THE EVOLUTION OF CLIMATES

MANSON

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BY

MARSDEN MANSON

NOTE

THIS ESSAY IS THE RESULT OF MORE EXTENDED STUDIES SINCE THE PUBLICATION, UNDER THE SAME TITLE, OF A PAPER IN THE *AMERICAN GEOLOGIST*, VOL. XXIV, AUGUST 1899; AND OF PREVIOUS AND SUBSEQUENT PAPERS IN VARIOUS PUBLICATIONS SINCE 1891.

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Dedication

This book is dedicated to my beloved wife, Julia Diana Elizabeth, whose sympathetic help and encouragement have been a constant aid.

ACKNOWLEDGMENTS

To the laborers in the fields of Glacial Geology and Meteorology into which the author has ventured, he feels deeply indebted. Nearly all of them differ radically from the views and conclusions now presented; but no unanimity prevails as to the cause or causes and the conditions which have governed the climates of the past. No conclusions which have been reached by those who have attempted a solution have been acceptable. The entire problem is therefore open for solution on other lines; hence the author feels less hesitancy in questioning the premises on which these unsatisfactory conclusions rest.

Among those whose works are utilized with gratefulness the author especially acknowledges his indebtedness to Doctor Charles Greely Abbot and his able assistant, Mr. F. E. Fowle, the late Professor Hilgard, and Professor Chas. Schuchert. To the first named for their notable researches in solar and atmospheric physics; to Professor Hilgard for adverse changed into favorable criticism; and, to Professor Schuchert for his valuable epitome of the facts of paleontology and geology bearing upon the subject.

The author feels gratified by the references to and endorsements of some of his interpretations by Professor F. H. Knowlton, of the U. S. Geological Survey, in his excellent contribution in Vol. 30, of the Bulletin of the Geological Society of America.

MARSDEN MANSON.

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PREFACE

The object of this work is to offer an interpretation of the causes, conditions and controlling principles of the climates which the earth has manifestly undergone during Geologic Ages and the Modern Era. The most important of these relate to the present and near future, but the great questions involved cannot be fully considered and set forth unless the whole range of the phenomena of climates and of the energies and the changing conditions under which they have acted be taken up in their entirety and in their intricate relations.

Climatic changes do not strictly belong to Geology and relate more intimately to Meteorology and Atmospheric Physics. But these changes are recorded in the crust of the earth, which so entirely belongs to geology that most of the special studies of the causes of the changes of climates recorded therein have been made by Geologists. The Astronomer and Physicist have added much to the knowledge of the subject, and their contributions will also be freely utilized in the present essay.

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THE EVOLUTION OF CLIMATES

PART I

THE SCOPE OF THE PROBLEMS

The most important problem in terrestrial physics . . . . and the one which will ultimately prove the most far reaching in its consequences, is: What are the physical causes which led to the Glacial Epoch and to all those great secular changes of climate which are known to have taken place during Geological Ages? (Dr. Croll, "Climate and Cosmology.")

An attentive study of the physical Geography of the earth and its influences on Climate, together with a judicious application of the simplest physical theories, will enable us to gain by and by a better knowledge of Geological Climates. (Prof. A. Woeikof, "Nature," March 2, 1882, p. 426.)

The principal problems are covered by the questions:

What were the causes and conditions which during the greater part of geologic time maintained eras of tropical and warm temperate climates of high humidity and wide distribution, broken by frequent and comparatively short glaciations and deglaciations of continental areas in low and middle latitudes, while oceans and high latitudes remained warm?

Why should two of these be zonal glaciations of marked severity, the first in tropical latitudes while oceans and polar latitudes still remained mild; the second, in middle and polar latitudes, was a period of "Phenomenal glaciation" which followed the widespread cold temperate conditions of Pliocene time and of which "the whole world felt its effects"?

What were the energies and conditions which caused this glaciation to include a series of short advances and retreats, or "interglacial epochs," gradually merging into the existing conditions of a zonal arrangement of climates different from any other which ever prevailed?

To what stage are these new conditions tending?

What analogies prevail between these great changes and possible conditions upon other members of the solar system?

These changes of climates, during the vast eras between the earliest Proterozoic and the Modern Era offer, therefore, an intimately related and complicated group of problems that has not been acceptably solved.

These failures to reach a satisfactory solution throw suspicion upon the premises upon which these unsatisfactory solutions rest, which suspicion, to the seeker for truth, not only warrants but requires their rejection.

There are two premises, one assumed and the other purporting to rest upon mathematical demonstrations, which the studies resulting in this work thus mark for rejection; the first is the generally accepted but unproved assumption, that solar radiation alone controlled the distributions of temperature and ice antedating the Modern Era; the second is, that mathematical calculations resting upon assumed premises and omitting far larger and more important factors, establish that the extremely low conductivity of the forming crust and the small amount of heat held within a shell of the lithosphere of an assumed thickness and temperature justify the conclusion that the influences and control of earth heat were of short duration, and hence the only other source of heat, solar energy, has alone controlled the climates of geologic time.

These two premises will, therefore, be rigidly questioned as to their basis and fortification by mathematical calculations purporting to buttress them. If found to rest upon an unproved assumption or inadequately fortified they will be rejected.

THE BASIS OF THE PRESENT INTERPRETATION

An attempt will then be made to interpret the secular changes of climates upon the basis that the limited and fluctuating supply of earth heat and its cognate energy radio-activity converted into heat, under the highly conservative conditions imposed by water in its various forms and the utilization of solar energy as a conservative factor throughout geologic time were competent to maintain the narrow limits of temperatures known to have prevailed; and, that under these conditions the limited supply of earth heat was recorded as a controlling factor in all geologic time until the inauguration of the sole control in the Modern Era of the greater and more constant source—solar energy. In other words, an appeal will be made only to the factors which have always been of importance in determining climates.[1]

THE LEADING AUTHORITIES USED IN THIS ESSAY

In addition to the standard texts and treatises heretofore utilized, the author finds two recent works well fitted for the presentation of

[1] Dr. Chester A. Reeds. Science, Jan. 7, 1921, p. 22.

the principles and facts to be utilized in this attempt to solve the problems herein essayed.

The energies and conditions which control climatic variations and the general physics of the atmosphere have recently been more firmly established by the exhaustive studies and extended observations by Dr. Abbot and Mr. Fowle.[1] The author, therefore, bases this effort to interpret the variations of past and present climates and to determine the causes, conditions and mode of action of the energies producing them largely upon the principles which the results of the above studies and observations confirm; and upon the principles and facts given in Bartholomew's Physical Atlas, Vol. III, Meteorology.

Another of the Smithsonian publications will be fully used; this work is entitled " Climates in Geologic Time,"[2] by Professor Charles Schuchert, of Yale University. It is such a comprehensive and authoritative epitome of all the facts of paleontology and geology bearing upon the subject of climatic variations, that the author accepts it as a succinct statement of the records in the case.[3]

It is not often that a student of a difficult and controverted problem finds in the publications of an Institution of high standing nearly all the principles and the facts which are needed to attempt the solution of the problem.

The first of these publications gives the results of the elaborate researches and study of the action of water vapor and clouds upon the wave lengths of the entire spectrum. These researches fully confirm principles previously applied by the author in earlier attempts to solve the problems of climates. The second is an authoritative compilation of the facts of Geology and Paleontology bearing on the subject.

The author hopes that in this application of these works—the one for the principles and the other for the facts—he may aid, in an humble way, in carrying out the noble motto—

" For the Increase and Diffusion of Knowledge among Men."

[1] Annals Astrophysical Obs., Smithsonian Institution, Vols. II-III.

[2] Report Smithsonian Institution, 1914, pp. 277-311. Also The Climatic Factor, Dr. Ellsworth Huntington Publication No. 192 of the Carnegie Institution of Washington.

[3] There is doubtless a very marked difference in the interpretation given by the author to the facts massed in the masterly work of Prof. Schuchert. For this the author apologizes; but he feels the more indebted by reason of this difference from an authority not sharing this interpretation.

