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Another Look at the Ice Age

William Lee Stokes

The recognition of widespread glaciation as an explanation for numerous details of topography, geology, and biological distribution ranks with the greatest achievements of scientific observation and reasoning. The underlying cause of glaciation, however, remains in doubt. Textbooks on geology and climatology usually devote a page or two to a listing of the various theories, with emphasis on the ones currently most popular, but it is significant that two of the latest textbooks on historical geology make no mention at all of the probable causes of ice ages. This may reflect a cautious attitude on the part of textbook writers and a lack of agreement among the experts, but it may also demonstrate a lag in interest or a feeling that the problem is hopeless of solution.

Certainly the subject is not diminishing in importance, for it has ramifications extending into the realms of astronomy, climatology, geology, and biology that were unappreciated a few years ago. The evidence of gradually changing climate and rise of sea level has become of increasing concern to business and military minds. Perhaps the problem of glaciation, like so many other interesting and vital subjects when they become dismembered among different departments of learning, is being avoided because no one feels justified to attempt a synthesis for fear of showing ignorance in related fields that are also involved.

At least 29 "explanations" have been advanced to account for widespread glaciations. Most of these had little chance of survival from the first, but others enjoyed some degree of success until they were rendered untenable by subsequently accumulated information. It is not the purpose of this article (*1*) to list or discuss these theories. They have been adequately treated in several widely available books (*2, 3*).

Ideal Theory

An ideal theory of glaciation should satisfy as simply as possible three chief requirements: (i) an initiating event or condition, (ii) a mechanism for cyclic repetitions or oscillations within the general period of glaciation, and (iii) a terminating condition or event. It is agreed by most students of the subject that the first requirement is met by mountain building. Elevation of large tracts of the earth is the one invariable prerequisite of the major glaciations proved by geology. Much more difficult is the problem of the great oscillations of climate, seemingly independent of topographic change, which occur within the glacial interval. The termination of glaciation apparently awaits only the lowering of land areas by erosion or crustal adjustments so that rainfall replaces snowfall as the chief form of precipitation.

Although extraordinary or even catastrophic events may have caused the ice ages and their oscillations, it is nevertheless true that the ideal theory ought to fit within the framework of uniformitarian principles. A theory that relies on unprovable, unobservable, or unpredictable conditions, when well-known or more simple ones will suffice, cannot be widely accepted. Among the more or less spectacular hypothetical events that have been invoked as possible causes of the ice ages are flooding of the ocean by submarine lava, radiations from a warm moon, rapid oscillations of the continents in and out of stratospheric elevations, and passage of the earth through great clouds of cosmic dust. Since none of these have been observed, they must remain merely hypothetical possibilities.

Less open to question but still lacking adequate scientific demonstration are such ideas as long-term variations in solar energy output, tilting of the earth's axis, wandering of the poles, variations in radioactive warming of the earth, and radical changes in distribution of continents and ocean basins.

Any theory will be greatly strengthened if quantitative data can be brought to its support. Of course, past events are difficult to analyze mathematically; but, if measurements of existing climatic phenomena can be shown to have a bearing on past glacial periods, the basis of proof will be greatly broadened.

The ideal theory must be prepared to explain simultaneous glaciations over the entire earth. Evidence is now conclusive that the glaciations on opposite sides of the Atlantic were concurrent events. Separate or alternating glaciations of the Northern and Southern hemispheres, once thought to be possible, evidently did not occur in the Quarternary period.

Last but not least, the theory must explain the greatest paradox of all—the evidence of cold and ice existing and increasing simultaneously with conditions that favored accelerated evaporation and precipitation. In other words, lowering temperatures and greater precipitation are considered to have existed side by side on a world-wide scale and over a long period in apparent defiance of sound climatological theory. Among the many quotations that could be cited reflecting the need for a more comprehensive explanation of this difficulty the following seems typical (*4*).

"In the Arequipa region [of Peru], as in many others in both hemispheres where Pleistocene conditions have been studied, this period appears to have been characterized by increased precipitation as well as lowered temperature. If, however, precipitation then was greater over certain large areas of the earth's surface than it is at present, a corollary seems to be implied that over other large areas evaporation was greater than normal to supply increased precipitation, and hence in these latter areas the climate was

Dr. Stokes is chairman of the Department of Geology at the University of Utah, Salt Lake City.

warmer than normal. This seems at first sight to be an astonishing conclusion. The reasoning may be fallacious and should not be accepted without much investigation and consideration, but we may pursue the idea a little farther. Where were these warmer areas? Were temperatures, integrated over the whole earth's surface, actually so different from those of the present as has been assumed? We might propose the hypothesis that climatic conditions were far from steady in any one area, but were subject to large shifts, and that intervals of ameliorated conditions in some regions coincided with increased severity in others. The Pleistocene, then, may have been a period of sharper contrasts of climate and of shifting climates rather than a period of greater cold."

