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PHANEROZOIC GLACIATION AND THE CAUSES OF ICE AGES

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ABSTRACT. Restudy of glacial strata and associated facies and current and ice-flow indicators suggests that late Paleozoic ice centers in Gondwanaland migrated through time. During the early Carboniferous, glaciers covered regions in the Andean belt of South America and also waxed in southern Africa and the then nearby Paraná basin of Brazil. According to paleomagnetic data, the south rotational pole lay in the Transvaal at this time; but, by the late Carboniferous, the assembled Gondwana continents had moved so that the pole was in Antarctica. Glaciation then culminated in South Africa, parts of southern South America and the Falkland Islands, and Antarctica, and began to affect Southern Australia and India. By the Permian the continents had glided so that Australia and Antarctica were broadly glaciated, but centers had dwindled or disappeared in Africa and South America. Ordovician ice sheets of the Sahara region, and perhaps those of the Silurian and Devonian of Brazil, may have developed when Gondwanaland occupied a polar position earlier in the same migration. Continental glaciation in Gondwanaland apparently occurred at intervals throughout the Paleozoic. Between the late Permian and the mid-Cenozoic, when continental sites lay outside of polar positions and latitudinal ocean-air circulation prevailed, no ice sheets developed.

Just prior to the major late Cenozoic glaciation, tectonic movements brought about the closing of the Tethys seaway, the widening of the Atlantic, and at the end of the Pliocene, the elevation of the Panama Isthmus. Latitudinal ocean currents in the tropics and sub-tropics were blocked by combined Eurasia and Africa on the one hand, and North and South America on the other; and ocean and air circulation thus became more meridional. A basic cause of glaciation is therefore probably the arrangement of continental masses and their effect on ocean circulation. Additional significant factors that interplay to bring about ice sheets are the elevation of continents, the elevation and extent of highlands, the availability of moisture sources, the freezing and thawing of polar seas, the effect of snow and ice cover and frozen seas on the Earth's albedo and the mean Earth temperature, the positioning and swinging of storm tracks along the polar front with the development of strong air-mass contrast, and others. When many of these factors reinforce, continental glaciation ensues.

INTRODUCTION

In the past huge glaciers have spread across continents and then have wasted away—at least twice in the Precambrian, at intervals in the Paleozoic, and in the late Cenozoic. Here we wish to describe briefly the arrangement of ice sheets during the Paleozoic and then to appraise factors that perhaps caused glacial episodes in the history of the Earth. Similarities between the arrangement of continental masses during the Paleozoic and Cenozoic ice ages suggest that drift of continents on our mobile planet may be a basic cause. Patterns of land and sea and highlands and lowlands have guided ocean and air circulation, which have in turn influenced the Earth's climate.

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For the late Cenozoic ice age, we now have a chronology of advances and retreats of ice sheets as the result of over a century of study by scientists of many disciplines (for example, Charlesworth, 1957; Flint, 1957; Wright and Frey, 1965; West, 1968). Maps show the extent of ice caps and the locations of nearby seas and highlands and climatic belts. Lakes and woodlands were widespread as the result of pluvial cycles corresponding to times of glacial advances and are found in regions that are now deserts. The crust was warped down under the weight of ice caps and then gradually rebounded when they melted. Sea level dropped when water was tied up in glaciers and then rose as they wasted. These and other effects lead us to search for their counterparts during ancient ice ages and need consideration in any general theory to explain ice ages. Moreover, the late Cenozoic glaciation was characterized by a fluctuating series of glacial stages interspersed with times of warmer climate; in fact, we are now almost certainly within an interglacial stage. The timing of these climatic fluctuations is becoming better known, and in the northern hemisphere the onset of glaciation on a continental scale occurred within the Pliocene and followed gradual cooling of climate (Axelrod and Bailey, 1969). Not only is an explanation therefore needed for an ice age or period as a whole, but also for the waxings and wanings—the glacial and interglacial stages—during the ice age.

Not as much can be said concerning the several glacial culminations in the Paleozoic; the preserved record is too piecemeal and stratigraphic correlations too uncertain and imprecise to establish intercontinental glacial and interglacial stages at present. Sedimentary rocks show that late Paleozoic glaciers also waxed and waned like those of the Quaternary, so similar mechanisms probably also operated in the late Paleozoic and, in time, glacial and interglacial stages will likely be proven and correlated (Bowen, 1958; Wanless, 1960; Wanless and Cannon, 1966).

At least two Precambrian ice ages are reasonably well established, but little is known about their extent and duration. Sedimentary rocks of glacial origin for example, have been recognized in the upper Precambrian, about 600 m.y. old, around the North Atlantic, in Britain, Scandinavia, Greenland, Spitzbergen (Harland, 1964a, b; Schwarzbach, 1963), and in Australia (summarized by Brown, Campbell, and Crook, 1968). A much earlier glaciation took place about 220 m.y. ago in southern Canada, recorded in Huronian sediments (Ovenshine, 1964; Schenk, 1965a, b). Other examples of glaciations are reported from most of the remaining continents, but for many rocks of these remote ages it is difficult first, to prove that they are truly glacial and second, to establish their age and contemporaneity. Many strata of tillitic appearance were laid down rapidly in troughs near rising mountains by non-glacial processes (Crowell, 1957; Dott, 1963; Winterer, 1964). For the genuine Precambrian ice ages, and for others that eventually may be discovered, it will be of interest in time to see whether a grouping of continental masses with attendant effects, as discussed in this paper, was instrumental in bringing about glaciation. These ancient glaciations show that meteorological conditions and temperatures on our planet about 2.2 b.y. ago were not very different from those at present.

In the following pages, after a brief review of suggested causes of ice ages, the distribution of Paleozoic glaciation, the subject of our recent research, is described. A comparison of this information with data on the arrangement of continents is timely because of improvements in the quality of paleomagnetic measurements and coverage and in recent understanding of the mechanisms of crustal movements through documentation of sea-floor spreading and continental drift and the development of new tectonic models (for example, Hess, 1962; Vine, 1966; Isacks, Oliver, and Sykes, 1968). In appraising the climatology of glaciation, heavy dependence has been placed on many outstanding papers, including especially Brooks (1949), Flint (1957), Ewing and Donn (1956; 1958), Donn and Ewing (1966; 1968), Lamb (1961), Emiliani and Geiss (1958), and Mitchell (1965; 1968a, b). We find ourselves in particular accord with Fairbridge (1961; 1964, fig. 2) and advocate as well an eclectic theory to explain ice ages.

EXPLANATIONS OF ICE AGES

Explanations usually advocated for ice ages and stages fall into two groups: those that are based on extraterrestrial influences, and those based on changes occurring on the Earth itself. Variations in the energy output of the sun have long been advanced as a cause, but there is as yet little evidence from about 50 yrs of measurement and calculation for variations in the solar constant much greater than 1 percent of the present value (Jezykiewicz and Serkowski, 1968). Öpik (1968), on the other hand, from theoretical studies, considers it likely that fluctuations in solar output have accounted for ice ages. In addition, energy received by the Earth conceivably could be reduced if the Earth were to pass through a diffuse dust cloud in space, but for this there is little evidence either. Relatively short-term variations in the orbital elements of the Earth do not affect the total amount of heat received, but rather its latitudinal and hemispherical distribution. These periodic variations are (1) the precession of the equinoxes, with a period of about 21,000 yrs; (2) changes in the obliquity of the ecliptic over 40,000 yrs, and (3) a variation in the eccentricity of the Earth's orbit over about 96,000 yrs. These and other astronomic variations and rotational wobbles (Munk and MacDonald, 1960) have certainly been in operation since well back in the Earth's history and were not suddenly "turned on" at the times of the ice ages. They are part of the background "noise" and may play a role in accounting for stages—a matter still under vigorous discussion (Broecker, 1965; Ericson and Wollin, 1968; Emiliani, 1955, 1964, 1967; Donn and Shaw, 1967a, b; Shaw and Donn, 1968; Mesolelia and others, 1969). The time scale of these variations in insolation is very much shorter than that of the ice ages, although they are probably influential in the timing of stages. Until more evidence for control by extraterrestrial influences comes to light, however, we should look on the Earth itself for causes of the ice ages.

Given a nearly constant heat flux from the sun impinging upon the Earth through time, the surface climate of our planet will be regulated largely by the atmosphere and hydrosphere. At present about 35 percent of the incoming solar radiation is reflected directly back to space by clouds and light-colored land surfaces, 18 percent is absorbed by ozone, water, dust, and haze within the atmosphere, and 47 percent is absorbed by land and water (Mitchell, 1965). Outgoing radiation from water surfaces and land, and from water vapor and CO_2 in the atmosphere, makes up 65 percent of the departing flux to balance the solar heat budget. Clearly, changes in the amount of heat retained within the Earth system are sensitive to changes in the albedo and to changes in the proportions of water vapor, CO_2, and dust in the air. Paleoclimatologists therefore traditionally search the geological record for factors through time which could change the Earth's albedo and the proportions of various gases and other products in the atmosphere. Nevertheless, although less than 2 percent of the heat comes from inside the Earth, Worthington (1968) has calculated that this heat could raise the temperature of a 1000 m thick layer of cold bottom water in the ocean about 7°C in 15,000 yrs—enough to overturn the density stratification and influence heat distribution and perhaps climate.