ANALOGIES PRESENTED BY OTHER PLANETS

The conclusions herein reached are so general that they have, at least an inferential bearing, upon the conditions apparently reached upon "The other members of the family of planets to which the earth belongs."

More than one and one-third centuries ago Sir Wm. Herschel gave the results of his observations and studies of the polar snowcaps of Mars and summarized them as follows:

> The analogy between Mars and the earth is, perhaps, by far the greatest in the whole solar system. Their diurnal motion is nearly the same, the obliquity of their respective ecliptics, on which the seasons depend, is not very different; of all the superior planets the distance of Mars from the sun is by far the most alike to that of the earth, nor will the length of the Martian year appear different from that which we enjoy.
>
> If, then, we find the globe we inhabit, has its polar regions frozen and covered with mountains of ice and snow, that only partly melt when exposed to the sun, I may well be permitted to surmise that the same causes may probably have the same effects on the globe of Mars, that the bright polar spots are owing to the vivid reflection from frozen regions, and that the reduction of those spots is to be ascribed to the sun.[1]
>
> The earth is in no very special way distinguished as a planetary body.[2]
>
> In reference to the melting of the south polar snows—I speak of these as "snows" for I feel perfectly convinced that the polar caps of the planet Mars are as much ice and snow as that which we have to deal with terrestrially every winter.[3]
>
> Some of the planets of our solar system may be passing through stages of existence that the earth experienced long ago, and others of our planets may be approximate examples of what is in store for the earth.[4]

Linked, therefore with the climatic development of the earth are questions touching the stages reached in the planets which are apparently more advanced and of those which may be less advanced than the earth; for, whatever may have been the dates and modes of their origin, differences in mass, distance and environment may have varied the rate of development of each. At any particular period progress cannot have been the same for all, and we find each one in that particular stage which the conditions just named have permitted it to reach. All are doubtless governed by the same general laws, and must be progressing toward the same general condition.[5]

[1] Phil. Trans. Vol. LXXIV, p. 260.

[2] Chamberlin and Salisbury, Geology, Vol. II, p. 2.

[3] Dr. E. E. Barnard, Popular Astronomy, 1895.

[4] Dr. W. W. Campbell, Science, N. S., Vol. LVI, No. 1169, p. 513, May 25, 1917.

[5] Manson Astronomical Soc., Pacific Coast Vol. VII, 1895, pp. 53-57.

E. C. Slipher, *ib.* Vol. XXXIII, No. 193, 1921, pp. 127-139, and especially pp. 9, 137-139.

The conclusions reached in this work will therefore be tested by the analogies expressed by the above quoted authorities, in order to secure any general confirmation which they may add.

CLASSIFICATION AND RANGE OF THE PHENOMENA TO BE EXPLAINED

The phenomena for which explanations are to be attempted are so correlated that a satisfactory assignment of the controlling causes and conditions must embrace them all—no one phase can be separated out for study although the range is wide.

(1) *In time* they embrace the entire geologic past, the present era and an indication as to the trend of activities yet marking the progressiveness of glacial retreat.[1]

(2) *In range* they embrace:

(a) The present concurrent existence of zones of temperate, tropical and torrid climates in middle and low altitudes, and of glacial climates in high latitudes, each zone of which is inhabited by groups of life especially adapted to its climatic conditions and is slowly emerging from Pleistocene glaciation, the greatest recorded in the crust of the earth;

(b) The past Permo-Carboniferous distribution of glaciations the reverse in latitudinal distribution of those during the Pleistocene namely, the glaciation of tropical latitudes concurrent with the prevalence of genial climates in high latitudes;

(c) The short period deglaciations and reglaciations during each of the above widely separated zonal glaciations; the last merged into present conditions, and the former merged into a world wide geniality more tropical than the polar mildness prevailing during the maximum glaciation of tropical latitudes;

(d) Ages of universally temperate and tropical climates interspersed with short glacial epochs during which ice covered areas in various latitudes and gave place to universal geniality.

(3) They call for an explanation of the phenomena of the present era with extremes of heat and cold, of aridity and precipitation, of frigidity and torridity probably exceeding in range any ever recorded; and, how these developed from Geologic Climates.

(4) Also for an explanation of the progressive retreat of glaciation in polar latitudes and an indication of the probable cumulative effects of the energies and conditions now active in this deglaciation.

Attempts to explain these apparently anomalous groups of climatic phenomena have been principally directed to the problems of glacia-

[1] Science, N. S., Vol. XLVI, pp. 639-640; *ib.*, Vol. XLVII, pp. 487, 488.

tion and deglaciation, although these do not form an integral problem, but are essential parts of the complicated whole.

These complications are such that they have been and are the most controverted fields of speculation and research before several generations of scientists. The writer, however, believes that the foundation for their satisfactory solution will be laid after the rejection of improperly fortified assumptions and upon the application of the present knowledge of the physics of the atmosphere and of the properties of water in its various forms and under various conditions in their action upon the radiations emitted by the sun and by the earth; and, that corroborative evidence will be found in the conditions existing upon some of the other planets.

The task of laying this foundation will be undertaken in this work. If properly laid it will stand of itself and sustain the superstructure.

THE GEOLOGIC RECORD OF CLIMATES AND CERTAIN POSTULATES ESTABLISHED THEREBY

The records of the variations of the climates which the earth has passed through and the stage now passing before us are generally acknowledged to be deeply complicated; and, that no satisfactory explanation of either the major or minor changes has been made.

The complications began with the recognition of the reality of the Ice Age or Glacial Period of Pleistocene time, during which glaciations reached their maxima in middle or temperate latitudes and extended into polar latitudes, and the oceans became glacial in middle and high latitudes.

Still more intricate complications were added upon the segregation of at least four interglacial epochs, or short warm epochs, between successive retreats and advances in Pleistocene glaciation.[1] These epochs were first recognized in middle latitudes where this great glaciation fluctuated and finally merged into the zonally disposed climates of today and has retreated to polar latitudes, where this retreat is yet progressing at a rate which calls for the deglaciation of these regions within a period which, geologically considered, is not remote.

Complications were also added by the necessity of accounting for other glaciations in earlier eras; of these one of the most extended and remarkable was in Permo-Carboniferous time, during which the glaciations were localized in two wide zones between 15° and 35° North and South latitude. During this glaciation of tropical lati-

[1] Schuchert, *L. c.*, p. 304.

tudes a broad zone in equatorial latitudes, and middle and high latitudes escaped. This glaciation was followed by the wide spread geniality of Triassic time.

Not only are these minor complications or interglacial epochs presented during the maximum glaciations of middle latitudes and as these gave way to the zonal ameliorations yet progressing, but they are also recognized during the vast Permo-Carboniferous glaciations of tropical latitudes which gave way to the universally mild climates of Triassic time.

We therefore confront a group of complications in regard to the distribution of temperatures and glacial ice involving vast eras of uniformly temperate or tropical climates interspersed with short glacial periods in which glaciation was nonconformable to both preceding and succeeding geniality as well as to the solar controlled climates of today.

These great changes in climates date back into the earliest geologic records, extend to the present, and reach forward into an immediate future in which progressive deglaciations of now useless polar wastes marks the extension of productive areas.[1]

Scott: "All these evidences and many others which space will not allow me to mention lead up to one great fact—namely, that the glaciation of the Antarctic regions is receding."[2]

"The ice is everywhere retreating."[3]

Shackelton: "Some time in the future these lands will be of use to humanity."[4]

Taylor, Geologist of Scott's Expeditions, speaks with confidence of the passage of the Ice Age from Antartica.[5]

Standing strongly out from these complications are some broad and significant facts which throw very rigid conditions around any assumptions which may be suggested and stubbornly hold their grounds against any "advances of discovery" which may happen to be in the wrong direction.

Among these facts are the following:

(1) None of these glaciations were conformable to present distribution of temperatures nor occurred in latitudes which could have been exposed to solar radiation of an efficiency equal to that now deglaciating polar latitudes.

[1] Science, N. S., Vol. XLVI, pp. 639-640. Dec. 29, 1917.

