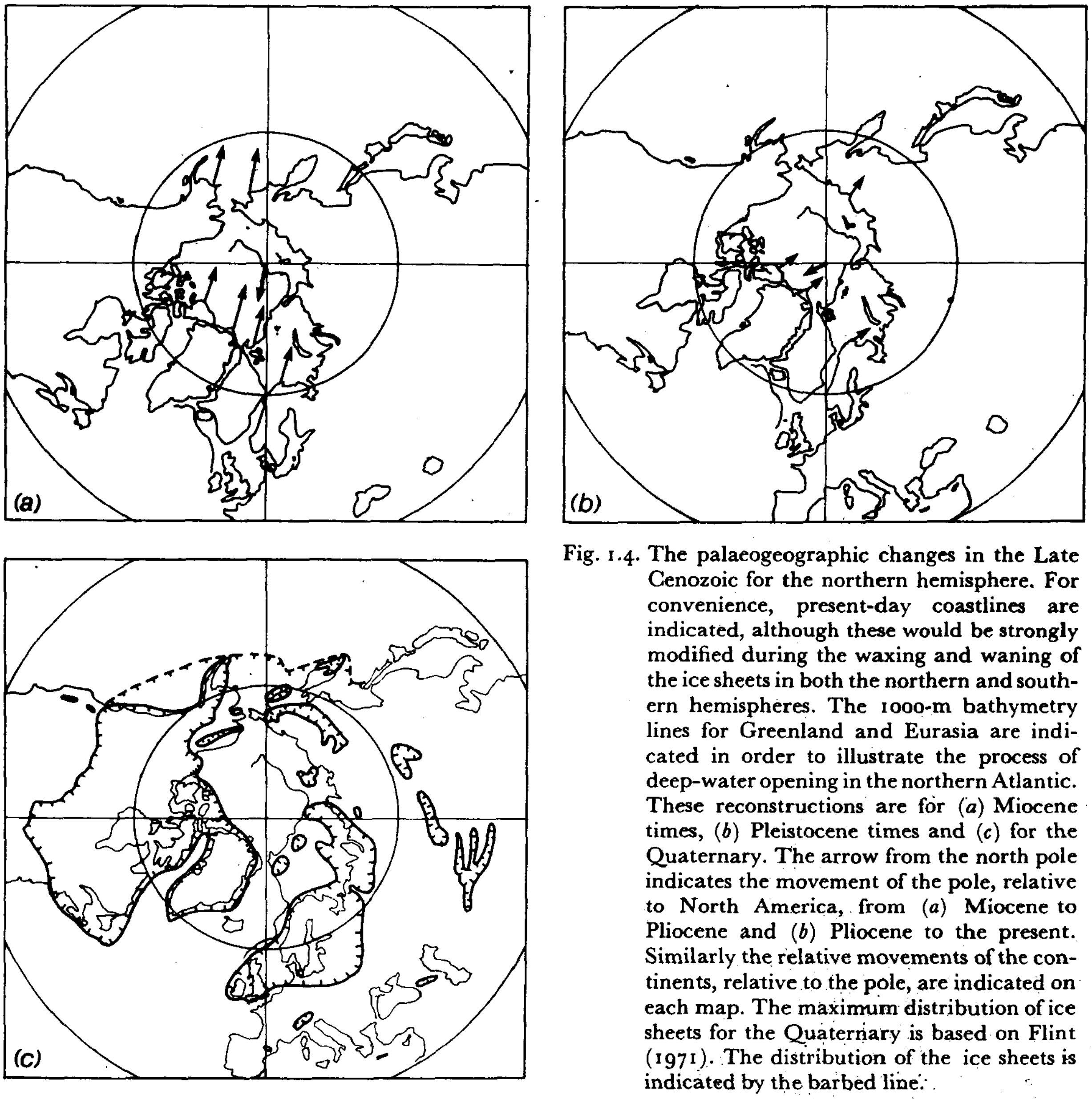

Fig. 1.4. The palaeogeographic changes in the Late Cenozoic for the northern hemisphere. For convenience, present-day coastlines are indicated, although these would be strongly modified during the waxing and waning of the ice sheets in both the northern and southern hemispheres. The 1000-m bathymetry lines for Greenland and Eurasia are indicated in order to illustrate the process of deep-water opening in the northern Atlantic. These reconstructions are for (*a*) Miocene times, (*b*) Pleistocene times and (*c*) for the Quaternary. The arrow from the north pole indicates the movement of the pole, relative to North America, from (*a*) Miocene to Pliocene and (*b*) Pliocene to the present. Similarly the relative movements of the continents, relative to the pole, are indicated on each map. The maximum distribution of ice sheets for the Quaternary is based on Flint (1971). The distribution of the ice sheets is indicated by the barbed line.

southern hemisphere and earlier Tertiary glaciations were of mountain glacial type and not ice sheets (Drewry, 1975). One major difference between the two hemispheres has been that ice seems to have disappeared off the land in the northern hemisphere during the interglacials (although an ice-free or frozen Arctic Ocean at such times is a subject of dispute) while glaciation on Antarctica has been continuous (Markov 1969; Mercer, 1972; Keany, Ledbetter, Watkins & Huang, 1976) with the ice front advancing and retreating so that there was an oscillation of the area of maximum glacial deposition in the surrounding oceans. Two types of Quaternary ice sheet are recognised (Andrews, 1975), with the present Greenland and Antarctic ice-caps being examples of stable conditions, while the extensive Laurentian and Scandinavian ice sheets were unstable and possibly formed and disappeared rapidly, probably in response to only small changes in environmental conditions (Flint, 1971; Hughes, 1975).