Some Climatic Prerequisites

Glaciers cannot form without precipitation, and it is obvious that most of the precipitation must be in the form of snow. However, the mere fact that snow falls in large quantities on a given area does not automatically guarantee that glaciers will result. There must be an excess of snowfall over melting in order that ice accumulation can take place.

Two factors are involved, and their relative effects are more important than the magnitude of either. During periods of glacial advance any of the following conditions can result in ice formation: (i) total snowfall remains constant but potential melting falls off; (ii) snowfall increases and potential melting remains the same; (iii) snowfall increases and potential melting increases at a slower rate; (iv) snowfall diminishes and potential melting decreases at a faster relative rate. Similar but opposite conditions can be visualized for periods when ice is diminishing.

The annual increments resulting from any of the conditions just noted can multiply with time until ice masses of continental proportions are created. The important thing is not the magnitude of the annual contributions but their ultimate number. The initiation of a glacier may be a relatively insignificant event. A slight temperature decrease or a small increase in average precipitation, if effective at the right time, will be sufficient to start an ice age. Every glacier had its inception from a thin layer of snow that remained on the ground where none had remained the summer before. The temperature need suffer no drastic decline and the precipitation no large increase at the time this happens. The important thing is that the trend be unidirectional and remain in effect for a very long time, so that short-term gains are not wiped out by reversals of one sort or another. Some mechanism that either increases the precipitation or lowers the temperature very gradually over a period of thousands of years would seem to be required.

Glaciers are in general retreat today mainly because of a decrease in precipitation accompanied by an increase in temperature (*5*). It is thought by many that the fluctuations observed within historic time are due mainly to variations in precipitation and that glaciers could flourish in spite of present warmth if snowfall were sufficient.

If decrease in precipitation is suspected of being the most important factor in eliminating glaciers at the present time, it is possible that an increase in precipitation may have been the most important factor in producing the glacial oscillations of the past. Heavy precipitation and cold are incompatible in long-term effects, and low temperature is therefore antagonistic to glacier growth. If lowered temperature and increased precipitation are considered to have been strictly simultaneous in origin, one could not have caused the other, and outside agents or agencies must be invoked to cause both. If, however, the increased precipitation and the fall of temperature are not strictly simultaneous, then it is possible that one may have caused the other.

In my opinion, it is reasonable to imagine and possible to prove that the fall of temperature could be caused by an increase of precipitation. This requires only the assumption that there be an annual increment of snow from which ice can form. The eventual creation of large masses of ice and the dispersal of cooling effects by circulating air and water systems is an inevitable chain of events. The creation of glaciers by simultaneous increase of precipitation and fall of temperature appears to be possible only on a small local scale and seems to require intervention of extraterrestrial influences of some sort.

We are too far removed in time from the onset of major glaciation to be able to judge the actual sequence of climatic events and have made the natural assumption that the fall of temperature and increase of precipitation were simultaneous and both due to the same outside cause.

Ocean-Control Theory

Preceding sections of this article have shown the desirability, if not the necessity, of finding the cause of glacial oscillations in long-term changes in precipitation traceable to thermal variations in the ocean. Brief mention has also been made of some of the fundamental data on which such an explanation must rest and the essence of an ocean-control theory may now be stated in more precise terms. The theory depends on the unique specific heat characteristics of water and its latent heats of freezing and evaporation. As one consequence of these properties, the temperatures of bodies of water tend to be very stable and to change relatively slowly. The ocean has such tremendous volume that many thousands of years are required to cool or heat it by ordinary means. The lag in response of the ocean to thermal change allows it to remain warm while cooling influences are in operation and to remain cool while warming influences are operating. It is the thesis of this article that the thermal lag of the ocean is responsible for the oscillation of cold and warm climates during ice ages.

The ocean receives heat from the sun and, unless it is disturbed by outside influences, must remain in thermal equilibrium with solar heating. Such an equilibrium has apparently been in effect during long periods of crustal quiet that have existed in the geologic past. The equilibrium or near-equilibrium has been disturbed during several shorter intervals by changes attendant to widespread mountain building and continental uplift. The last thermal upset during the Quarternary was marked by four superposed cycles of shorter duration. Uplift of land areas allowed the initial accumulation of glacial ice, and this in turn had a cooling effect on the atmosphere and ocean which initiated a chain of events known collectively as the Quarternary Ice Age.

Cold water from glaciers enters the rivers and cools the surface layers of the ocean. Chilled water near the polar regions tends to sink and spread into the lower latitudes, so that the bottom waters are likewise chilled. Eventually conditions are right for the formation of sea ice in the north polar regions, and icebergs from this source and from the land areas exert further cooling influences. With periodic overturns, which may be expected from time to time, the whole ocean experiences a lowering of temperature (*6*). The climatological effects of this cooling are complex, but the most notable is a decrease in evaporation. This gradual and slow decline is closely followed by a decrease in precipitation over most of the earth. As a consequence of this, the glaciers gradually waste away and largely disappear; inland lakes dry up and other signs of aridity are common.