[2] National Antarctic Expedition 1900-1904, Vol. I, p. 94.

[3] Scott's Last Expedition Vol. II. pp. 294 and 286, photograph following p. 286 and p. 292.

[4] Lecture to Commonwealth Club, San Francisco, Nov. 7, 1916.

[5] Scott's Last Expedition, Vol. II, p. 288.

(2) All glaciations were inaugurated and effected during periods in which the temperatures of oceans were more uniformly distributed and higher than those which have prevailed since Pleistocene glaciation began to decline.

(3) Each of the maximum glaciations was zonally disposed; the earlier in tropical latitudes, now the zones of minimum cloudiness and precipitation and of maximum barometric pressure and anticyclonic activity, it was preceded, accompanied and succeeded by genial climates in other latitudes and warm oceans in all latitudes. The final glaciation was localized in middle latitudes (although extending into polar), now the zones of temperate rains and of denser cloudiness, of secondary minima in barometric pressure and maximum cyclonic activity; it was preceded by cold temperate oceans, accompanied by glacial oceans in middle and polar latitudes and succeeded by oceans which are of so low a temperature in the aggregate that inadequate water vapor is generated to sustain glaciation even in polar latitudes, and which have been, as well as continents, dependent upon solar radiation for the increase in temperature which has followed the last glaciation.

(4) During the interglacial epochs deglaciations were conformable, and glaciations and reglaciations were non-conformable to climates controlled by solar radiation; or, unless we assume very short-period and wide range variations in solar radiation, not warranted by any known facts nor bases, we are confronted with an alternation of exposures to solar radiation giving deglaciations with interceptions of this exposure giving glaciations and reglaciations.

ANALOGIES AND APPARENT ANOMALIES OF THE TWO PERIODS OF MAXIMUM GLACIATION

The two periods of maximum glaciation, the Permo-Carboniferous and Pleistocene, present remarkable and significant analogies and apparent anomalies. These are brought out by contrasting the distribution of the two glaciations in latitude, the preceding and succeeding distributions of climates, and the fluctuating deglaciations and reglaciations during each.

(1) Permo-Carboniferous glaciation reached its maxima in the tropical latitudes; Pleistocene glaciation reached its maxima in temperate and polar latitudes.

(2) Each of these periods of maximum glaciation appears to have been accompanied by a series of short interglacial epochs.

(3) The maximum glaciation of tropical latitudes in Permo-Carboniferous time was preceded by the non-zonal tropical climate of

Carboniferous time and merged after a series of deglaciations and reglaciations or interglacial epochs, into the non-zonal, warm temperate or tropical climate of Jurassic time.

The maximum glaciations of temperate and polar latitudes in Pleistocene time was preceded by the widely distributed and cold temperate climate of the Pliocene, and merged after a series of deglaciations and reglaciations or interglacial epochs, into the distinctly zonal climates of the Modern Era controlled by solar radiation, under which deglaciation is yet progressing in polar latitudes.

(4) Both of these great zonal glaciations reached maxima in latitudes which could not have been glaciated under solar control of an efficiency equal to that now deglaciating polar latitudes.

(5) During the maxima in tropical latitudes, temperate and polar latitudes escaped; and, during the maxima in temperate and polar latitudes, tropical and equatorial latitudes appear to have had the snow line lowered several thousand feet.

(6) Deglaciations in each case appear to have followed lines of zonal exposure to solar radiation.

(7) The Permo-Carboniferous glaciations were about coincident with the limits of the tropical *arid belts,* and, those of Pleistocene time with the temperate *rain belts* of the Modern Era.

REASONS FOR DOUBTING THE ASSUMPTION OF SOLAR CONTROL OF GEOLOGIC CLIMATES

RECONSIDERATION OF THE BASIS OF PREVIOUS EFFORTS TO SOLVE THE PROBLEMS OF CLIMATES

The assumption of solar control of geologic climates is a premise in all efforts to solve the " climate controversy," and all conclusions resting thereon have failed in the crucial test of fitting the geologic record of past climates, and, require " other factors " in the test of meeting the requirements of the short " interglacial epochs " which characterized the Pleistocene glaciation of temperate and Permo-Carboniferous glaciation of tropical latitudes.

As none of the conclusions heretofore reached has been found to fit the geologic record of climates, it has been impossible to accept them. This makes it manifest that some assumption or premise is radically erroneous. Prominent among these premises and common to nearly all attempts to solve the problems of the evolution of climates, stands this unproved and badly fortified assumption of *solar control of the climates of all, or nearly all, of geologic time.*

THE INADEQUATE BASIS OF MATHEMATICAL CALCULATIONS OF THE AVAILABILITY AND DURATION OF EARTH HEAT AS A CLIMATIC FACTOR

The problem of climatic control must therefore be reconsidered, and each premise or assumption which has entered into these rejected and unsatisfactory conclusions must be challenged, irrespective of the universality of its acceptance and however firm its hold upon the scientific mind; for, some broad and important premise or assumption must be radically wrong to yield results which fail so radically to fit the geologic record.

There can be little, if any, doubt that at some period within the range of geologic history the planetary or earth heat, however derived, was stored in its primitive oceans and of influence in its climates; and that denudations and ruptures of the crust, etc., set free at various intervals additional increments of this heat which would restore in whole or in part this stored heat which had been lost in the intervals.

There were then two sources of potential heat: *Earth heat* and *Solar Radiation.* Each had its functions, and, during the eras of the prevalence of both sources a different order of temperature distribution must have prevailed than prevails since the lesser source has been exhausted and only the more powerful source, solar radiation, remains.

It is held that the differences in these two climatic eras must have been so marked that geologic processes and the differences in the distribution of temperature as recorded by life and ice cannot have failed to have legibly recorded the existence of the dual source, the decadence and failure of the lesser and the establishment of the single source of control now distinctly prevailing. It is not permissible to rule out the influence of the lesser source without convincing geologic evidence of its decadence and failure as a climatic factor, and of the distinct establishment of the greater.

There lies directly athwart this course of reconsideration above laid out, the almost universal acceptance of the assumption of solar control of geologic climates fortified as it is by the results of mathematical calculations of the limited quantities of earth heat available in an assumed depth of the lithosphere and the impossibility of its effects through conductivity. The results show possibilities of influence of such slight moment that they are insignificant and the available supply so small that it would be exhausted so as to be inconsiderable in geologic time.[1]

But these calculations are based upon assumed data and conceptions which in the light of the principles of atmospheric physics and the properties of water in its various forms, particularly as established by recent researches of Abbot and Fowle,[2] and of the possibilities of the store of energy emanating from radio-active substances, appear to place the results upon an inadequate and erroneous basis.[3] For instance, it is found therein that an assumed quantity of heat in an assumed depth of the cooling and forming crust was insufficient to produce climatic effects of any duration by reason of its early exhaustion by radiation; and, that this source could not reach the surface of the lithosphere by reason of the extremely low conductivity of the crust.

On the contrary this store of energy having been locked up in a crust of extremely low conductivity and slowly liberated therefrom by other processes far more efficient than conductivity, successively

[1] Sir William Thomson (Lord Kelvin), Mathematical and Physical Papers, Vol. III, pp. 295-311 (Camb. Ed. 1890). Also estimates by Prof. Harry Fielding Reid, Science Vol. XXIX, pp. 27-29, Jan. 1909.

[2] Annals Astrophysical Observatory Smithsonian Institution, Vols. II, and III.

[3] See Prof. Joly's Address Geol. Sec. B. A. A. S. Dublin Meeting, 1908. Report Smithsonian Institution, 1908, pp. 355-384. Also Prof. Knowlton's views, Vol. 30, Bull. Geol. Soc. of America.

stored in the oceans, and, conserved by highly efficient agencies were causes of the long duration of its effects.

Again it is assumed or calculated that whatever earth heat was brought into effect during geologic eras was quickly exhausted by radiation. On the contrary, it was conserved by agencies of the highest efficiency and stored in the oceans so as to be available in prolonging these conserving agencies.