Although the air and oceans have accumulated and changed in composition slowly as water and gases rose from within the Earth and were then modified by biochemical activity, the rate of change in composition by the Paleozoic had decreased as the atmosphere and oceans began to approximate their present compositions (Rubey, 1951; Cloud, 1968). Green plants and oxygen-breathing animals have been abundant on land since the middle Paleozoic and in the sea from the early Paleozoic. Variations in CO_2 concentrations in the air-ocean system probably have occurred since the Precambrian, but there is no convincing evidence of great fluctuations associated with either ice ages or stages. In fact, the complex interplay between rates of volcanic CO_2 emanation, chemical weathering and biochemical processes, carbonate fixing in rocks, and concentrations dissolved in the air-ocean system as a function of temperature damps the influence of CO_2 variation on climatic change (Revelle and Fairbridge, 1956). Nevertheless, the influence of CO_2 changes on climate still needs appraisal (Plass, 1956, 1959) but probably operates at best as a third-order effect. Volcanic products thrown high into the air would have a similar influence and hold heat in the lower atmosphere. Enhanced warmth and circulation associated with an increase in CO_2 and other products would be unfavorable to glaciation unless they increased the average cloudiness and albedo markedly. Correlation between the ice ages and increased volcanic activity or plutonism is unconvincing, even allowing for a long time lag. It is therefore probable that changes in gas and dust concentrations only weakly influence glaciation and are overshadowed by other factors.

On the other hand, changes in the positions and patterns of continents and oceans with reference to the rotational axis of the globe will affect the circulation of the air-ocean system and therefore the climate in diverse ways, including those discussed by Ewing and Donn (1956, 1958), Donn and Ewing (1966, 1968), Irving and Robertson (1968), and Tanner (1968). Perhaps a comparison of the arrangements of land and sea during the Paleozoic with arrangements during the late Cenozoic will reveal similarities.

LATE PALEOZOIC GLACIATION

Striated pavements with overlying remnants of till have long been described in now distant areas of the southern hemisphere, in Australia (Selwyn, 1859), in southern Africa (Sutherland, 1870), in South America (Woodworth, 1912), in the Falkland Islands (Halle, 1912), and in India and Pakistan (Blanford, Blanford, and Theobald, 1859). More recently, other exposures have been discovered in Antarctica (Long, 1962). For well

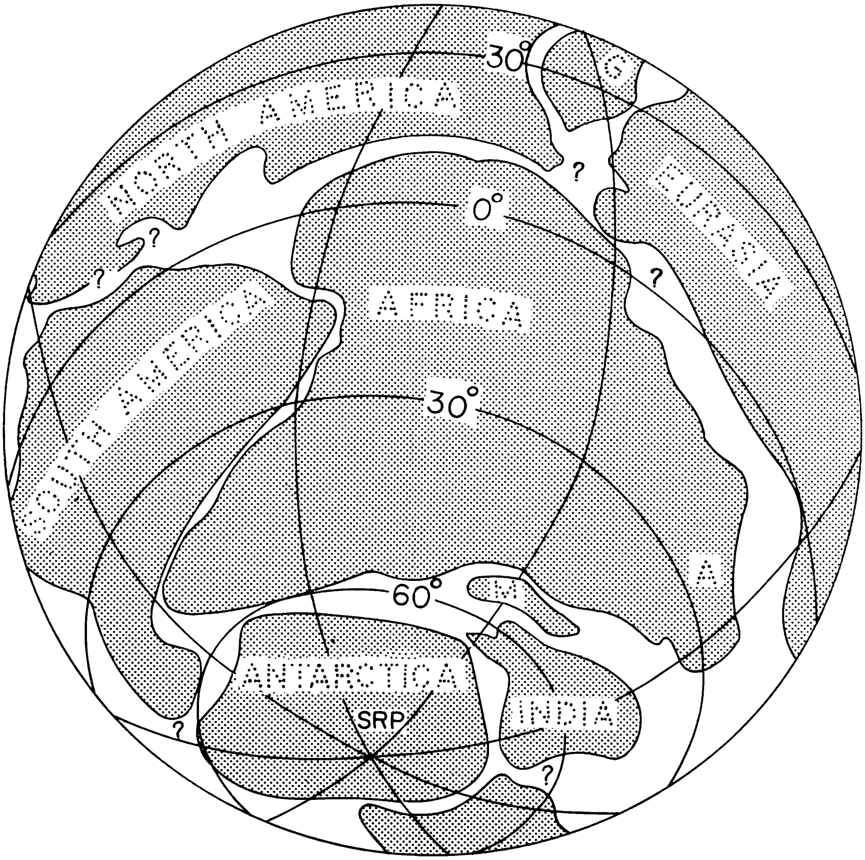
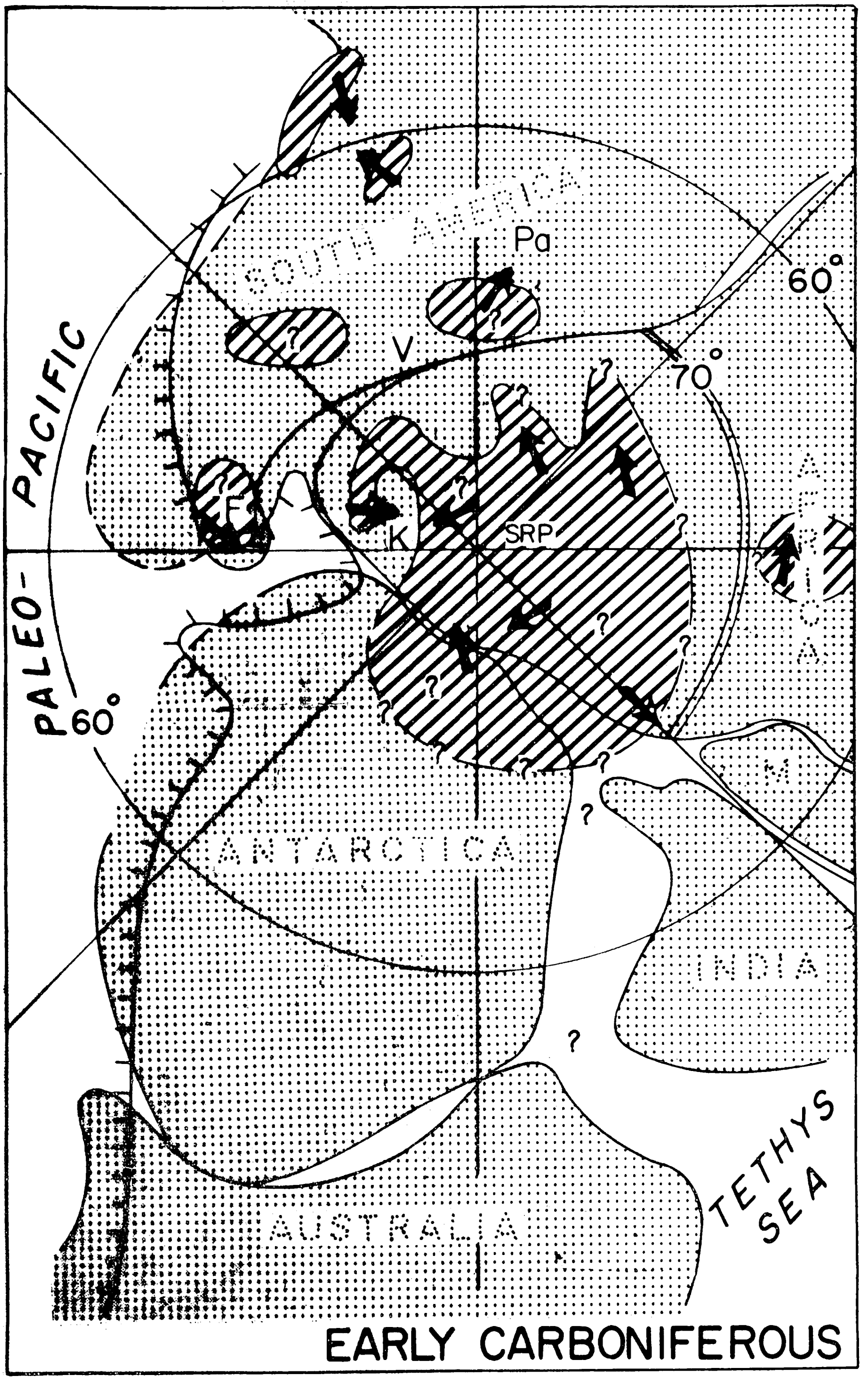


Fig. 1. Reconstruction of Gondwanaland during the Permian, viewed from the south, with Laurasia to the north. SRP = South rotational pole; A = Arabian block; G = Greenland; M = Madagascar. Data from Frakes and Crowell, in press; Creer, 1967, 1968a, b; McElhinny and others, 1968; Irving, 1964; Allard and Hurst, 1969; Hurley and Rand, 1969; L. C. King, 1962.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F
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AFRICA
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INDIA
TETHYS
SEA
AUSTRALIA
EARLY CARBONIFEROUS