While the ocean is still cold from the glacial effects, the land receives and retains more heat and the river waters run warmer than when they are derived partly from ice. Solar heat commences to assert itself, cloud cover diminishes, water area of the ocean is expanded over shallow continental shelves, icebergs and eventually sea ice disappear, albedo (reflection) effects fall off, and the ocean commences to warm. After a lapse of time measured in thousands of years, the evaporation and precipitation again show an increase, and there is a rather sudden rebirth of the glaciers, provided that topographic conditions are still favorable to creation of snow and ice fields.

The process is repeatable and periodic as long as precipitation provides an increment of snow from which ice can form. If the topography becomes sufficiently subdued either by erosion or by isostatic adjustments, it is apparent that rain will fall where snow had fallen before, and there can be little storage of ice to bring on another cycle of cold. Ocean temperatures will now be dominated by ordinary solar heating. The terminating condition of glaciation, like its initiation, is topographic and, in the final analysis, is governed by the interaction of orogenic and epirogenic forces within the earth and degradational forces on its surface.

Glacial Cycle Analyzed

Any system showing cyclic changes, such as the stages of the Quaternary Ice Age apparently do, should exhibit at any time a predisposition of components capable of carrying it from the preceding stage into the succeeding stage. In other words, a relationship must exist that allows prediction of the succeeding effect and reconstruction of the preceding cause. If this is true, the present world climatic conditions, if properly understood, may contain the key to what has already happened and what will happen. The complete cycle need not be observed if any of it is correctly interpreted. Figure 1 shows in diagrammatic fashion the conditions in four selected stages of the glacial cycle.

An analysis of the ice age may best commence with the present, for which relatively more data are available. The present obviously lies somewhere between a minimum and a maximum of glaciation, and the glaciers appear in general to be wasting away. It may be argued that we are in a minor recessional phase and that the general trend is toward an increase of ice, but for the purposes of this discussion this makes little difference. The oceans are relatively cold, possibly about as cold as they can become. As is shown by paleotemperature studies, they are surely much colder than they were during the Cretaceous and much of the Tertiary and probably colder than they were during the period when glaciers were advancing.

Evaporation and precipitation are relatively lower than average, as is witnessed by the retreat of the glaciers, the low volume of rivers, the absence of lakes in regions of internal drainage that were filled a few thousand years ago, and the distribution of plant and animal life.

The polar ice is diminishing at a rapid rate, and it is possible to foresee the time when there will be none at all. As is the case with land ice, the present melting of the polar ice cap may represent a minor oscillation on either a waxing or waning phase of glaciation, but the weight of evidence points to the possibility of a complete disappearance.

Although the most recent trend of climate is distinctly toward warming, climatologists are not convinced that this trend will continue for long. We may have reached the minimum of glaciation during the so-called "climatic optimum" of 4500–2500 B.C., or we may see even greater warming in the centuries ahead. There is no doubt that previous interglacial stages were warmer than the present, and it may therefore be assumed that we are in the waning stage of glaciation.

During the typical interglacial phase, conditions are significantly different from the stage of glacial retreat. The ocean is still cold from the effects of the recently melted ice, but it will begin to warm later in the interval. It is not possible to know just when the warming influences commence to gain the ascendancy, but it could be while there are still many glaciers in existence, probably including the Antarctic icecap.

The total period of warming, as will be shown later, would seem to require at least 50,000 years. When ice is at a minimum, the rivers run at or near their