THE TRUE RADIATING SURFACE OF THE EARTH

HEAT CONSERVATION AGENCIES

The surface of the lithosphere and the oceans are not now and never could have been exposed to loss of heat by radiation into space. "The true radiating surface of the earth as a planet is chiefly the water vapor of its atmosphere at an elevation of 4000 meters or more above sea level."[1]

Moist air and clouds are almost, if not absolutely, impenetrable to the long wave length radiation which the land and oceans emit, and clouds intercept solar radiation almost completely,[2] especially those outside the visible spectrum. The gauziest cirri intercept all heat radiations in the solar beam.[3]

Beyond this "true radiating surface" additional conservative activities are and must always have been active up to and in the region of inverted temperature gradients. Not only are convection currents turned back at this region, but from above this region more solar derived heat may have been radiated for one-half the time than planetary derived heat was radiated outward.

Moreover, upon this "true radiating surface" and the clouds beneath it was received the conservative power of solar radiation throughout the entire period of the earth's existence. The ultimate loss of earth heat must therefore have been a differential process of extreme slowness.

THE OMITTED FACTORS

In calculating the duration of earth heat as a climatic factor it is important to consider not only how and in what intervals and increments it reached the surface of the lithosphere and how much was available within an assumed thickness thereof, *but also what*

[1] Abbot and Fowle Ann. Astrophysical Obs. Smithsonian Institution, Vol. II, p. 175.

[2] Geological and Solar Climates, Manson 1893, p. 13 and authorities there cited.

[3] Ann. Astrophysical Obs., Smithsonian Institution, Vol. II, p. 134.

disposition was made of it when available at the surface; how conserved; how lost; ***what conservative factors and energies were active in prolonging its duration, and in its partial replacement.***

Among these conservative agencies are:

(1) The absorption of the radiation of a dark body by water vapor in the atmosphere.

(2) The conservative effects of clouds on (a) the escape of earth heat, (b) through the action of intercepted solar radiation.

(3) The heat stored in the primitive oceans and that set free by crustal ruptures, denudation, exposure of radio-active substances, chemical and physical actions and reactions, etc.: and the renewal of conservative factors thereby.

(4) The utilization of solar radiation during the prevalence of effective remnants of earth heat in the oceans.

(5) The functions of each of the two sources of heat and their combined effects upon the duration of the lesser source.

(6) Were the values of each of these factors the same throughout geologic and present time? And were any of their effects modified during the prevalence of the two sources?

Whilst the effects of these factors have recorded themselves in geologic history and their relative possibilities can be judged, it is doubtful whether the values of these controlling factors are known in that form and definiteness which mathematical formulae require. Their omission and the use of assumed, inadequate and erroneous data in their stead is fatal.

> The fascinating impressiveness of rigorous mathematical analysis with its atmosphere of precision and elegance, should not blind us to the defects of the premises that condition the whole process. There is perhaps no beguilement more insidious and dangerous than an elaborate and elegant mathematical process built upon unfortified premises.[1]

> The exact formulas of a mathematical science often conceal the uncertain foundations of assumptions on which the reasoning rests and may give a false appearance of precise demonstration to highly erroneous results.[2]

REJECTION OF THE ASSUMPTION OF SOLAR CONTROL OF GEOLOGIC CLIMATES AND OF THE RESULTS OF MATHEMATICAL CALCULATIONS WHICH ARE USED TO FORTIFY THIS ASSUMPTION

The author therefore declines to be beguiled into accepting the results of the calculations above referred to, which omit the vital

[1] Prof. Chamberlin, Science, Vol. IX, No. 235, p. 889.

[2] Barrell, Bull. Geol. Soc. Am. Vol. 28, p. 749. Knowlton, Bull. Geol. Soc. Am., Vol. 30, p. 565.

and important factors herein pointed out, and are based on unfortified premises. He feels obliged to reject the conclusions as "incompetent, irrelevant and immaterial."

It is held that both earth heat and solar radiation prevailed as active factors in temperature control during all of the eras of geologic history and until the Modern Era of Solar control; that the former was available as ocean stored heat, but the supply was held in the forming crust by reason of its low conductivity and was slowly made available by denudation and the exposures of radio-active materials, etc., or by "periodic changes in the topographic form of the earth's surface" which made increments of the interior sources of energy available. These increments partially restored the temperature inside the cloud sphere and added to the amount of heat stored in the oceans and thus replaced in part that slowly lost in the long intervals between the successive adjustments and ruptures of the crust which demark the time divisions of geologic history.

The conductivity of the crust of the earth is so low that the heat which could be made available as a climatic factor through this process is negligible, except for very short periods over very limited areas. This extremely low conductivity was therefore one of the highly conservative factors imposing the long duration of this source, and its liberation is recorded in the denudation of the crust, the altered and unaltered sedimentaries, and severe crustal ruptures up to the Modern Era.

It must be again noted that these additions to ocean stored heat and the high specific heat of water caused the oceans to fluctuate through more moderate limits than continents, and, with slight fluctuations, to retain some of this intermittently liberated heat until the close of Pleistocene time, when for the first time boreal ocean life and ice cold oceans recorded the final loss of earth heat by that agent most competent to hold it. Moreover, cold oceans do not supply the water vapor necessary for severe glaciations nor to maintain the integrity of the cloud sphere in any latitude, as made manifest by present cloud density and by the deglaciations which have progressed since oceans fell to the temperatures which inaugurated the Modern Era.

Now oceans "the world over tropical or sub-tropical" as in Lower Cambric time; "world wide warm water conditions" of Carboniferous time; "warm throughout the greater part of the world" as in Jurassic time; or when "polar waters were cool" as in late Pliocene time, would undoubtedly generate more water vapor and impose a greater cloud density and persistency than now prevails with polar oceans and with ocean depths ice cold, and, only the surfaces of oceans in equatorial, tropical and temperate latitudes above this degree. Moreover, oceans are now dependent upon exposure to solar radiation for any increase in temperature.

Now, with warmer and still cooling oceans, no colder in their deeps than the coldest surface temperatures,[1] the existence of a cloud sphere of greater extent and persistence than the prevailing 52 per cent of permanent cloudiness over the earth's surface is not only a legitimate inference, but its effects are geologically recorded in frequent glaciations of latitudes which could not have been glaciated under solar control, unless it be assumed that the intensity of this energy was greatly reduced or that its effects were intercepted by some highly efficient agent. Now, neither the short period glaciations nor the still shorter interglacial epochs can be ascribed to solar control or to variations in its intensity, for these variations in climate occurred with warm oceans and in all glaciations, except the last of universally colder climates, *polar latitudes were mild.* Mild polar climates and warm oceans concurrent with glaciations of tropical latitudes are not manifestations of the solar control of climates, and no effort of the scientific imagination to make them appear as such has met with the approval of the scientific judgment and the contradictions and anomalies involved in trying to fit these facts to solar control are positive and insurmountable.

In Professor Davis's very able discussion of the possible causes and conditions of the glaciation of tropical latitudes in Permian time and under the assumption of solar control, he rejects all of the causes which he considers, and thus negatives solar control during this glaciation under the hypotheses discussed.[2]

It is therefore held:

(1) That earth heat stored in the oceans and conserved by moist air and clouds and in part restored in and above " the true radiating surface " by the effects of intercepted solar radiation, imposed its influences until its exhaustion was registered by the cold oceans of Pleistocene time; that during all of geologic time the two sources were active in determining the climates of the earth; the lesser source was, under the conditions, the dominating factor and was conserved and reinforced by the greater through its absorption in the upper atmosphere; and, by its admission to the surface by temporary impairments of the cloud sphere.

[1] Chamberlin and Salisbury, Geology, Vol. II, p. 658.

[2] Bull. Geol. Soc. Am., Vol. 17, pp. 415-420.