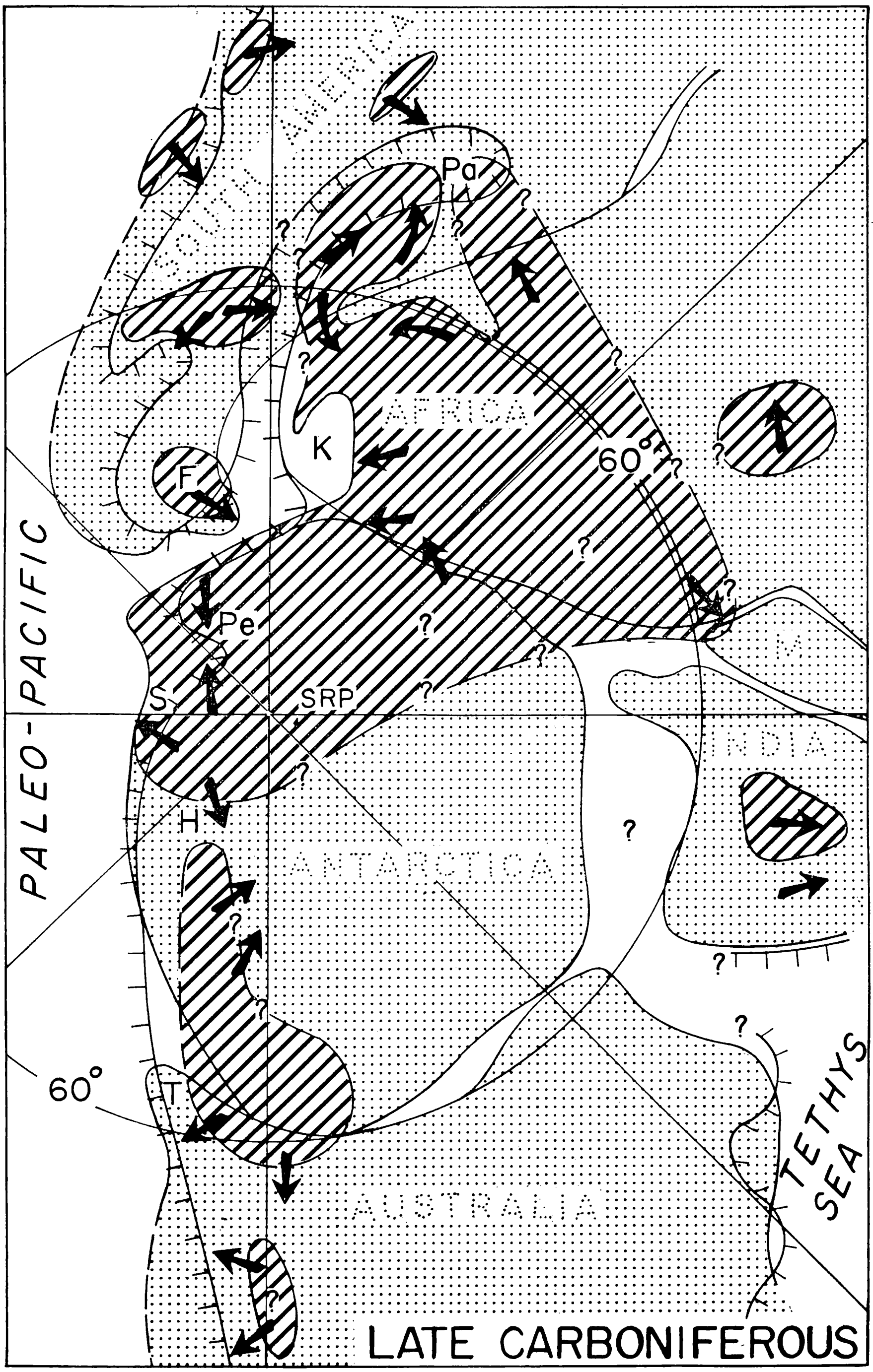
Fig. 2

over a century descriptions of these glacial features and deposits have therefore been accumulating along with interpretations. Wegener ([1915], 1966) and du Toit (1921, 1937), for example, used data on the distribution of glacial deposits and directions of glacial flow in support of their reconstructions of Gondwanaland and for documentation of continental drift.

Our research recently has been concerned with studying these glacial deposits, widely distributed in the far southern hemisphere (for example, Frakes and Crowell, 1967; Crowell and Frakes, 1968; Frakes and Crowell, 1969). The emphasis of these field and laboratory studies has been to establish, if possible, whether the deposits were truly glacial, and if so, whether the glaciers were continental ice sheets or local alpine accumulations. Striated floors and pavements, stoss and lee features and trends of ice-sculptured valleys, and the data from till fabrics provide information on the directions of ice flow. Current structures and the distribution and type of sedimentary facies, such as lateral changes from glacial deposits to outwash accumulations and their more distant transitions to subaqueous deposition in large bodies of water, have provided useful information on the variety of the topography. Problems of timing and correlation have received special attention. These data are being described in detail elsewhere, and only summaries and some interpretations are presented here.

Several converging lines of evidence indicate that the Gondwana continents were grouped together in the Late Paleozoic so that we also follow the concept of the breaking up of an ancient supercontinent, Gondwanaland, and the drifting of the pieces to their present positions (Wegener, [1915], 1966; du Toit, 1921, 1937; L. C. King, 1962). Figures 1 to 4 present our reconstruction of Gondwanaland based on (1) fitting the shapes of the continental masses near the 500 fathom subsea isobath (Bullard, Everett, and Smith, 1965), which is well down the continental slope and relatively unaffected by erosion and deposition; (2) the matching of geochronologic and tectonic trends (Frakes and Crowell, in press; Hurley and Rand, 1969; Allard and Hurst, 1969); (3) the reconstruction of a sensible glacial terrain, with associated highlands and basins; and (4) paleomagnetic data, assuming that they reflect the position of a dipole coinciding statistically with the Earth's rotational axis. The reconstruction of Gondwanaland during the Permian (fig. 1) is based on data in L. C. King (1962), Irving (1964), Creer (1967, 1968a, b), McElhinny and others (1968), Allard and Hurst (1969), Hurley and Rand (1969), and Frakes and Crowell (in press). Data from facies studies and paleomagnetism—those that show systematic changes during the late Paleozoic—are

Fig. 2. Southern Gondwanaland during the early Carboniferous, showing ice sheets. Double line in Africa is 70° paleomagnetic latitude from McElhinny and others (1968). Arrows are generalized ice-flow and current indicators from outwash and associated sedimentary facies. SRP = South rotational pole; M = Madagascar; Pa = Paraná Basin; K = Karroo Basin; F = Falkland Islands; V = Sierra de la Ventana.


SOUTH AMERICA
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LATE CARBONIFEROUS
Fig. 3

shown on figures 2, 3, and 4. Many striated floors and pavements, till fabrics, and current indicators in associated strata are summarized by the arrows and document variety in the topography of the polar regions at the times shown.

During the early Carboniferous (fig. 2), when the pole was in the Transvaal (Creer, 1967; McElhinny and others, 1968), glaciers radiated from several centers in southern Africa and perhaps westward into the Paraná Basin of South America. Plumstead (1964), on the basis of paleobotanical remains, considers the base of the Dwyka Tillite to range down into the lower Carboniferous and probably into the Devonian. Glacial marine tongues in basins parallel to ancient Andean trends contain early Carboniferous fossils (Amos, 1954; Frakes and Crowell, 1969). Here sediments display an imprint of glaciation as shown by striated stones and dropstones from ice rafting in thin-bedded sequences, but the stones may have come from alpine glaciers rather than from large continental ice sheets. In the Paraná Basin of Brazil most paleontological control indicates a Carboniferous and Permian age, but the thick basal portion without fossils may be of middle or early Carboniferous age (Caster, 1952). Similarly, the range in age for the Lafonian Diamictite of the Falkland Islands, in the absence of fossils, can permissively range down to the base of the lower Carboniferous (Frakes and Crowell, 1967). Striated floors and pavements in the Pensacola Mountains of Antarctica indicate a major glacial center near the present Weddell Sea and Queen Maud Land which at this time may also have contributed to the deposits in Natal where upglacial directions are now occupied by deep Indian Ocean (L. C. King, 1962, figs. 16, 17). Although the dating and correlations of the mostly unfossiliferous glacial sediments and their outwash and downslope and downcurrent counterparts are still incomplete, it is likely that early Carboniferous glacials are more widespread than generally recognized.

Glaciation reached its maximum extent in the late Carboniferous (fig. 3) when the Gondwana supercontinent had moved so that the south rotational pole lay somewhere in West Antarctica. At this time a lobe of the principal ice-mass, which covered most of southern Africa, extended through glacial valleys and on westward into the Paraná Basin (Martin, 1961; Maack, 1957; Frakes and Crowell, 1969; in press). It also probably covered a large part of Antarctica (Long, 1962; Frakes and Crowell, 1968), although the geological record on that continent is so fragmentary or unexplored that the extent is unknown. An ice cap occupied Victoria Land and provided glacial material for Tasmania and the southern part of Australia, another region now bordered by deep water in an upglacial direction. Along the Andean belt and west of the Falkland Islands, glacial centers also waxed, as well as in India and in Carboniferous moun-