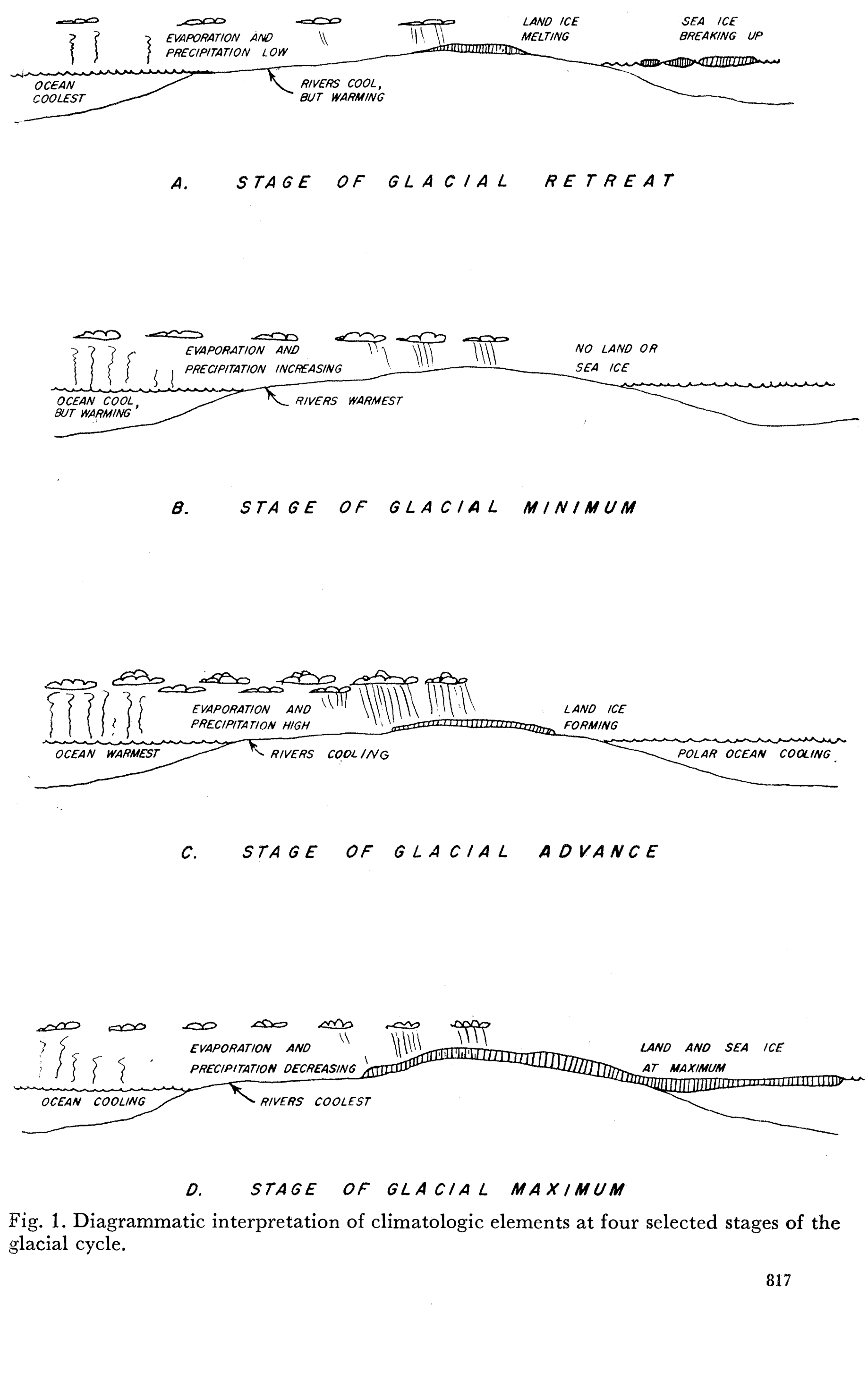

Fig. 1. Diagrammatic interpretation of climatologic elements at four selected stages of the glacial cycle.

warmest stages. Although the total volume of rivers may be rather low at first, it will increase as the cycle advances and the oceans warm. Icebergs will be few or nonexistent. The polar pack ice will have entirely disappeared, and the Arctic Basin will cease to contribute cold water to the deeper parts of the Atlantic. With the disappearance of the land and sea ice, the atmospheric zones of frontal activity that are responsible for much of the precipitation will probably weaken and shift poleward. The final removal of the ice may be a rather sudden event, for the last thin remnants may melt away or break up during a single season. All the climatic zones will shift northward, and milder climates will prevail over broad areas formerly dominated by cold.

Evaporation and consequently precipitation will be low. This will be due not only to coldness of the ocean but also to diminished windiness. Hot, dry conditions will prevail over broad continental areas. Interior lakes will be relatively low, and saline deposits will form. Loess and dune sand may accumulate over broad areas where vegetation has not established itself.

Conditions are right at this time for the gradual passage into the third stage, that of glacial advance. Preparation for the actual creation of the ice sheet may require a relatively long time. The gradual warming of the ocean may take at least 100,000 years to reach the point where the precipitation is great enough to leave a summer increment for ice formation. Once a large, permanent snow field is created, the climate may change rather rapidly, and there will be a great speeding up of the ice-forming process. The atmosphere at and over the snow and ice will be chilled and will affect the temperature of a wide belt of adjacent land. This will allow the snow cover to expand at an accelerated rate. More important will be the evaporating effects as the chilled air is carried over adjacent relatively warm oceans. The cold dry air will be capable of receiving much water vapor, which can be precipitated almost immediately. Windiness will increase, and eventually a zone of frontal storminess will be created with consequently greater precipitation on the edges of the ice sheet.

Meltwater from the snow and ice fields will commence to enter the ocean, and its most significant effects will be in the partially landlocked Polar Basin. Freezing of sea water is facilitated in many ways (*7*), but actual creation of a floating icecap must await the chilling of practically the entire body of subjacent water. The chilled surface water sinks because of greater density, but at about 37.2°F no further density differences exist, and at this crucial point sea ice will form (*7*, p. 112).

The cooling of the polar ocean may take a long time, but it will be aided by the increasing amounts of cold, fresh water from the land. By the time conditions are right for polar ice formation, the land ice may have already reached the ocean over a broad front, with icebergs adding to the cooling effects. Once initiated, the polar icecap will spread and thicken with great rapidity, and the areas of sinking water will be forced outward along its periphery into the Alantic where they are now located.