(2) That the more powerful source, solar energy, acted as a conservator until it was intermittently and gradually admitted to the lower regions of the atmosphere and to the surface of the earth through impairments in the cloud sphere; these impairments first became permanent in the regions of least, and later in regions of greatest cloud density and were due to the decreasing amounts of water vapor supplied from the gradually cooling oceans;

(3) That this admission of solar energy was registered, first in the partial and then in the permanent deglaciations in the latitudes of least cloud density in Permo-Carboniferous time; next in the partial, fluctuating and permanent deglaciations in the latitudes of greater cloudiness under the temperate rain belts during Pleistocene glaciation; and finally, as recorded by the progressive deglaciation of polar latitudes;

(4) That between Triassic and Pleistocene time, both inclusive, the two sources prevailed coincidently; earth heat control prevailed in regions of greatest cloud density, and, solar radiation in the tropical regions of least cloud density which condition was established at the close of Permo-Carboniferous glaciation; and which was extended to the rest of the world at the dawn of the Modern Era.

(5) That between Triassic and Pleistocene time, both inclusive, a variable control by earth heat was registered in the glaciations recorded at the close of Triassic and Cretacic time and in those of Pleistocene time, which latter were complicated with the "interglacial epochs," and finally gave way to the Modern Era.

(6) Finally that in the close of Pleistocene glaciation and the complete and world wide establishment of solar climatic control is recorded the most profound change in the history of the earth.

It therefore cannot be assumed that variation of geologic climates have been controlled by solar variations, for the distributions neither of temperature nor of ice has been conformable thereto.

With warm oceans and the earth swathed in clouds maintained by water vapor generated by its own heat, it would make no difference in its surface temperatures to double or halve the intensity of solar radiation. The time of earth heat exhaustion would be increased in one and reduced in the other. Mantled in clouds formed and maintained from water vapor generated by its own heat the earth could be moved up into the orbit of Venus or out into that of Mars with no other effect upon its surface temperatures than to prolong or to shorten the period of control of its own heat supply, with corresponding effects in the establishment of solar climatic control, and with corresponding expansions or contractions of the cloud sphere.

We consequently have the combined effects of earth heat and solar energy to deal with under the conditions imposed by slowly cooling oceans and a forming crust gradually losing its heat to water by denudations, etc., and by periodic adjustments of its form.

It must be noted also that these glaciations and deglaciations imposed irregular variations in isostasy by withdrawing uniformly distributed loads from ocean bottoms and imposing them, to a greater degree per unit of area and non-uniformly, as ice upon continents: these loads having been distributed at times upon large continental areas irrespective of latitude; in Permo-Carboniferous time they were distributed in the broad zones between 15° and 35° North and South latitude; and, in Pleistocene time in middle latitudes, notably on the great continental areas in the Northern Hemisphere. After each continental overload they were withdrawn and restored to the oceans and during each of the two greater glaciations were partially withdrawn and replaced several times.

The adjustments and readjustments of the crust due to these disturbances of isostasy are in part known by the continental record but can only be inferred over the greater portion of the crust covered by the oceans.

THE LESSONS OF PLEISTOCENE DEGLACIATION

The progressive deglaciation which has proceeded since the culmination of the Ice Age has imposed very rigid conditions upon assumptions of the sources of temperature control by recording this control in legible and impressive terms.

The records in the temperate latitudes of both America and Europe are particularly significant: (1) These latitudes could not have been glaciated during solar control of an effectiveness now deglaciating polar areas. Solar energy must therefore have been intercepted by the only efficient agent—namely, the constant presence of a cloud sphere in these latitudes; they could easily have been deglaciated by the further chilling of the oceans, which would impair the efficiency of the heat-intercepting cloud sphere, which in turn would expose these latitudes to the direct effects of that energy which is proving its deglaciating efficiency even in polar latitudes. A slight increase in ocean temperatures from crustal adjustments and ruptures would slightly rewarm the surface of the ocean and restore the intercepting cloud sphere and also yield the water vapor necessary for reglaciation; upon the exhaustion of that portion of this increment which reached the oceans solar energy would again deglaciate.

These alternations of control manifestly imposed conditions first favorable to glaciation and then favorable to deglaciation; and were imposed some four or more times in both North America and in corresponding latitudes in Europe. These alternations were, therefore, not due to short period fluctuations in the intensity of solar radiation, but to fluctuations in the available but fading earth heat as set free by crustal adjustments etc. The effects of the alternation of the two sources of control cannot reasonably be ascribed to variations in the great and practically constant source—the "factors other than those mentioned" by Professor Schuchert[1] appear to be supplied by the effects of increments of earth heat set free by crustal readjustments as the oceans reached the critical temperature between generating a sufficiency or an insufficiency of water vapor to maintain the cloud sphere—first in the regions of least cloudiness, and lastly, in those of more persistent cloudiness—the temperate rain and cloud belts.

The interglacial epochs, of the Pleistocene period, occurred before the final chill of the last glaciation had culminated in the colder winters of the Modern Era, and hence solar energy did not have the chill of winter to remove from temperate land areas before the warmth of spring could be established. The same latitudes were therefore slightly warmer in the interglacial epochs than at present.

[1] *L. c.* p. 311. Carnegie Institution, Pub. 192, p. 298.

THE NON-AVAILABILITY OF BOTH SOURCES OF HEAT DURING GLACIATIONS

As the weight of opinion against the prevalence of the effects of earth heat up to the Modern Era is decidedly preponderant, and as the two great Institutions of research, hereinbefore referred to, have given wide publication and high standing to this opinion, it becomes necessary, before proceeding farther, for the author to state specifically his reasons for dissenting therefrom.

In order to disprove any possible effect of earth heat as a climatic factor Professor Schuchert cites the early Huronian glaciation in Canada as proof that earth heat was not sufficient to prevent such glaciation even in this remote period of geologic history. "The evidence of the tillites is in favor of the view that the glaciation in Huronian Canada, was not 'the work of merely local mountain glaciers' but rather due to 'the presence of ice sheets comparable to those which formed the Dwyka.' * * *" "This implies that the climates of the earlier parts of the world's history were no warmer than those of later times, and that in Lower Huronian times, the earth's interior heat was not sufficient to prevent the formation of a great ice sheet in latitude 46°."[1] This is a sound implication, so far as it goes. Carrying it to its logical conclusion it applies with equal force to any other source of heat which may be assumed to have controlled climates during that period. The author, although realizing that his views and those of Professor Schuchert are widely apart, would change but one word of the above quotation, namely, *available* instead of "sufficient."

This evidence of glaciation shows that in Lower Huronian times *neither* of the sources of heat was available, under the prevailing conditions, to prevent the glaciation of large areas in the interior of continents, in this case only one degree north of the median latitude between the equator and the north pole. The same is true of the maximum glaciation of the same latitude in Pleistocene time; or, in the period of maximum glaciation of tropical latitudes in Permo-Carboniferous time, when earth heat was not available to prevent the severe glaciation of immense continental areas in tropical latitudes; neither does it appear that solar radiation was available to prevent these glaciations, even in the zones of its vertical and maximum effects.

[1] Smithsonian Report, 1914, p. 287. Carnegie Institution Publication, No. 192, p. 243. Also, Coleman, Am. Jour. Science, Vol. 23, p. 192.

If these glaciations are to be assigned to solar control it must be admitted, either:

That solar radiation in north latitude 46° in two cases, and, in the zones of its vertical incidence in the other, fell to an efficiency less than that now deglaciating polar latitudes;

Or the alternative, that it was intercepted by some efficient agent for considerable periods of geologic time when earth heat was not available to prevent such glaciations.

There is no warrant for assuming that solar efficiency should have been reduced to such an extremely low ebb—particularly during eras when the oceans were warm and capable of generating sufficient water vapor to yield a cloudiness capable of effectually intercepting it, and the concurrent presence of mild climates in polar regions precludes ascribing Permo-Carboniferous climates to solar control.

In fact, glaciations only appeared when neither source was available to prevent them, the lesser and fluctuating source having been locked up in a non-conducting crust and the intervals between its liberation having been long enough for the quickly cooling continents to lose their heat before the stored heat of the oceans was exhausted, which stored heat, until its later exhaustion, maintained a dense cloud formation. The more powerful and constant source was not available by reason of being intercepted by the cloud sphere maintained by this stored heat of the oceans. This interception and the utilization of this great source as a conservator of the conditions prevailing on the earth's surface was an effective agency in maintaining the control of surface temperatures by the lesser source which fluctuated in its availability and exhaustion, and which failed first to maintain land areas and later ocean areas at mild temperatures.