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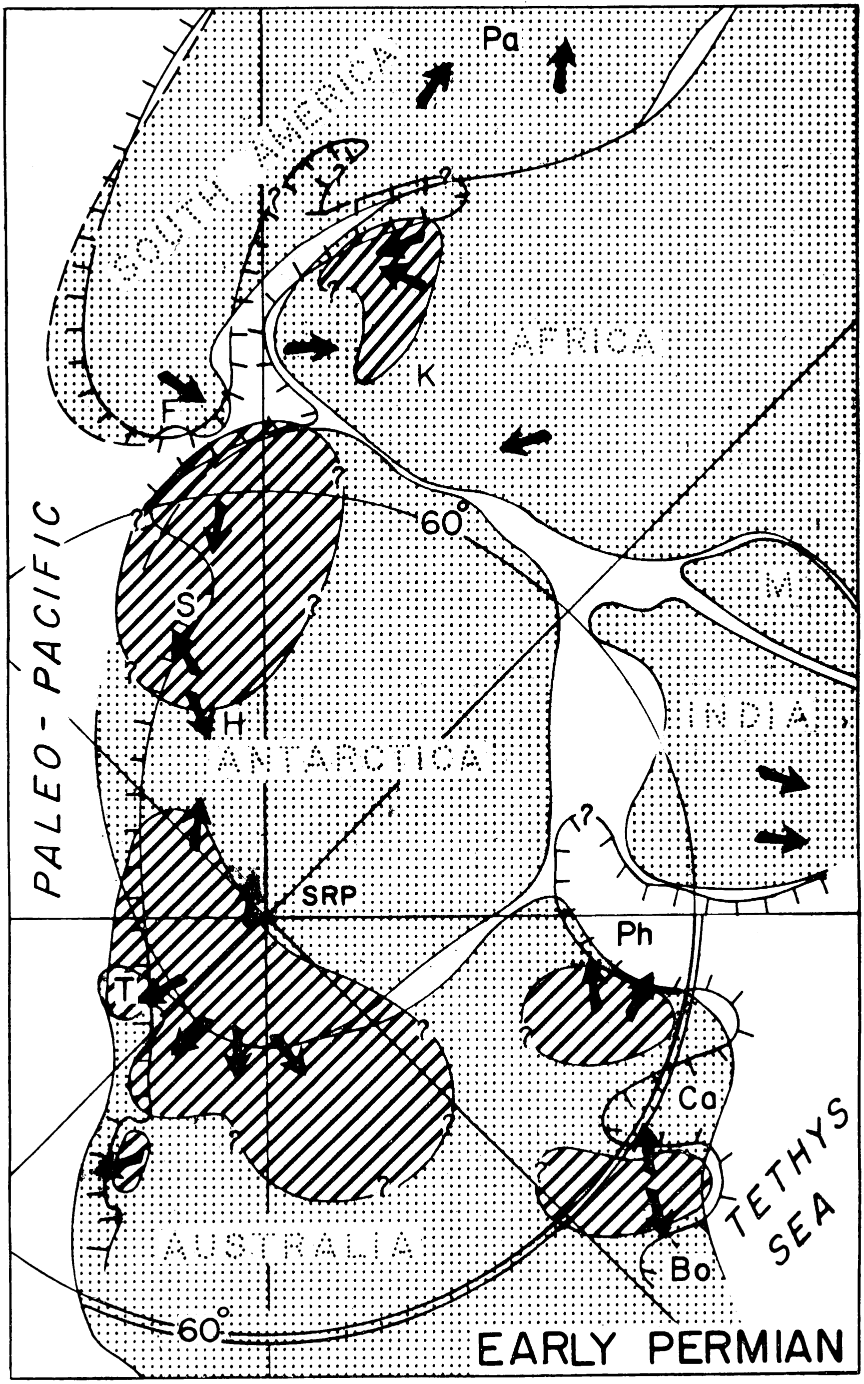
Fig. 3. Southern Gondwanaland during the late Carboniferous. Symbols as in figure 1, and Pe = Pensacola Mountains; S = Sentinel Range; H = Horlick Mountains; T = Tasmania; L = Victoria Land.



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60°
EARLY PERMIAN

Fig. 4

tains of central eastern Australia. Around an ancient polar embayment in the vicinity of the join between Antarctica, Africa, and South America thick deposits containing large deformed sandstone bodies, interpreted as remobilized till or outwash, probably accumulated on subsea slopes beneath or bordering shelf ice (Crowell and Frakes, 1968). Marine fossils in the Paraná basin (Rocha-Campos, 1967) and thick downslope deposits in the Sierra de la Ventana, Argentina (Coats, 1967), suggest a connection with this sea, somewhat as shown (fig. 3). Except for the polar sea and its northward extension, there is at this time no suggestion of an incipient fragmentation of Gondwanaland. The polar sea may have either provided, when unfrozen, a source for moisture to glacial centers or contributed to broad expanses of high albedo and the generation of cold air masses when frozen over.

Early in the Permian (Fig. 4) glacial centers had nearly disappeared except in Antarctica and Australia and in South West Africa in highlands near the inland sea. In South Africa nonglacial beds of the Ecca Formation were being deposited in the Karroo basin (Haughton, 1963), and in South America, beds of postglacial sequences (Guatá, Rio Bonito, et cetera) in the Paraná basin (Rocha-Campos, 1967). According to the paleomagnetic data these areas were near 30° latitude and the two still-joined continents had moved rapidly away from the south rotational pole (Creer, 1967). Permian limestones with fusulines (Cecioni, 1956) now in southern Chile near 50° latitude, accumulated near 25° latitude, and similar rocks at Lake Titacaca, Bolivia (Newell, Chronic, and Roberts, 1953), near the equator. The occurrence of the marine pelecypod, *Eurydesma*, in South West Africa and in the Sierra de la Ventana, Argentina, provides evidence for the long cold seaway extending northeastward from the paleo-Pacific. The glaciation lingered longest in Australia and perhaps Antarctica, presumably in part because of their proximity to the pole. Centers at this time contributed glacial debris to the Perth, Canning, and Fitzroy basins, and to scattered localities in central and eastern Australia.

The distribution of land and sea at the beginning of the Paleozoic is even less clear. Note that the reconstruction of Pangaea in figure 1 places parts of Europe and North America next to Africa at the Paleozoic and in the vicinity of the south rotational pole (point A on fig. 5). It is therefore possible that the late Precambrian ice age, as recorded both in North Africa (Furon, 1963) and in strata around the North Atlantic at present, resulted in part from proximity to that pole. This interpretation leads to the startling speculation that areas as far north now as Britain and Norway were near the south rotational pole only 600 million or so years ago! The same scheme of glide of Pangaea with regard to the Earth's rotational axis suggests that Precambrian tillites in Australia

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Fig. 4. Southern Gondwanaland during the early Permian. Symbols as in figures 1 and 2, and Bo = Bonaparte Basin; Ca = Carnarvon Basin; Ph = Perth Basin. Sixty degree paleomagnetic latitude in Australia from Irving (1964).

(Brown and others, 1968, p. 27) were laid down by glaciers near the north rotational pole. This line of argument leads further to the thought that late Precambrian glaciers over the world were not necessarily synchronous, as suggested by Harland (1964a, b), but moved about with respect to movements of Pangaea in a manner similar to the migration of glacial centers in the late Paleozoic. Methods of correlating from place to place in the late Precambrian are still too coarse to allow us to resolve the short time-differences implied by such migrations.

EARLY AND MIDDLE PALEOZOIC GLACIATION

In northern Africa, excellent evidence of widespread late Ordovician glaciation has recently been described in the Sahara over an immense area extending from Morocco to the Niger River and eastward to the Sudan border (Beuf and others, 1966; Arbey, 1968; Fairbridge, 1969). Striated floors lie beneath tillite (see photographs in Beuf and others, 1966), and Silurian coldwater faunas in overlying strata were deposited in an epeirogenic post-glacial sea (Berry and Boucot, 1967). Around the southwestern rim of the Sahara the sedimentary section lies unconformably upon metamorphosed Precambrian "basement" and extends upward through Infracambrian sandstone and stromatolitic limestone into fossiliferous lower Cambrian beds (Furon, 1963, p. 8). Locally coarse and muddy conglomerates at the base are interpreted as tillites, and within the Cambrian section, units such as the Jbeliat Tillite in southern Mauretania and Mali may have been deposited from the west by floating glacial ice (Furon, 1963, p. 127). Although these possible evidences of pre-Ordovician glaciation have not been studied nor described convincingly, further investigations may establish widespread glaciations here during these times.

In equatorial Africa, lower and middle Paleozoic strata are apparently missing from a vast region although Precambrian and Infracambrian as well as post-Paleozoic beds are widespread. The lower Paleozoic, including marine Devonian, extends no farther toward the south and southeast at present than the Gulf of Guinea. Karroo sediments (upper Paleozoic) crop out in a few places, especially in the eastern Congo Republic and southern Tanzania (Frakes and Crowell, in press) and have been penetrated in boreholes in the Congo Basin (Hübner, 1966). Inasmuch as early and middle Paleozoic records of any kind in this large region are absent or unrecognized, it is unknown whether glaciation took place here at those times.

In eastern South America, glacial sedimentation has been reported from the Lavras "Series" of Cambrian(?) age in northern Minas Gerais state and from the Silurian Iapó Formation in Paraná state (Oliveira, 1956; Grabert, 1965). These units are deformed and locally metamorphosed and lie unconformably beneath nearly horizontal sediments of the Devonian and Gondwana sequences. The Iapó consists of bedded pebbly mudstone, crowded with stones of many types, but is considered by Salamuni and Bigarella (1967) to have originated as mudflows not necessarily associated with glaciation, although striated clasts are present (Maack, 1957, 1964). Pre-Devonian strata in Brazil, still largely unstudied in detail, need careful scrutiny for evidence to document or refute glacial events. The Devonian, including the widespread Furnas Sandstone of the Paraná basin, contains rare striated and faceted cobbles interpreted as derived from floating ice by Salamuni and Bigarella (1967, p. 21).