Unfortunately, there is little information on

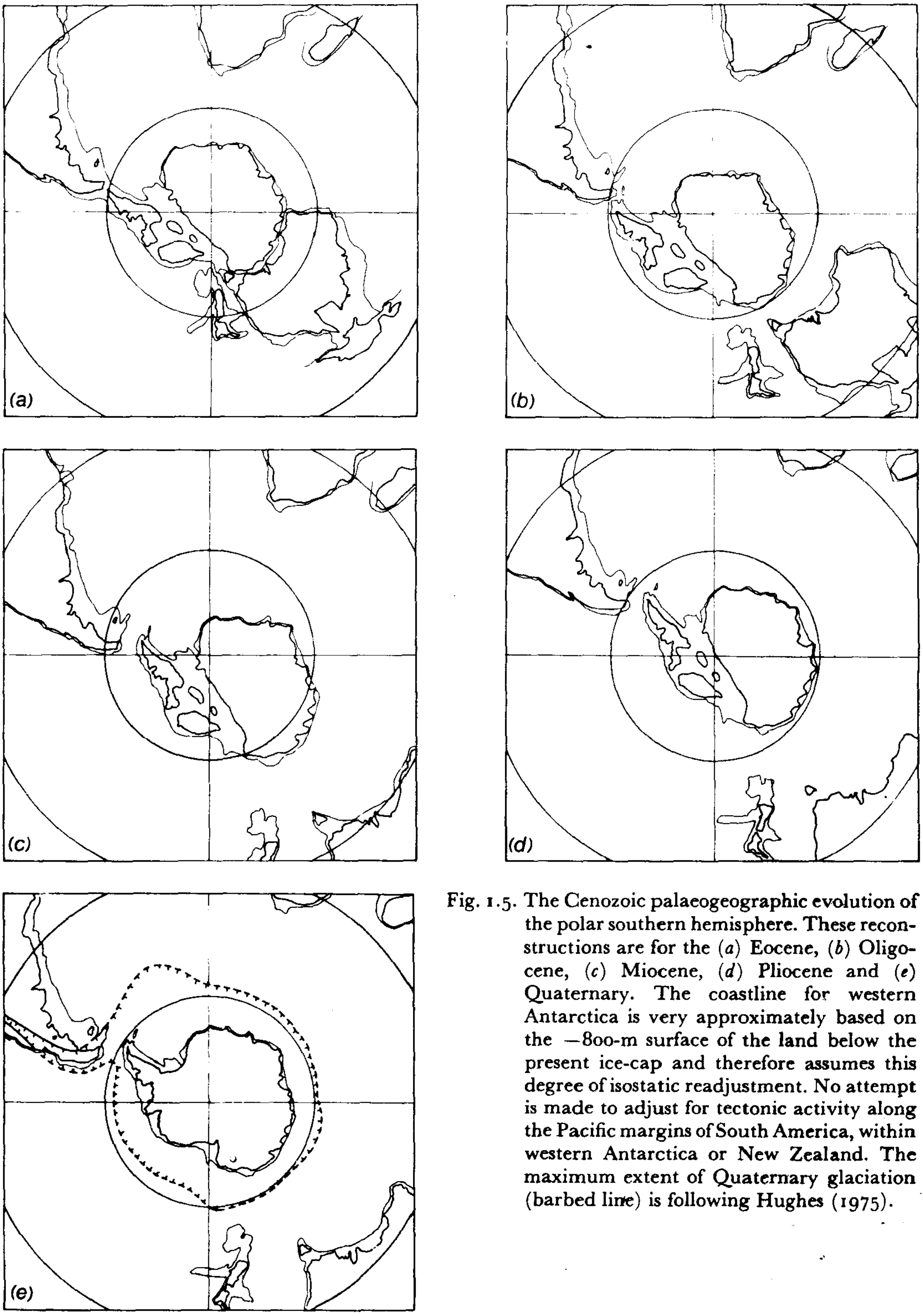

Fig. 1.5. The Cenozoic palaeogeographic evolution of the polar southern hemisphere. These reconstructions are for the (*a*) Eocene, (*b*) Oligocene, (*c*) Miocene, (*d*) Pliocene and (*e*) Quaternary. The coastline for western Antarctica is very approximately based on the −800-m surface of the land below the present ice-cap and therefore assumes this degree of isostatic readjustment. No attempt is made to adjust for tectonic activity along the Pacific margins of South America, within western Antarctica or New Zealand. The maximum extent of Quaternary glaciation (barbed line) is following Hughes (1975).