Either source was *sufficient* to remove glaciation when conditions rendered it *available,* as evidenced by the deglaciating effects of crustal ruptures in the earlier Eras; and, by the polar deglaciations yet progressing from the direct exposure to solar radiation which followed the chilling of the oceans to about the point of maximum density and the consequent impairments in all latitudes of the cloud sphere to an aggregate extent of 48 per cent of the earth's surface.

It must also be kept in mind that the distributions of temperatures prior to the Modern Era, were not conformable to those imposed by solar control, and that the oceans were not glacial prior to Pleistocene time.

It appears that there were frequent short periods during which sufficient heat of neither source was available to maintain temperatures above glacial conditions upon easily chilled continents; and, that during these periods earth heat, stored in the oceans, furnished abundant water vapor to be condensed into glaciers of great area and depth, and, to maintain an intercepting cloud sphere of such efficiency that temperate and tropical latitudes, which could not have been glaciated under solar control, were deeply and widely glaciated, also that upon the occurrence of maximum glaciation and the loss of the last effective increment of earth heat by the oceans, they ceased to yield sufficient water vapor either to glaciate or to shield the earth's surface from permanent deglaciation under solar radiation.

During all of these glaciations and deglaciations the other effects of solar radiation, namely, the fixing of zones of maximum and minimum atmospheric pressure, of consequent minimum and maximum cloudiness and precipitation and of the activities of anti-cyclonic circulation, were not interfered with. The effects of these factors of climate were fixed by the greater and more constant source of heat and were consequently zonally disposed about the earth.[1]

Either source was therefore sufficient at any time to prevent glaciation or to deglaciate; but solar energy was not fully available at the earth's surface until the close of Pleistocene time, although it was available in the tropical latitudes of least cloudiness subsequent to the final deglaciation of these latitudes at the close of Permo-Carboniferous glaciation. After this deglaciation a dual control appears to have been maintained, Solar control in tropical latitudes, and a fading, fluctuating control by earth heat in other latitudes, until its final exhaustion in later Pleistocene time.

Earth heat was not available to prevent glaciation when the intervals between its liberation from the crust were too long, but as stored heat in the more slowly cooling oceans it was available to maintain water vapor for a denser cloudiness than now prevails. *For the foregoing reasons, and others more specifically given later, it is held that earth heat was an effective climatic factor during all of geologic time, that its effects varied in intensity, notably upon continents; and, that glaciation was caused by the interception of solar radiation by clouds maintained by successive increments of ocean-stored earth heat during intervals between its liberation from the non-conducting crust long enough to permit land areas to cool below freezing;* ***and, that no glaciation under Solar control of climates has been recorded.***

[1] Hilgard. Proc. International Geol. Congress, Mexico, 1906.

THE INFLUENCES OF SOLAR RADIATION

The influences of solar radiation have been undoubtedly imposed upon the earth throughout its existence. Variations in the conditions under which these influences have been imposed have within themselves the potentials of profound effects upon the results. This is of particular moment in that all of the solar effects are not influenced to the same degree by varying conditions.

It is therefore necessary to briefly review the influences of solar radiation and the varying conditions under which they have been imposed. This also is the more necessary when it is considered that some of the forms of water impose different conditions upon solar radiation than upon radiation from the earth. Moreover, solar radiation in fixing the zones of its influence restricts certain factors of climate in some zones and imposes an excess upon others.

The effects of none of these factors could have been interfered with during geologic time *except those of heat,* which is intercepted by clouds. Therefore. should the degree or loci of cloudiness have varied, marked variations in heat control and effects must have followed and must have been recorded; variations in the combined influences which barometric pressures and winds could have imposed upon clouds, precipitation, and temperatures must also have occurred.

Should any of these conditions and their effects be omitted in the consideration of the problems of climate the interpretation of the records of geologic climates and of their transition into present climates is rendered difficult if not impossible.

EFFECTS OF CLOUDS

The intercepting power of clouds upon the radiations emitted from each of the two sources of heat is so great that in the presence of an extensive clouded area their effects are kept separate and apart. The radiations from the superior source, the sun, are intercepted to such an extent that the wave lengths in the visible spectrum which filter through are of almost negligible effect at freezing temperature[1] and those of the infra red region of the spectrum are almost, if not entirely absorbed. All wave lengths emitted by the inferior source—the earth—are almost completely absorbed by water vapor and are intercepted entirely by clouds. Any variations in the degree of cloudiness would therefore impose restrictive variations in the effects of both sources of heat, shutting out solar energy, except a small portion of

[1] Maury, Physical Geography of the Sea, 6 Ed. p. 212 *et seq.* Croll, Climate and Time, p. 60, Climate and Cosmology, p. 51.

the radiations in the visible spectrum and shutting in whatever radiations the earth emitted. If the temperature of the oceans were such as to increase the amount of water vapor until cloudiness was for long periods continuous, the controling effects of the two sources of heat would be separate—those of the superior source, solar energy, would be principally restricted to the outer surface of the clouds, and the air above it and would be conservative; those of the interior source would be dominant in surface temperatures and held beneath the cloud surface, subject to such variations as the available increments of this source would impose and subject farther to the conditions imposed by atmospheric circulation, zones of cloudiness and precipitation and barometric pressures as fixed by solar energy.

OCEAN TEMPERATURES AND THEIR EFFECTS

The geologic record is to the effect that at no time prior to the Pleistocene period were the oceans as cold as at present; and, the data brought together by Professor Schuchert indicate that they were at all times between temperate and tropical until the cold temperate of Pliocene and early Pleistocene time, followed by the glacial temperatures of late Pleistocene and the Modern Era.

Until glacial surface temperatures were recorded by ocean life the temperatures of the deep sea were no lower than their coldest surface temperatures. Of this control of deep sea temperatures Professors Chamberlin and Salisbury say:

> The deep oceanic circulation is now dominated by polar temperatures, for it is the cold waters of the polar regions that, descending and flowing towards the equator, control the temperatures of the deep sea. This is now low because of the low temperatures of the polar regions; but, if the circulation of the sub-carboniferous and carboniferous periods, whatever its nature kept the polar regions at a mild temperature the great body of the deep sea must have had temperatures correspondingly higher, and the water must have had so much the less depressing influence on the temperatures when it rose to the surface. This must have contributed to the widespread warmth which the sub-carboniferous, and perhaps the carboniferous periods, enjoyed. The mildness of the climates in these and several other periods, before and since, is one of the most remarkable features of geologic history. The crucial feature is the maintenance of mild temperatures throughout the long polar night. *Almost the only approach to a satisfactory solution seems to lie in a warm ocean circulation blanketed by a heat retaining atmosphere, in which the vapor of water and carbon-dioxide, abetted by a prevalent mantle of clouds, generated by warm oceans, conjoined their equalizing and conservative influences.*[1] Italicised by the present writer.

[1] Geology Vol. II, pp. 658-659.

If this were true for sub-carboniferous time, it must also have been true throughout any and all periods during which mild ocean temperatures prevailed.[1]

It is therefore held that the mildness of geologic climates, although "one of the most remarkable features of geologic history," is confirmed by "the maintenance of mild temperatures throughout the long polar night;" and, although tropical land areas, exposed to cold anti-cyclonic winds, were severely glaciated in Permo-Carboniferous time, these deep and prolonged glaciations were possible only with warm oceans, which alone can generate sufficient water vapor for glaciations, and, at the same time maintain the essential cloud density to shield them from solar energy, and in these anti-cyclonic latitudes the cold outer air first zonally descended to the surface as the spheroidal isotherms shrank towards the cooling surface of the earth.

THE OCEAN TEMPERATURES OF PLEISTOCENE TIME

For the first time in geologic history ocean life recorded the complete chilling of the oceans in Pleistocene time, and, the cloud sphere manifestly became impaired in latitudes of maximum cloud density and precipitation. Glaciation reached its maxima under the rain belts of maximum cyclonic activities in middle latitudes and extended into polar regions.