These hypothetical events are different from those postulated by Bell (*8*), who believes that the polar sea ice must form first and that this precools the ocean in preparation for the land glaciation. Brooks has analyzed the influence of a polar icecap and has shown that the final effects appear superficially to be out of all proportion to the initial causes (*2*, p. 40). The ultimate lowering of the winter temperature brought about by an initial small fall of temperature of 0.6°F will amount to about 45°F. The contribution that the present theory makes is a mechanism whereby the original small temperature decline may occur; the rest of the process follows Brooks' analysis.

As long as precipitation exceeds melting, the glaciers will continue to advance; and as long as temperatures are low enough, sea ice will continue to freeze in polar regions. Four times during the Quaternary the ice sheets advanced to very nearly the same positions in central North America and then melted away. The catastrophe of almost complete smothering of the continent by ice was prevented by reversal of the process of accretion, either by a rise of temperature or by a fall of precipitation. The direct and indirect cooling of the ocean by ice would seem sufficient to lower evaporation and precipitation enough to bring about starvation of the glaciers without intervention of any outside agent.

The self-regulating process will suffice to starve the land ice, which will disappear first, perhaps irregularly and in patches, and the sea ice later when temperatures rise to the point where sea water does not freeze. During the period of glacial retreat the climate may be very unsettled. Adjustments in ocean currents, shift of wind belts and storm tracks, and overturns in the ocean may be expected. This is the climatic situation of the present time, with the stage set for the complete disappearance of the ice for a lengthy interglacial period.

Sufficiency of Causes

Most glacial theories have failed for one of two reasons: either they did not fit the facts of distribution and chronology or the postulated agents were of insufficient strength to bring about the observed effects. The ocean-control theory must be subjected to rigorous examination on both of these points before it can be considered a worth-while idea. The correlation with observed facts has been discussed in a general way, and some consideration must now be given to the sufficiency of the postulated mechanisms to bring about an ice age. Many factors are involved, some of which can be evaluated in a general way, and others scarcely at all with present information.

The ocean is calculated to have a total volume of about 300 million cubic miles (*9*). The annual evaporation from the ocean is equal to about 80,000 cubic miles, and of this about 24,000 cubic miles falls as precipitation on the land. Of this land precipitation, about 6500 cubic miles returns to the ocean through the rivers. This is a relatively small amount, but during a century a total of 650,000 cubic miles is recirculated. Assuming for very rough calculations that the average river water is 5°C warmer than the average ocean water, a condition that might easily obtain when the ocean is coldest and warming influences are operating on land, it would require 45,000 years for the rivers to raise the temperature of the ocean by 4°C. This is roughly the time required to recirculate a volume of water equal to the total content of the oceans with present river capacity.

If the temperature difference between river and ocean water is maintained at only 1°C, then 100,000 years would be required for a 4°C change. It is well to point out that all ocean water can be classified according to the place of origin at the surface and that the properties acquired at the surface are most important in tracing the movements of the component parts of the oceans. The effects of river waters in determining salinity and temperature of areas of the ocean surface have probably not been entirely determined but are certainly important.

The cooling of river water by glaciers is only one of the effects that ice has in lowering the temperature of the earth. Ocean water is cooled by direct contact with ice or cold air and tends to sink and spread along the ocean bottoms. When the continental glaciers are discharging directly into the ocean along thousands of miles of coastline, the refrigerating effects must be tremendous. The summation of these influences would seem sufficient to cause a lowering of ocean temperatures perhaps by as much as 10°C.

When the glaciers have disappeared owing to lack of precipitation, no special mechanism is needed to restore warmth to the ocean other than normal solar heat. The rivers merely help to transmit to the ocean some of the heat that falls upon the land.

There are certainly a great number of

modifying terrestrial influences, perhaps including some totally unsuspected ones, that exercise important effects, but it appears safe to conclude that those just mentioned are operating within time periods of the right order of magnitude and along lines capable of achieving the observed effects.

Prelude to the Pleistocene

The ocean-control theory would be open to serious criticism if it made no correlation with climatic conditions before the first continental glaciation. The trend that culminated in Pleistocene ice formation may have had its inception millions of years before the actual ice age. The Cretaceous period was characterized by wide, shallow epicontinental seas, low-lying lands, and mild climates. Fossils indicate that dinosaurs lived almost to the Arctic Circle and that semitropical vegetation grew in Alaska. The mean temperatures of late Cretaceous oceans in the Gulf Coast of the United States and near England and Denmark were nearly uniform, as is shown by study of oxygen isotopes, and were about 15° to 16°C, considerably higher than they are at present (*10*).

Although ocean currents must have been quite different during the Cretaceous by comparison with the present, a difference in circulation is not needed to explain the warmer oceans and lands. During the Cretaceous there was considerable folding and faulting, but there were few really high mountains to generate ice, and the Canadian shield was relatively low. Judging by paleogeographic maps, the area of ocean exposed to the sun was perhaps 10 to 15 percent greater than it is at present, thus allowing greater heating.