During the Paleozoic, therefore, when Africa and South America were joined, two definite periods of glaciation are established: in the late Ordovician one was centered in the Saharan region, and from the early Carboniferous to the middle Permian other centers moved southeasterly across southern Africa and into then-adjacent Antarctica. In addition, future studies may show that the pre-Ordovician diamictites in northwesternmost Africa, and Silurian and Devonian diamictites in eastern Brazil, were laid down near glacial centers. The path of these glacial centers, both established and conjectured, across Gondwanaland through time fits the paleomagnetic data (Creer, 1967; McElhinny and others, 1968), which suggest that Africa-South America moved across the south rotational pole during the Paleozoic (fig. 5). Perhaps we can conclude tentatively that North Africa formed the leading edge of the

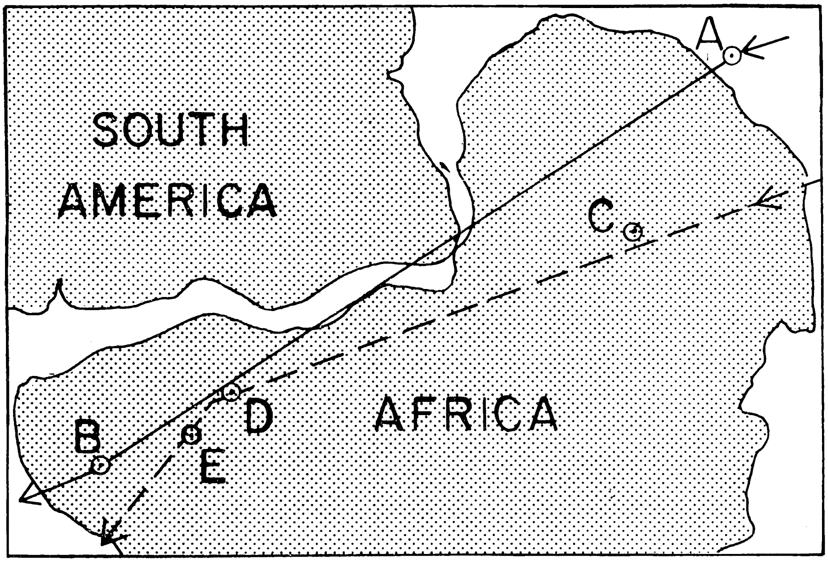

Fig. 5. Sketch map of joined Africa and South America showing paths of the magnetic dipole from the end of the Precambrian to the early Carboniferous after McElhinny and others (1968) (with a solid line) and after Creer (1967) (with a broken line). Pole positions determined from paleomagnetic studies: (A) McElhinny and others (1968), no. B1, Hook intrusives Zambia, Precambrian-Cambrian (600 m.y.); (B) McElhinny and others (1968), no. B4, Dwyka varves, central Africa, Lower Carboniferous; (C) Creer (1967), no. 5(i), Red beds, Bolivia, Devonian (350-400 m.y.); (D) Creer (1967), no. 6(ii), Dwyka varved clays, Rhodesia, Lower(?) Carboniferous (280-315 m.y.); (E) Creer (1967), no. 6(i), Taiguati Formation, Bolivia, Lower(?) Carboniferous (270-320 m.y.).

grouped Gondwana continents and was glaciated first, beginning at the end of the Precambrian, and that the continental glaciation in Africa-South America was intermittent or nearly continuous during the whole of the Paleozoic. L. C. King (1962, p. 33), as well as Ahmad (1966), has also stressed that the Late Paleozoic centers moved sequentially and that the "climate was cooling over Australia towards glaciation in the late Carboniferous while it steadily warmed up in South America because the glaciation was past". As we do in part here, King explained these relations by a movement of Gondwanaland across the south rotational pole, but it now seems possible that these continental movements took place throughout most of the Paleozoic and were associated with earlier glaciations.

GONDWANALAND DURING THE PALEOZOIC

These patterns of glaciation raise several questions: Did the polar position of Gondwanaland primarily cause glaciation? Did the movement of the giant continent in and out of high latitudes bring about the beginning and ending of this long period of intermittent glaciation? What effect did these movements have on oceanic circulation, which in turn influenced climate and the growth of glacial centers? What was the effect of land elevation and the position of highlands? In examining the record at the end of the Paleozoic first, paleomagnetic data show that Australia, then joined to Antarctica, remained in a near-polar position during the Permian and early Mesozoic (Irving, 1964). The margin of the Gondwana supercontinent lay near the south rotational pole until well into the Mesozoic and long after the end of the Paleozoic glaciation. The glaciation was therefore not "turned off" by the simple movement of the supercontinent away from the pole. According to our reconstruction (fig. 1), Gondwanaland stretched out northward at the end of the Paleozoic without a break or a seaway across it, for a distance of about 105° of latitude. North Africa reached to 10° or 15° north latitude. The immense continent faced onto a broad paleo-Pacific ocean from Queensland, southerly along the margins of the Tasman geosyncline, around Antarctica, and northerly along the coast of South America. The paleo-equator crossed both northern South America and then-attached Africa.

The position of Gondwanaland with respect to the northern continents (Laurasia) during the Paleozoic has recently been examined by Creer (1968b). Paleomagnetic data from North America, Eurasia, and Africa suggest a grouping of these three continents as shown here in figure 1. The Tethys Sea was a broad oceanic wedge between Africa and Eurasia, narrowing and probably ending at the west; in Morocco and the Pyrenees the Permian is represented by terrestrial redbeds (for example, Kummel, 1961, p. 156; Gignoux, 1955, p. 234). North America lays close to both Europe and Africa-South America during the Paleozoic, and Creer obtains a satisfactory fit of paleomagnetic data with the Laurasion continents moving along with the Gondwana continents rather than independently. To him these data suggest that nearly all of the Earth's continental crust moved together as a unit with respect to the rotational axis. At the end of the Paleozoic, Laurasia extended to within about 15° of the north pole which lay well out within a giant paleo-Pacific (under this reconstruction, essentially the only ocean on Earth and constituting about two thirds of the globe's surface).

This global reconstruction, based largely on reinterpretation of paleomagnetic data (Creer, 1968a, b), differs from studies by Irving (1964) in which the Permian equator in North America is drawn from central California to northern Newfoundland and in Eurasia from Brittany to Syria. To fit the latter positions of the paleo-equator with Gondwanaland as depicted in figure 1 requires that Laurasia lay within the Pacific during the Permian and has moved to its location north of Gondwanaland since then—gross movements for which there is little independent evidence. On the other hand, geologic comparisons, as outlined below, suggest that Laurasia lay north of Gondwanaland during the Permian. Inasmuch as most students of paleomagnetism arrange the Gondwanaland fragments as shown here (Irving, 1964; Creer, 1968a, b; McElhinny and others, 1968; Irving and Robertson, 1968), and the reconstruction is compatible with independent geological data, we have elected to build around this interpretation. Red beds, deserts, and evaporites fall into broad belts near 30° latitude, quite compatible with their distribution today. The paleo-equator as shown by Irving (1964, p. 208) may therefore be as much as 30° in error.

Some geological comparisons support the reconstruction that Gondwanaland was closely related to Laurasia during the Paleozoic. Maxwell (1969), for example, emphasizes that the Mediterranean region developed in the Late Triassic and the severe Alpine deformations followed much later. Older rock units in contrast are similar between the two regions. Boucot, Berry, and Johnson (1968) conclude upon examining the distribution of Lower Paleozoic facies that Eurasia and Africa have formed a single block since the Cambrian. Nevertheless, along the North African margin of Gondwanaland, Cambrian, Ordovician, and lower Silurian non-marine sandstones fringe the African craton and grade northward into marine sand and shale (Klemme, 1958). Such relations are preserved in western Algeria and nearby Morocco and in the northern part of the Arabian shield, but such strata are not known in the vast region in between. Upper Silurian, Devonian, and Lower Carboniferous strata, including thick carbonates and reefs, show similar distribution, although the zone of no known exposures is narrower and extends from mid-Egypt to the Algerian-Libyan border. Marine Carboniferous and Permian strata, in contrast, are found patchily distributed all the way across the region. They are interspersed with thick volcanic sequences, ultrabasics, and local evaporites, especially through the central Alps and in Morocco. Hercynian (Variscan) deformations in western Europe, as well as Caledonian before, beyond doubt contributed variety to the Paleozoic geography (Brinkmann, 1960; Aubouin, 1965), but there is little to suggest at present that these orogenic belts represent the closing of wide oceans.

In the Permian, continental basins formed in the western Mediterranean and in central Europe, but to the east the marine Alpine geosyncline expanded (Brinkman, 1960, p. 67).

North America probably fitted against both Europe and Africa during the Paleozoic, and at the 500 fathom isobath the fit is impressive (Bullard, Everett, and Smith, 1965). Caledonian geosynclinal trends, including a wide variety of rock types and tectonic styles and historical sequences, match Appalachian trends in North America (Kay, 1967; Dewey and Kay, 1968). Similarities of basement rocks in Florida and South Carolina with those in northwestern Africa suggest to J. T. Wilson (1968, p. 314) that the two continents may have been attached. An intermittent seaway probably followed the trend of the Caledonian-Appalachian geosyncline, but in the later Paleozoic it became infilled and deformed over broad stretches (P. B. King, 1959, p. 64), so that throughgoing oceanic currents were blocked. Deep water with oceanic crust may have existed at times until the Devonian (Rodgers, 1968), but as yet paleogeographic maps along the mobile belt, and incorporating the large amount of new information on the region (for example, Zen and others, 1968), have not been drawn at intervals through the Paleozoic. Nevertheless, the southeastern margin of the Appalachian geosyncline may well have been attached to Africa and Europe and provided the source area ("Appalachia") for much of the sediment within it (P. B. King, 1959, p. 60). The structural complexities, including the juxtaposition of sedimentary facies within the Appalachian belt may have resulted from the closing of an ancient ocean (Wilson, 1968, p. 314). Research to reveal the continuity and width and history of opening and closing of the Caledonian-Appalachian Seaway during the Paleozoic is urgently needed. Our understanding of factors influencing climates during the Paleozoic is incomplete without it.