The loads of glacial ice in these latitudes again disturbed isostasy, depressed the crust under the weight of glacial ice of a maximum depth of more than a mile or $4.5\ (10)^{10}$ tons per square mile. As the cloud sphere in these latitudes fluctuated in efficiency with fluctuating ocean temperatures and these depended upon the liberation of increments of earth heat, the alternation of conditions favorable or unfavorable to glaciation in these regions ensued. Each failure of increments of earth heat to maintain the integrity of the cloud sphere admitted the deglaciating effects of solar radiation, until effective increments of liberated earth heat brought the oceans above the critical temperature of generating the water vapor to restore the cloud sphere temporarily in these regions of its maximum density, glaciation was thus temporarily reimposed.

When the oceans, chilled to their maximum degree, and no longer yielded water vapor in sufficient quantity to maintain the cloud sphere in any latitude—any further heating became dependent upon

[1] See also the views of Svante Arrhenius. The Destinies of the Stars, pp. 89-91. Also the description of moisture and clouds when quite persistent, by Hann, as quoted by Arrhenius, pp. 86-88 of work just cited.

surface exposure to solar radiation.[1] This exposure does not generate sufficient water vapor to sustain glaciation in even polar latitudes, where it is yet retreating according to the high authorities who have explored these regions and are referred to herein.

THE CRITICAL OCEAN TEMPERATURES IN THE MAINTENANCE OF THE CLOUD SPHERE IN VARIOUS ZONES

As cloudiness is disposed in zones of greater or less density, and as the cloudiness in each zone is dependent for its maintenance upon the amounts of water vapor generated from the oceans, there necessarily follows in cooling oceans two critical periods in the maintenance of the integrity of the cloud sphere: (1) That degree which would just maintain this integrity in zones of minimum cloudiness, and (2) a lower degree which would just maintain this integrity in zones of greater cloud density. Now, at either degree a comparatively slight chilling of the oceans would check the generation of water vapor and reduce the cloudiness in the particular zone affected, and a slight rewarming would restore it; or, when that degree which just maintained continuous cloudiness in 15° to 35° North and South latitude was reached a slightly lower degree would impair the integrity of the cloud sphere in these latitudes and expose the surfaces beneath to direct solar energy. Under these conditions of control loading and unloading of more quickly cooling and rewarming continents disturbed isostasy to such extents that crustal ruptures followed. Earth heat thus liberated would raise the ocean temperatures slightly above the critical point and sufficient water vapor would then be generated to restore the integrity of the cloud sphere in the regions of least cloud density. These conditions would impose reglaciation and deglaciation until crustal stability was attained in so far as the alternate glacial loading and deglacial unloading of these latitudes would accomplish it, and account for the interglacial epochs during Permo-Carboniferous time.

At a later stage of cooling the oceans reached that temperature which just maintained the integrity of the cloud sphere in the zones of greater cloud density of middle and polar latitudes. The more easily chilled continents would then have received their loads of glacial ice. These likewise caused ruptures liberating heat and warming the oceans, thus increasing or restoring glaciation until the oceans fell to slightly lower temperatures than would maintain cloudiness in

[1] Unless in some cataclysm the liberation of earth heat should rewarm the oceans from the bottom, when geologic climates would be reinaugurated.

these latitudes, and glaciations were exposed to the deglaciating power of solar energy. The repeatedly disturbed isostasy manifestly had its effects and crustal ruptures distinctly recorded the liberation of increments of earth heat with the resultant acquistion and storage of heat by the oceans and the re-establishment of the integrity of the cloud sphere and reglaciation in these latitudes. This process was manifestly repeated in the reglaciations and deglaciations of these latitudes until crustal stability checked the outbreak of farther increments of earth heat and the chilled oceans of late Pleistocene time ceased to yield sufficient water vapor to maintain the integrity of the cloud sphere in all latitudes. This variation of ocean temperatures at the critical stage of denser cloud formation accounts for the glaciations and deglaciations or interglacial epochs during Pleistocene time.

In the interim between these two great glaciations it is probable that solar control prevailed in tropical latitudes; and that the chill of Pleistocene glaciation was felt in these latitudes only by a marked lowering of the snow line.[1]

EFFECTS OF SOLAR RADIATION DURING THE PREVALENCE OF WARM OCEANS[2]

The outer media " the true radiating surface of earth as a planet " and the cloud sphere during its maintenance, received and utilized or reflected and radiated the full power of solar radiation. A small fraction of the energy in the spectrum filters through clouds of moderate density; but this fraction does not maintain temperatures above 0° Cent.

The fraction of solar energy not reflected by the high albedo of clouds was utilized as a conservator; and part of that reflected and radiated was further conserved by the atmosphere beyond this reflecting surface.

[1] The author is inclined to the opinion, based upon the descriptions of others and the small areas accurately mapped in the equatorial zone, that this zone of maximum cloud density was more heavily glaciated in Pleistocene time than is at present recognized. Topography in this zone is so masked in dense forests and undergrowth and the modifying effects of torrid heat and heavy rains have obscured the evidence, if there be such, to a greater degree than elsewhere. Dr. Branner's description of the existence of the remains of gigantic mammals mixed with cobbles and boulders in the swamps of equatorial Brazil,[3] and the topographic forms on the southerly edge of the Sahara and the northerly edge of the Kalahari Desert mark these as fruitful fields of research.

[2] Hilgard. International Geol. Cong., Mexico, 1906.

[3] Trans. Am. Phil. Society, Vol. XVI. N. S., pp. 421-422.

So long as oceans remained warm enough to maintain the integrity of the cloud sphere continents would be protected from the direct effects of solar radiation, at any temperature they might reach. Whenever, from elevation, remoteness from ocean influences, from exposure to anti-cyclonic cold winds or as the final loss of earth heat approached in Pleistocene time, continental areas fell below 0° Cent. conditions favorable to glaciation would be imposed, namely, cold continental areas, warm oceans and the interception of solar radiation.

Glaciation under these conditions could be checked only from one or the other source of heat, by the liberation of effective increments of earth heat, or by the further chilling of the oceans to such a degree as to check the generation of water vapor to the temporary or permanent impairment of the efficiency of the cloud sphere, thus letting into the enclosing constant temperature chamber of moist air and clouds the effects of the powerful and practically constant source, solar radiation.

Now this source at present fixes, and throughout geologic time fixed the zones of maximum and minimum barometric pressure, the corresponding distribution of anti-cyclonic and cyclonic circulation, minimum and maximum zones of cloudiness and precipitation. This anti-cyclonic circulation was the reciprocal circulation of that in the cyclonic regions and this circulation was the principal mode of passing warm, moist air through the cloud sphere, and returning cold air, rain and snow therefor.

When the oceans ceased to generate sufficient water vapor to maintain the heat-intercepting cloud sphere, it yielded first in the anti-cyclonic zones of least cloudiness, in which continents of lower specific heat had been previously glaciated under the effects of cold snow laden anti-cyclonic winds. The balance between oceans cold enough to generate sufficient or insufficient water vapor to maintain the integrity of this cloud sphere is a delicate one, and the concentrated loads of glacial ice laid down in these zones disturbed the isostasy previously existing. These loads probably depressed and ruptured the crust until isostasy was restored, to be again disturbed upon the melting of the load and its distribution evenly over the ocean floors. That these disturbances ruptured the crust, liberated increments of earth heat which in turn were gradually lost and the process probably repeated several times, is noted in two ways—1st by the record of the dislocations and crustal ruptures known to have taken place; and 2nd by the alternation of earth heat glaciations and solar heat deglaciations of the interglacial epochs which mark both Permo-Carboniferous and Pleistocene glaciations.

That regions outside of these zones of anti-cyclonic cold winds and of least cloudiness were not exposed to glaciation is recorded in the fossil forms of temperate life throughout polar and temperate latitudes.