During the Tertiary, a gradual cooling of the ocean and continents took place. This is shown by the study of near-shore marine organisms along the Pacific border of North America by Durham (*11*), by the study of land floras of the western United States by Chaney (*12*), and by the study of open ocean faunas of the Pacific Ocean by Emiliani (*13*). Similar cooling of Europe is indicated by the studies of Kerner as quoted by Brooks (*2*, p. 135). Without going further into details, it is evident that the time interval from the Paleocene to the Pleistocene was in general one of increasing cooling and decreasing precipitation.

The cooling was simultaneous with increasing emergence of North America and by elevation of its interior portions. The same is true of other continental masses in varying degrees. The paleogeographic maps of the late Tertiary show world-wide evidences of emergence, as compared with earlier periods.

Although the Rocky Mountain or Laramide revolution is popularly supposed to have occurred at the transition from the Cretaceous to the Tertiary, it has become increasingly evident that mountain building was continuous from place to place from the late Jurassic or early Cretaceous and that deformation continued through the early Tertiary and Quaternary. In spite of extensive folding and faulting in the early Tertiary, the western United States remained relatively low at that time. The Green River lake that occupied many thousands of square miles in the western United States during the Paleocene and Eocene is thought to have stood less than 1000 feet above sea level and to have formed in tropical or subtropical climates (*14*). The corresponding beds today are 5000 feet above sea level. The Oligocene and Miocene witnessed truly widespread movements, which brought about regional uplift of much of western North America. The Florissant lake beds of Oligocene age in Colorado, which have an abundant flora and fauna, are thought to have been deposited between 1000 and 3000 feet above sea level (*15*). These beds are at present about 9000 feet in elevation. It is thought that the uplift from the initial position to 6000 feet happened before the mid-Pliocene and the remainder since that time.

What took place in the continental shield areas during this time cannot be determined, but it may be concluded that the entire North American continent became higher and more extensive than it was at any other previous time. The continental emergence, cooling of the oceans, and decreasing precipitation on land are probably not unrelated events. Behind the climatic effects lie diastrophic causes. The creation of larger and higher continental masses could have influenced the ocean temperatures in many ways. The decrease in water area exposed to the sun's rays would have had some cooling effects; the increased radiation of heat from the elevated tracts would represent a loss of heat to the earth as a whole; and, finally, the change in temperature of the river waters could have culminated in cooling the ocean by many degrees.

The suddenness of the onset of glaciation at the beginning of the Pleistocene may be more apparent than real, for there could have been both mountain and continental glaciers of some sort immediately before this time, the effects of which have been totally erased. It may be that the numerous sharp uplifts that came about in North America and other parts of the world were sufficient to insure the formation of ice fields where none had existed before. This would entail no increase in precipitation, only a lowering of temperature through uplift. The possibility of actual increase of precipitation is suggested by the fact that the Panama land bridge connecting North and South America made an appearance, or rather reappearance, late in the Pliocene. This by itself could have had the effect of diverting increased amounts of warm water to more northerly regions or of permitting higher temperatures and evaporation in the Gulf of Mexico with consequent great precipitation in areas to the north.

The conditions at the beginning of the Pleistocene are difficult to reconstruct, and at the present no entirely satisfactory explanation for the onset of glaciation is apparent to me.

Importance of North American Glaciers

Most of the facts regarding paleotemperatures and Tertiary climatic changes that have been appealed to in this article have been derived from North America or nearby oceans. It is neither scientific nor safe to ignore the remainder of the earth, but there are good reasons to believe that the North American glaciers may have played a major, if not absolutely essential, role in the glaciation of the rest of the earth. This is because the North American glaciers constituted such a large proportion of the total volume of Pleistocene ice.

According to Antevs (*16*), there was 27,050,000 cubic kilometers of ice in the North American glaciers at the maximum of the fourth glacial period and a grand total of 36,850,000 cubic kilometers for the entire earth. Daly (*17*) gives comparable figures of 22,600,000 cubic kilometers for North America and a world total of 34,300,000 cubic kilometers. A very detailed analysis by Flint (*3*, p. 435) gives a total of 28,426,545 cubic kilometers for North America and a world total of 49,621,804 cubic kilometers.

It is evident that from one-half to two-thirds of the total world ice was in the North American glaciers. This means that the glacier-making process was most favored on this continent. According to the ocean-control theory, glaciation once begun is a self-regulating process, and it seems probable that the effects of the great North American ice sheet could have governed the glaciation of the smaller ice-covered areas of the North.