What Earth events during the Permian might have brought on the ending of glaciation? Did the single giant continent represented by the combined Laurasia and Gondwanaland (Pangaea) begin to fragment and change the ocean-air circulation? For example, the divergence of paleomagnetic poles suggests that Europe began to move relatively away from North America in the Permian (Creer, 1968a, p. 42; Irving and Robertson, 1968, p. 168), marking the birth of the North Atlantic Ocean. Under these circumstances oceanic currents would be free to flow nearly latitudinally to the south of North America and into the Pacific if the Caribbean region were open (fig. 1). Unfortunately, however, the Late Paleozoic history of the Caribbean region and Central America is still largely unknown (for example, Lloyd, 1963, p. 88), so that this suggestion is difficult to evaluate. In the Permian, Africa was still joined to South America (for example, L. C. King, 1962), and the South Atlantic did not open until the mid-Mesozoic. In fact, the lack of known Permian and Triassic sediments within the deep ocean and the interpretation of magnetic anomalies on the sea floor suggest a somewhat later origin for both the North and South Atlantic (Le Pichon, 1968, p. 3689). The ending of the glaciation in the Permian could be related therefore to some other circumstance such as a time of high-standing lands in critical locations. Speculations are therefore not very fruitful until satisfactory paleogeographic interpretations of the Caribbean and Atlantic regions (both north and south) and the relative elevation and location of highlands in the Northern Hemisphere are forthcoming.

LATE CENOZOIC GLACIATION

By early Cenozoic time, the Atlantic Ocean had widened to more than half of its present width, and North America was well embarked on its west-northwesterly drift away from Eurasia (fig. 6). The Arctic

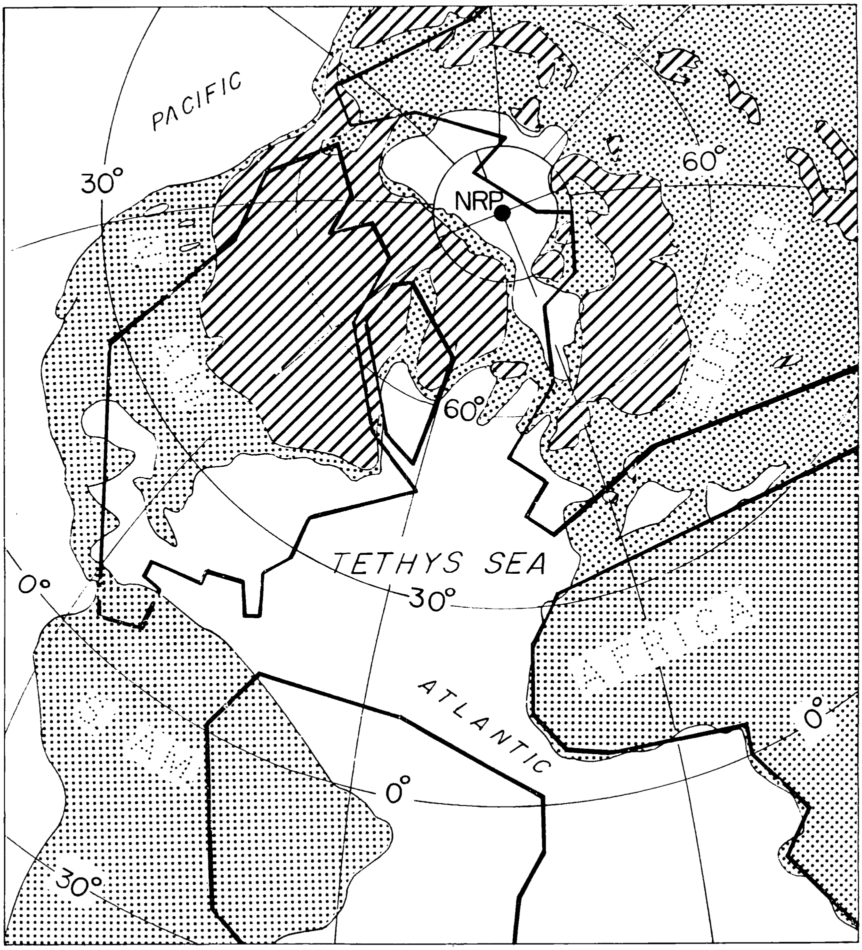

Fig. 6. Late Cenozoic distribution of glaciers in Northern Hemisphere. Extent of last glacial maximum shown by shading, after Flint (1957). Provisional position of continents in Paleocene shown by heavy lines, modified after Le Pichon (1968). Africa considered as relatively immobile. NRP = North rotational pole.

Ocean widened as part of the Atlantic during these movements and in time encompassed the north rotational pole which previously lay in the North Pacific. Complex tectonic events modified the configuration of the Arctic Ocean throughout the Cenozoic, and Bering Strait was at times open and at times closed (Hopkins, 1967) but probably never deep and continuous enough to allow major oceanic currents to sweep between the Atlantic and the Pacific. Opinion is still divergent on the history of freezing and thawing of Arctic seas (Beschel, 1968). At times, however, the Arctic Ocean was frozen over, vastly increasing the area of the white polar capping.

As North America and Eurasia diverged during the late Mesozoic and early Cenozoic, oceanic circulation freely moved latitudinally in low latitudes. The Tethys geosyncline stretched as a broad seaway along southern Eurasia and reached from the Pacific and Indian Oceans westward to the Atlantic. Waters from the Atlantic in turn had free access to the Pacific between North and South America. The Isthmus of Panama developed as a land barrier to circulation near the end of the Pliocene (Woodring, 1966) and was followed by continental glaciation, as pointed out by Stokes (1957). The growth of the isthmus perhaps strengthened the Gulf Stream and North Atlantic Current sharply so that vastly larger amounts of warm and relatively more saline tropical water were carried farther north into the Atlantic. Evaporation and precipitation and ice accumulation in Geenland and Scandinavia were plausibly enhanced appreciably as a consequence. Since warm seas evaporate more readily than cold, and, in turn, the volume of moisture contained in a column of warm air is greater, there is a proportionately greater source for snow if winter temperatures are such that precipitation falls in this form. According to present information, however, the closing of the Panama gap took place as much as 2 m.y. before the onset of glaciation in North America and Europe (West, 1968, p. 181), so that either the time-lag of the effect is very long, or other factors tipped the balance after the stage was set. Geographic factors, such as elevation of highlands and opening and closing of the polar sea come to mind (Ewing and Donn, 1956, 1958; Donn and Ewing, 1966, 1968). There is but little evidence based on middle North America as a sample that the Quaternary was a time of unusual tectonics (P. B. King, 1965).

During the early northward movements of North America and Europe, the leading portions of Africa and South America reached and crossed the equator into the Northern Hemisphere. Paleomagnetic data indicate that the early Mesozoic equator in Africa passed from near its present position on the west coast through central Ethiopia on the east (Irving, 1964; Creer, 1967; McElhinny and others, 1968). Also, it seems likely that the Tethys geosyncline extended southwestward from the Mediterranean region in the mid-Mesozoic. Perhaps it reached into the Caribbean and Gulf of Mexico regions where thick accumulations of Mesozoic carbonates attest to the existence of large and irregular basins. However, in the mid-Cenozoic, especially along the Alpine-Himalayan belt, the Tethys strata were severely deformed, and the through-going latitudinal seaway closed. Oceanic circulation on the whole was thus forced from zonal or latitudinal flow to a meridional pattern, first by the restriction and closing of the Tethys seas, and then near the end of the Pliocene, by the closing of the Panama gap. Profound effects on heat distribution by the oceans might be expected so that relatively local geographic changes could bring on glaciation.

THE GEOGRAPHY AND METEOROLOGY OF ICE AGES

What similarities in the arrangement of land and sea unfold upon comparing the Paleozoic and Cenozoic ice ages? And how might these similarities bring about glaciation? In both cases, continental land masses occupied high latitudes to provide a seat for the ice. Wide unfrozen oceans reached poleward and polar seas, intermittently frozen over, extended irregularly from them. Continents were grouped so that they stretched into tropical waters and even well beyond. Such a pattern is reasonably well established in the Cenozoic ice age, but the picture at the end of the Paleozoic ice age is much less certain, and we are in the dark concerning continental and oceanic arrangements at the beginning of Paleozoic glaciation and in Precambrian ice ages. Nevertheless the spread of ice seems to coincide with times when oceanic currents were forced far north and south through blocking by continents. The arrangement of continental masses deflected vigorous zonal circulation in low latitudes and carried warm waters into polar regions; the fundamental distribution of heat over the Earth in the ocean-air system was affected. This suggested mechanism implies that temperatures and climates upon the Earth are always near a balance that can be tipped toward or away from glaciation with changes in continental configurations and in air-ocean circulation patterns and changes in local geography and land elevation. In addition, "feedback" processes may operate so that if glaciation gets started, world-wide coolness ensues, or in contrast, if zonal flow in low latitudes is marked, world-wide warmness results. These processes are enhanced through effects on the Earth's mean albedo; for example, with broad expanses of whiteness due to snow and ice cover, the mean temperature will be lowered.