A thorough analysis of the thermodynamics of North American glaciation cannot be made at present, but interesting possibilities exist. At the north is the Polar Basin, and adjoining it to the south is the Canadian Shield, constituting a tremendous cold-producing area. When the glaciers are mature, some of this cold is conveyed southward by water of the Mississippi drainage, which in glacial times would be much larger than it is now. The Gulf of Mexico lies to the south and is a great warmth- and moisture-producing area. From it and nearby oceans springs the Gulf Stream, which carries warmth into the polar areas. It seems likely that much of the precipitation for the ice fields came from the Gulf of Mexico. The thermodynamics of this system, if fully comprehended, may explain almost by themselves glaciation of the Pleistocene.

Some Supporting Arguments

Arguments for the ocean-control theory to this point have taken the form of correlated facts and inferences that directly support it, but some attention must also be paid to possible advantages it has to offer over competing theories. A few of the most widely accepted contemporary ideas should be briefly considered.

The Milankovitch theory (*18*) is essentially astronomical in aspect and in the recent past has enjoyed the support of many scientists (*19, 20*). Without going into detail, it is assumed that the combined and coincident effects of periodic changes in the eccentricity of the earth's orbit, the longitude of the equinox, and the inclination of the earth's axis to the ecliptic will determine the amount of radiation received by each point on the earth's surface. When these effects are plotted, they are believed to show maxima and minima corresponding to the changes of climate of the Pleistocene.

The Milankovitch theory has been largely discarded, in America at least, as an adequate explanation of the glacial oscillations of the Pleistocene. Arguments against it have been summarized by Flint (*2,* pp. 403–404, 506–507) and are obviously sufficient to cast serious doubt upon its validity.

Although Milankovitch's theory may not satisfy many scientists, it is nevertheless true that astronomical theories are more popular than "terrestrial" ones. In the recent symposium on climatic change (*21*), the weight of authority and the general tone is toward a solar control mechanism.

Granting that solar variations may be the cause of the ice ages, the great weakness of dependent theories is the lack of proof that sufficient changes could or do occur. Theoretical considerations supporting the possibility of solar variations of major proportions have been put forth (*22*), but actual observations spread over a significantly long period are not at hand. For practical purposes, a theory based on solar variation may not be susceptible to the necessary observations, and the problem will be removed from all but theoretical investigation. It seems evident that we are entitled to look with some degree of skepticism on astronomical theories as they are presently constituted.

Most recent writers are agreed that more than one factor is probably necessary to bring on an ice age, and that one of these factors is elevation of the land. This, however, fails to account for the oscillations within the general glacial period; geologists have found no evidence of significant topographic changes corresponding with the minor glacial stages other than those traceable to the action of ice itself.

The most popular present theory is that of Flint, which combines the terrestrial effects of mountain building with the astronomical effects of solar variation (*2,* pp. 512–550). According to Flint, the following items of basic data must be considered. (i) During glacial ages the regional snowline was lowered roughly parallel with itself. (ii) The Pleistocene climatic changes affected and are continuing to affect the whole world at the same time, and the pluvial climates coincided with them. (iii) The climatic zones in the Northern Hemisphere maintained their relative positions throughout the Pleistocene epoch. (iv) Glaciers are genetically related to mountains and other highland areas. (v) Solar energy is observed to fluctuate at present through a small range. From these facts it is deduced, among other things, that "lowered temperature, not increased precipitation, started the glacial age." This, if true, would prove fatal to the ocean-control theory, which assumes that increased precipitation preceded the formation of ice and that the refrigeration followed soon thereafter.

The postulated chain of events by which increasing precipitation (with elevated land) could cause fall of temperature is fairly simple and straightforward. The increased snowfall would produce ice almost immediately; and, if the ice masses became large enough, their cooling effect upon the atmosphere, land, and ocean would become inevitable. If, on the other hand, the fall of temperature came first, it is very difficult to see how an increase of precipitation would follow, especially on a large scale and as a cause-and-effect phenomenon.

With regard to the snowline, it should be borne in mind that its position is determined by two things, the temperature and the amount of snow. Flint (*2,* p. 32) gives some impressive data showing how the snowline is influenced by the total snowfall. It seems permissible to assume, on the basis of present evidence, that the increased precipitation not only could precede the fall of temperature but also is the most likely thing to occur.

Gilbert N. Lewis (*23*) has approached nearer to the idea of ocean control of glaciation than any previous investigator known to me. Lewis visualized the immediate cause of a great glaciation as an increase in evaporation but made no specific suggestion as to how this could come about, except by accident such as the upthrust of a portion of the ocean bottom. He suggested that the termination of glaciation could be brought about by a general lowering of temperature by loss of solar energy through excessive reflection from snow and ice fields. Lewis made no provision for self-perpetuation or cyclic mechanisms and thus failed to account for the four stages of the Pleistocene Ice Age.

Conclusions

Serious and perhaps fatal objections to an ocean-control theory of glaciation will probably have occurred already to some who have read the foregoing summary. Criticisms and suggestions will be welcome. The theory is susceptible to mathematical analysis on many points. Quantitative data on the heat budget of the ocean could be brought to bear on the subject, and the relative temperatures and volumes of rivers and the bodies of water into which they flow could also be examined. Myriads of climatologic, meteorologic, oceanographic, biologic, geologic, and topographic details should be considered in any attempt to solve the problems of glaciation, always with the aim of integrating an acceptable overall hypothesis.

The ocean-control theory requires a rather clear-cut course of events during the progress of a glacial-interglacial cycle. These postulated events can be checked against what is known or what may be learned about the chronological sequence of geologic events during the Pleistocene. The theory requires a warm ocean coincident with the early and mature stages of glaciation. This rather novel concept is in opposition to most previous theories, which postulate world-wide cold affecting both the land and the ocean simultaneously. Means of checking the coincidence of warm oceans and cold lands appear to be offered by study of fossils and coral reefs, and usable results may already be at hand in this field. It is apparent that some reliable means of assuring contemporaneity of basic data from land and sea deposits must be introduced before results can be conclusive.

The theory requires a coincidence of fluvial periods and glacial advances, with the filling of interior basins running slightly ahead of the growth of the ice sheets. The times of most severe continental cold should be during the waning stages of the glaciers, and the cold periods should overlap into the early part of the succeeding interglacial period. The loess-forming intervals may be mainly late in the glacial stages.

Crucial tests based on the foregoing considerations and also many others can be devised to test the possible validity of an ocean-control theory. I intend to pursue some of these tests as they concern the geologic aspects of the problem.

References and Notes

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C. P. Berkey, Pioneer in Engineering Geology

Geologic knowledge has been applied intuitively to the building of man-made structures for centuries. But only in recent years has the geologist become a member of the teams that plan and construct great dams, bridges, and aqueducts. Charles Peter Berkey was foremost among those who demonstrated the value of geologic advice in the construction of public works. Born on a farm in Indiana on 25 March 1867, he moved with his family to Texas and then to Minnesota, where he completed his doctorate at the University of Minnesota in 1897. His first work was on rocks and fossils in Cambrian sandstones at Taylors Falls on the St. Croix River. But in ensuing years his interests turned to petrology, the study of igneous and metamorphic rocks, which he had seen through his college days only as erratic boulders in the glacial drift of southern Minnesota. In 1903, he came to Columbia University.

The City of New York undertook the surveys for the Catskill Aqueduct in 1906. The geologic advisers to the city at the time were James F. Kemp and William O. Crosby, professors at Columbia and Massachusetts Institute of Technology. In that summer they left for Mexico City to attend the excursions and meetings of the International Geologic Congress and were otherwise engaged. Hence, independent responsibility fell on Berkey. The practical problems were investigated, and the answers were given with such clarity and success that he was to be engaged in such undertakings for the succeeding half-century, until his death on 22 August 1955.

Charles Peter Berkey was associated with scores of engineering projects. The Catskill aqueducts of New York and the water supply systems of Boston and Los Angeles gained his attention. He advised on the dams of the Tennessee Valley Authority and of the Bureau of Reclamation; the Hoover Dam owes its present location largely to his judgment of the merits of the foundations and tunnel conditions at this and alternate sites. The George Washington Bridge across the Hudson River bears his name on its tablets. His reports had influence on the construction of public works in half of the states of the United States and some in foreign lands. The responsibilities were a reflection not only of his good judgment and experience but also of his facility in presenting in speech and writing the nature and causes of the problems that might be encountered in such manner that his advice could be understood; hence, design and construction were altered to meet the conditions that he described. Berkey made geology a useful tool. The American Society of Civil Engineers elected him an honorary member in 1941, and the Geological Society honored him at its dedication of the *Berkey Volume on the Application of Geology in Engineering Practice.*

Berkey was Newberry professor of geology in Columbia University in his later years. His courses in petrology were particularly valued; his lectures and discussions emphasized the reasons for things—he was skilled in showing the favorable and unfavorable aspects of possible solutions and the considerations that led to his conclusions. In his most distinctive course, the students examined the rocks and sections he had used in reports on hundreds of practical problems that he had investigated. He was executive officer of the department of geology for many years, and his counsel was valued on administrative committees in the university. One of his earliest experiences in exploration was an expedition in the Uinta Mountains, Utah, about the turn of the century. But his greatest satisfaction came from the expeditions of the American Museum of Natural History in Mongolia in 1922 and 1925; much publicity was gained from the latter trip through the finding of dinosaur eggs.

One of his greatest services was as secretary of the Geological Society of America through 20 years, from the time when it was a small organization with limited resources to that when it became more richly endowed through the benefactions of R. A. F. Penrose in the early 1930's. His judgment and enthusiasm were undoubtedly largely influential in this development of the society, which elected him president in 1941. He was a member of the National Academy of Sciences and of the geological societies of London and France. The Kemp medal was awarded him in 1951 for distinguished service in geology. His greatest monuments are the enduring structures that grew under his skilled advice. His influence will affect the lives of generations who will not know his name.

MARSHALL KAY

Department of Geology,
Columbia University, New York