Ice caps on Antarctica and Greenland at present suggest that we are within an ice age, although probably an interglacial interval. We can perhaps learn something concerning the causes of glaciation by examining the influence of patterns of land and sea today upon world climate. Although the northern hemisphere is largely continental, the southern is distinctly more oceanic and the ocean and air can move zonally with little to restrict flow, especially between 50° and 70° south latitude. Unfortunately for purposes of sorting out influences, the summer solar energy impinging on the southern hemisphere is about 6 percent higher than in the north owing to the inclination of the Earth and the eccentricity of its orbit (Rasool and Prabhakara, 1966), so that differences between weather and current patterns in the two hemispheres are not wholly due to differences in land-sea distribution. However, recent satellite measurements of the Earth's radiative budget, which compare the energy input from the sun with the output from the top of the atmosphere (Vonder Haar and Suomi, 1969), indicate that on a mean annual basis there is no significant difference between the radiation budgets of the northern and southern hemispheres. Inasmuch as the surface features of the two hemispheres are very different, this emphasizes that processes within the ocean-air system operate to bring about a nearly constant mean radiative balance between the two hemispheres, and that cloudiness must be especially significant in determining the energy exchange between Earth and space. In addition, these studies show that there are distinctive geographic differences in the distribution of mean-annual outgoing radiation and mean-annual albedo. The tropical region between 30° N and 30° S is a major source of energy for the Earth system, but there is considerable variation from place to place within this band. Minima of net radiation lie over deserts and over a region of the eastern Pacific known to have special weather activity. Areas poleward from 30° latitude display zonal albedo and infrared patterns owing to the west and east migration of weather systems in these latitudes. In these regions, however, meridional patterns that may mark routes of strong meridional exchange of energy are also discernible. Surface reflection as influenced by snow and ice significantly affects the albedo measurements over the Northern Hemisphere. The two polar regions are different, and over the year Antarctica is a greater energy sink. For the time being we can only conclude that continental arrangements show up markedly in maps of albedo and heat radiation from the Earth, and that ocean-air processes operate to bring the total Earth system into radiative balance. We cannot tell from these data, in view of the complexity of the system, whether the mean Earth albedo might be more or less with different continental arrangements. If it were either, however, we might expect a significant change in the mean temperature of the Earth, but geologists must wait upon meteorologists to elucidate these complex interactions.

Theories of climatic change and factors that might bring on ice ages have been reviewed in detail recently (Mitchell, 1965, 1968a; UNESCO, 1963), so that only brief comments concerning the effects of the distribution of land and sea are appropriate here. Much work is still needed to explain fully the onset and dying out of ice ages and to sort out the casual factors championed by all the competing theories (Mitchell, 1968b). Among the factors, ocean currents on the Earth today, guided by the arrangement of continental barriers, carry warm and saline waters of tropical and subtropical origin to high latitudes. The Gulf Stream in particular gathers waters that have been funneled into the Caribbean and Gulf of Mexico from both the North and South Equatorial Currents by the orientation of the northeastern coast of South America. It then flows strongly as the North Atlantic Current and its distributaries almost to the Arctic Ocean, to provide warm water in high latitudes as an abundant source for evaporation. In addition, sea ice readily forms only if there is shallow and sharp density stratification in the ocean, so that convective mixing is limited to a thin layer of less-dense water (cold but of low salinity) on top of a denser layer (warm but of high salinity). Only the thin top layer needs cooling to freezing, and sea ice thus forms quickly. Weyl (1968) has cited these phenomena as bringing about freezing of the Arctic Ocean in response to flux of atmospheric water vapor westward across the Isthmus of Panama. According to him, with the isthmus closed, salinity in the Caribbean region is raised as moisture is carried to the Pacific. The source area for the Gulf Stream System would therefore become both warm and saline. So two interrelated factors—the availability of warm water in high latitudes and a density distribution in near surface layers to foster quick freezing—need appraisal when currents reach poleward.

The onset and continuation of glaciation is assisted when large areas of sea ice lower the regional temperature as the result of their high albedo. Restricted polar seas, partly landlocked and thus protected from deep surface mixing by great storm waves and ocean currents, are suitable sites for sea ice to form extensively. Note that during both the late Paleozoic and late Cenozoic ice ages, restricted polar seas existed, so that their effect also needs evaluation. Before the closing of the Panama gap near the end of the Pliocene, if the factors discussed above are correctly appraised, the Gulf Stream was weaker so that waters reaching the Greenland Sea were probably less saline and cooler. A thick relatively homogeneous surface layer resulted, and sea ice was not formed as readily and as widely as today. Perhaps a chain of events, bringing about a thin layer of less saline water on top of denser saline water in turn caused or aided the freezing of the Arctic Ocean, a regional drop in temperature, the generation of cold air masses, cloudiness near the boundary between sea ice and much warmer open water, and precipitation as snow on highlands in nearby Greeland and Scandinavia. If this snow failed to melt entirely in these cloudy regions before the next winter, in time glaciers would be formed.

In addition to providing seats for glaciers, broad land expanses in high latitudes, as well as frozen seas, abet glaciation in several ways. They furnish locales for the generation of very cold air masses through outward radiation of heat to space on clear nights. Such cold masses are responsible for great contrast in air properties at the polar front when the air masses flow outward from their sources. The contrast in turn causes storminess and high precipitation, largely in the form of snow. Expanses such as those in the subarctic of Canada and Siberia today, for example, generate immense volumes of very cold air which occasionally burst southward. In North America, where such moving masses are not blocked by mountain barriers as they are in Asia ,they travel southward even beyond 30° latitude. South-swinging storm tracks carry belts of clouds nearer the equator to a region where the sun's rays impinge more vertically and therefore may raise the mean albedo. High-altitude land areas abet large meridional swings in the storm tracks, that is, favor highindex over low-index weather situations. During the swings poleward, large volumes of moisture in damp subtropical air are carried by the polar front to high latitudes where they may precipitate as snow. Such patterns also may add to the summer cloudiness and therefore aid in preserving snow and ice cover until the next winter. In the southern hemisphere today, where the Earth is ringed by the broad Southern Ocean, cold-air masses breaking from Antarctica are instead quickly modified by the sea and arrive at the southern polar front with largely maritime properties. In summary, these considerations indicate that continentality in high latitudes must be appraised in a theory of glaciation. The distribution of land significantly affects the generation of air masses and the vigor of the polar front. The availability of moisture as a cause of glaciation has been discussed in greater detail by Simpson (1940), Ewing and Donn (1956, 1958), and Donn and Ewing (1966, 1968).

Several other geological and geographic factors need further study as to their influence on glaciation. Broad highlands near at hand, as in Scandinavia and the mountains rimming Greenland and Antarctica, make ideal sites for the slow and continued accrual of snow which in time turns to ice. Nevertheless, continental glaciers during the Pleistocene occupied large areas of relatively low elevation in both Canada and Europe (Brooks, 1949; Flint, 1957). Greenland and Antarctica resemble ice-filled saucers with large parts below thick ice near sea level. The highlands in Greeland, Scandinavia, and Antarctica, located where maritime air masses frequently reach them, probably provided the first ice centers from which larger ice sheets later grew. As emphasized by Flint (1957, p. 499) we can safely conclude that glaciers form most readily where moist air rises upon highlands, with altitudes and latitudes appropriate for precipitation as snow. The variability of the geography of the Earth today, with variation in associated air flow, indicates that there is a wide range of appropriate altitudes, latitudes, and air-flow patterns that balance and interplay to cause glacial growth. Similar interplay probably took place in the past on a regional scale, and ice sheets grew whenever latitude, altitude, and the availability of moist air combined appropriately. Ice sheets occur at present in Antarctica, despite dryness, in view of its extremely high latitude and thermal isolation. At the other end of the spectrum, alpine glaciers occur in New Guinea at high elevations but near the equator.

In looking at the Earth as a whole, do ice ages correspond with world-wide times of uplift (Flint, 1957, p. 503), which in turn might be credited with causing glaciation? Western North America, perhaps in view of its situation on top of the East Pacific Rise, now stands unusually high, and so does central Asia. Immense regions in South America, Africa, Siberia, Canada, Australia, and the eastern United States, on the other hand, lie at relatively low elevations. In the past, especially during the Cambro-Ordovician and Cretaceous, large expanses of continents were flooded by epeiric seas. Whether these variations in emergence and flooding are significantly variable through time and closely related to tectonic processes, as, for example, the collision of continental plates to form the Alpine-Himalayan chain, is not yet established. Instead, times of flooding may correspond largely with times of no glaciation when sea level rises to a maximum. The average elevation of continents as the result of tectonic causes has no doubt fluctuated somewhat in the past but not necessarily between large extremes corresponding to times of glaciation. In addition, the system will be influenced by alternations between flooding and emergence at low latitudes which affect the albedo: for example, expanses of epeiric seas will lower the mean albedo and raise the temperature.

Evidence from land floras and from shallow-water marine invertebrates provides information on climatic changes throughout the Tertiary (Durham, 1950; Axelrod, 1957; Bandy and Arnal, 1960; Axelrod and Bailey, 1969). Cooling in North America began in the middle Oligocene; in Eurasia there were irregular climatic changes in the Oligocene and then cooling in the Miocene; and in Australia and New Zealand, warming in the Eocene that culminated in the Miocene followed by cooling. A part of these changes is probably due to latitudinal continental drift so that continents have moved with respect to climatic belts (Hamilton, 1968). North America, for example, has travelled relatively northward through about 15° of latitude, and California west of the San Andreas fault an additional 4° or 5°. Australia moved northward under the impetus of sea-floor spreading along the Southeast Indian Rise. Eurasia has moved a few degrees northward. But changes in air-ocean circulation, as basically controlled by land-sea distribution, are probably more significant in affecting climate. The hot deserts originated during the Pleistocene along belts where tropics flourished previously (Gill, 1961) and result largely from cold ocean currents flowing equatorward on the west sides of continents, and from the effect on air of upwelling of cold deep coastal waters. The maritime air temperatures here are mainly controlled by the upwelled-water temperatures which in turn are controlled by the deep flow of cold waters from higher latitudes. As cold water became more abundant and was carried to shallower depths at mid latitudes, it affected surface sea temperatures through upwelling. With stronger winds and stronger subsidence aloft as air moved around the eastern ends of anticyclones, very dry air was available to make deserts. Thus, it can be argued again that changes in ocean-air circulation patterns and ensuing climates can result from small changes in land-sea distribution and elevation. These, in turn, affect the albedo and the whole system. Hot deserts, for example, will have a higher albedo than verdant plains.

Glaciation existed in Iceland about 3 m.y. ago (McDougall and Wensink, 1966), in the Sierra Nevada of California about 2.7 m.y. ago (Curry, 1966), in Southern Argentina more than two m.y. ago (Mercer, 1969), and in Antarctica within the Tertiary (at least by the late Miocene or Pliocene) (Armstrong, Hamilton, and Denton, 1968; Rutford, Craddock, and Bastien, 1968). Although these localities include mountains as well as lowlands, the onset of the ice age was not controlled by a synchronous and sudden world-wide drop in temperature, but by a more gradual event that affected high latitudes and high altitudes first. A drop in world temperature is interrelated with an association of a large number of factors, including the growth of glaciers themselves.

The Pleistocene glaciation, and most certainly the other glaciations, were characterized by waxings and wanings of the ice which were irregularly cyclic or episodic—the glacial stages. Warm pluvial stages were interspersed with colder epochs. These fluctuations probably resulted from auto-variations induced in the air-ocean system and have been discussed by Ewing and Donn (1956, 1958) and Donn and Ewing (1966). As glacial centers grew, the centers themselves tended to displace storm belts farther and farther equatorward until the latitudinal perturbations became unstable. Accretion of the ice cap took place at the equatorward margin beneath the storm track and less and less accrued on the poleward side, away from the track. If the meridional perturbations were very large, the track moved equatorward into a latitude where precipitation fell predominantly as rain instead of snow, so that ice dissipated. Long before this, however, the system probably became unstable, and more and more storms followed paths much more poleward, so that the cycle began all over again. Ice caps induced weather situations with extreme meridional swinging of storm tracks, which became unstable, and normal flow with a marked zonal pattern took over.

Other factors in such a complex system probably displayed a cyclicity as well. For example, as glaciers grew, sea level was proportionately lowered, salinities increased, and sea temperatures and evaporation rates reduced. Maritime air was therefore colder and held less moisture so that precipitation was reduced, and the glaciers waned. At the heart of the Ewing and Donn (1956, 1958; Donn and Ewing, 1966, 1968) theory of glaciation, which is particularly applicable to the late Cenozoic and its stages, is an open polar sea to provide abundant moisture to nearby sites. The initial accrual of ice sheets is followed by freezing of the sea, lowering of sea level, and attendant effects that all operate to bring on and perpetuate the ice stage. When the polar sea is frozen, however, the source of evaporation is closed off so that ice sheets dwindle and the episode of glaciation terminates. Other effects probably contributed to the cyclicity of stages. With increased ice and snow cover there was increased albedo resulting in reduced world temperatures and waxing glaciation. As glaciers grew to oversize they perhaps spread out suddenly as the weight of ice at their centers exceeded the shearing strength of ice at the base. A. T. Wilson (1964, 1966; see also Weertman, 1964; 1966) visualizes this process as important in contributing to sudden dissolution of ice caps with attendant broadening of shelf ice, increase of albedo, and resulting effects on world weather. In summary, although it is inappropriate to discuss the cause of stages here in detail, auto-variations in the air-ocean system are no doubt of prime importance in causing them. They will probably continue in their irregular cyclicity until the land-sea arrangement changes significantly.

SUMMARY AND APPRAISAL

The Phanerozoic glacial history of the Earth, although not yet reconstructed in detail, shows that ice caps probably waxed and waned from time to time in Gondwanaland all through the Paleozoic and culminated near the end of the Carboniferous. Late in the Tertiary, glaciers grew again, and we now are within an ice age characterized by cycles of glacial advances and retreats. On the whole, however, glaciation on the Earth has not been notably cyclic on a long-time scale; it did not sweep the Earth suddenly at the end of the Precambrian, at the transition from the Carboniferous to the Permian, and at the end of the Cenozoic. During the Paleozoic, for example, conditions apparently permitted continental glaciation intermittently for over 400 m.y., although the record for much of the Silurian and Devonian at many places is missing. This period was followed by about 200 m.y. with no record of widespread ice sheets. The late Cenozoic episode followed this non-glacial interval in turn and grew slowly from a beginning several million years ago. Ice ages upon the Earth are therefore relatively common, and the climate of the Earth is near balance so that it is easily tipped toward or away from glaciation. It follows that extraterrestrial causes for the cold episodes are probably not necessary, and we should look to Earth events as primarily responsible for them.

Data from tectonics and paleomagnetism suggest that the supercontinent of Gondwanaland moved across the south rotational pole during the Paleozoic. In the Cambrian and Ordovician, what is now North Africa lay above the pole, and the central Sahara region was widely glaciated. South Africa arrived over the pole in the Carboniferous, when the Dwyka tillite was deposited. Eastern Antarctica had moved above the pole by the Permian and was broadly glaciated along with nearby Australia. For over 400 m.y. the ice centers apparently were grouped in suitable places near the poles such as on highlands over which flowed moist air from nearby open oceans and polar seas. During this long interval of occasional glaciation, the Gondwana supercontinent, with Laurasia probably attached, stretched out meridionally from the south rotational pole to the verge of high latitudes on the north. The termination of glaciation in the Permian seems to be associated with the birth of the North Atlantic and the fragmentation of Laurasia from Gondwanaland. Perhaps oceanic and atmospheric circulation, long forced into meridional patterns across the globe, was able to break into a more latitudinal pattern. Throughout the Mesozoic, and well into the Tertiary, when the Tethys sea dominated the subtropical geography, latitudinal air-ocean circulation prevailed.

In the mid-Cenozoic, orogenic activity along the Alpine-Himalayan zone closed the Tethys sea to through-going oceanic circulation between Africa and Eurasia. At the end of the Pliocene, the Panama Isthmus grew and blocked latitudinal currents still further and turned the flow into even more distinctly north-south patterns. Continents were clustered around the Arctic Ocean, and Antarctica was centered over the south pole, so glaciation again ensued when highlands and moisture sources were properly positioned.

These changes in land and sea distribution, as they affect the air and sea currents and the distribution of heat on the Earth, are deemed to be primarily responsible for the waxing and waning of ice ages. If continents are located near poles, in order to provide seats for ice caps, and open oceans are near at hand to yield large volumes of moisture to nearby highlands, the prime conditions for an ice age are met. Glaciation is abetted if broad expanses of land and frozen seas are spread in high latitudes so that cold air masses are easily generated. This situation yields vigorous polar fronts with marked contrast in air masses and resulting snow precipitation over appropriate areas, especially highlands. In short, if several factors interplay in the right way (fig. 7) such as arrangement of land and sea, availability of oceanic moisture sources upflow from highland sites, vigorous weather activity with high precipitation as snow and summer cloudiness, an ice age will ensue. Unfortunately, the case for this hypothesis rests on a very insecure base at present, and it will be some time before information on past continental arrangements is accurate enough to reconstruct patterns of ocean currents and air flow with confidence.

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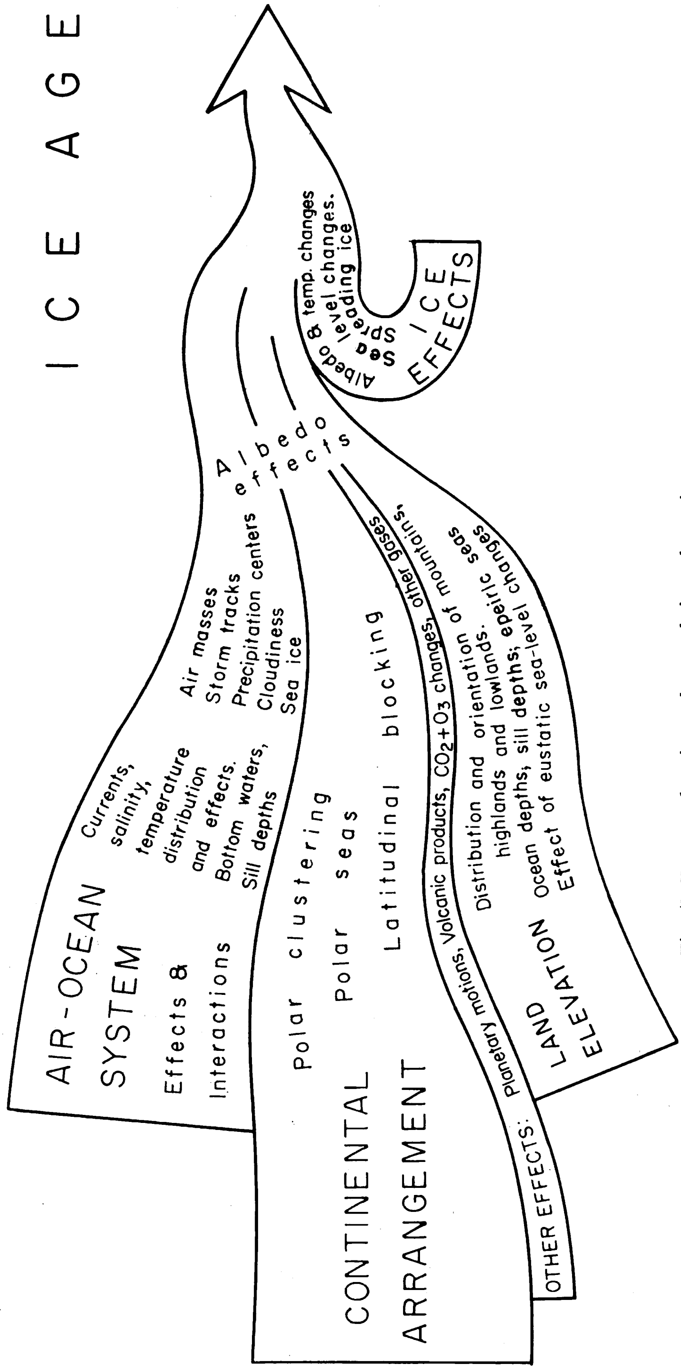

Fig. 7. Factors that interplay to bring about ice ages.

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