The ocean, during the periods succeeding this great glaciation of tropical latitudes, were notably uniform in temperature distribution to Pliocene time. Two marked periods of cold continental conditions marked the divisions of the Mesozoic-Era: one between the Triassic and Jurassic, when ruptures of the crust seem to have restored ocean temperatures sufficiently to supply the water vapor for quite extensive glaciations; the other depression in continental temperatures was between upper Cretacic and Eocene time, when vast and successive outpourings of lava, each at least 200,000 square miles in area and several miles thick, were laid down on the weakest portions of the North American and Asian land masses. These great lava plains occupy median positions on the two land masses of the Northern Hemisphere, and the meridians bisecting them are almost in the same plane.

The heat from the Columbian lava plain yet makes itself manifest in insignificant outbursts in Yellowstone Park, but was an efficient agency in protecting the "Unglaciated Area" and in checking the southerly flow of the various invasions of ice in the great glaciations of Pleistocene time, which reached their maxima under and flowed from the North temperate rain belt.

During the two cold periods in the interval between the great or zonal glaciations the progressive chilling of the continents was noted by the retreat of land animals to the oceans, where they became permanently marine in habit, and by the cold temperate oceans of the Pliocene.[1]

CONTROL OF GLACIATIONS AND DEGLACIATIONS—EFFECT OF CLOUDS DURING THE PREVALENCE OF THE TWO SOURCES OF HEAT

Under the interpretation herein rendered, glaciations and deglaciations were dependent upon the maintenance and impairments of the cloud sphere, which in turn were dependent upon ocean temperatures, and upon the liberation of earth heat.

Fluctuations in the heat stored in the oceans due to the effects of successive increments of earth heat and their gradual exhaustion would cause corresponding variations in the generation of water vapor and thus cause variations in the integrity of the cloud sphere.

[1] Chamberlin and Salisbury, Geology, Vol. III, pp. 45, 185 and 239.

When the oceans chilled to that degree which began to impair the integrity of the cloud sphere this impairment would take place first in regions of least cloudiness, namely, the regions of maximum barometric pressure and of cold anticyclonic winds; next in regions of greater cloud density; the final stage being when the oceans lost the last effective increment of earth heat and became dependent upon exposure to solar radiation as a source of heat and further evaporation.

This exposure is manifestly not capable of warming the surface of the oceans to a sufficient degree to generate adequate water-vapor to maintain glaciation in any latitude and it has been and is decreasing in all latitudes. In the greater or zonal glaciations this retreat was fluctuating by reason of the causes and conditions elsewhere discussed.

Under these conditions variations in the temperatures of the oceans would impose four (4) distinct stages in the integrity and efficiency of the cloud sphere:

(1) Periods during which ocean temperatures were sufficiently high to generate water vapor in adequate quantity to maintain the efficiency of the cloud sphere in all latitudes. These periods in the aggregate covered the greater part of geologic time, through which tropical and warm temperate oceans and non-zonal, generally humid climates prevailed.[1]

During long intervals between successive increments of ocean stored heat continents might fall quite markedly in temperature and glaciations ensue in any latitude, notably upon continents remote from ocean influences, under exposures to anticyclonic activities, and in elevated regions. Deglaciation would result from additional increments of earth heat or possibly from temporary impairments of the cloud sphere as under (2).

(2) Periods during which milder oceans generated insufficient water vapor to maintain the integrity of the cloud sphere in regions of minimum cloudiness or over continents and in the zones of anticyclonic activities between 15° and 35° North and South latitude. Before this stage could be reached continents in these latitudes would have been deeply glaciated by reason of their lower specific heat, exposure to cold anti-cyclonic winds, and being protected from solar radiation by clouds maintained by an abundance of water vapor from the still warm oceans. They would be deglaciated by impairments of the cloud sphere as above. Or, at this critical stage of cloud maintenance in regions of least density they would fluctuate between con-

[1] White and Knowlton. Science N. S., Vol. XXXI, p. 360.

ditions of exposure, alternately favorable or unfavorable to glaciation. Regions of low barometric pressure, or cyclonic regions of maximum cloudiness, would not at that time be exposed to such glaciation, as the winds reaching them would be warm cyclonic and not cold anti-cyclonic.

(3) Periods during which still colder oceans generated insufficient water vapor to maintain the integrity of the cloud sphere in regions of more persistent cloudiness, or under the temperate rain belts and in polar regions.

This stage would follow a more extended chilling of continents when glaciation of regions least exposed to cold winds would have reached their maxima. Deglaciation would follow impairments in the cloud sphere in these regions.

Glaciations in regions of least cloudiness would not be very extensive for in them a greater impairment of the cloud sphere would have taken place, and greater or even permanent exposure of these regions to solar radiation would have been previously imposed.

Glaciations under these conditions manifestly reached maxima at different latitudes at different periods, that is, maxima were imposed first in the latitude of the tropics, by reason of the maximum anticyclonic circulation of these latitudes, which brought the cold of space to the slowly cooling surface; then, upon the final chilling of Pleistocene time maxima were imposed in the belts of maximum precipitation; and finally, as deglaciation progressed polar regions were left as apparent maxima by reason of being least exposed to solar energy.

In Pleistocene deglaciation temperate latitudes may have been deglaciated before maxima had been reached in polar latitudes. These latter maxima have been reached and permanent deglaciation is progressing.

(4) The final or permanent stage; during which greater crustal stability having been attained and effective increments of earth heat are no longer received by the oceans, they have chilled to their lowest degree, and have ceased to generate sufficient water vapor to maintain the efficiency of the cloud sphere or to maintain glaciations at any latitude. During this stage only about 52 per cent of the earth's surface is permanently clouded.

Solar control of climates under this stage is being established, under this control glaciation does not occur—except possibly in some remote eon of stellar evolution when solar radiation shall decline. A light glaciation from cold oceans and comparatively clear skies would then follow, commencing in polar regions. Such a glaciation has not been recorded in geologic time.

It will be noted that under (2) and (3) the balance may have been easily turned between ocean temperatures capable or incapable of generating sufficient water vapor to maintain the integrity of the cloud sphere either in regions of least or later in regions of more persistent cloudiness. During either stage, and notably in (3), changes in the topographic form of the earth's crust, whether continental or submarine, due to disturbances of its isostasy by glaciations and deglaciations, and other crustal strains, liberated sufficient earth heat to restore milder temperatures both on land and in oceans,[1] this restored the cloud sphere and again intercepted solar radiation. These increments of earth heat were, in time, lost on continents earlier than by oceans; and, thus imposed an alternation of control, which caused glaciation and deglaciation in either of the great glaciations, and accounts for interglacial epochs in both temperate and in tropical latitudes. Such reglaciations followed deglaciations caused by temporary or short period exposures to solar radiation in latitudes which could not be glaciated under this latter control. Deglaciations were generally conformable to solar control, and glaciations and reglaciations were non-conformable to such control. These phenomena followed one another at such short intervals that they could not be attributed to short period and wide variations in the more constant and powerful source, solar radiation. They belong rather to exhaustions of and additions to available increments of the lesser source—earth heat—and also to variations in ocean temperatures when the balance was easily turned between the generation of a sufficient or an insufficient amount of water vapor to maintain the efficiency of the cloud sphere, thus causing an alternation of control.

The only remaining cause of the order of decreasing ice loads is the gradual unloading of polar regions of their remaining glacial overloads and the restorations of these as uniformly distributed loads to the ocean bottoms. This may cause slight elevations of polar land areas accompanied by corresponding adjustments to the equatorial bulge imposed by axial rotation.

CONDITIONS OF GLACIATION

Under the interpretation of geologic climates herein offered, glaciations were possible under the following conditions:

When by the exhaustion of an increment of earth heat continents were chilled:

[1] That such disturbances took place in Pleistocene time, see The Great Ice Age, p. 790 (4th Ed.), Prof. Jas. Geikie.

(1) By reason of elevation above sea level.

(2) By reason of remoteness from ocean influences.

(3) By exposure to the cold of anti-cyclonic winds in latitudes of their greatest activity.

(4) By the final cold at the approach of the exhaustion of the last effective increments of earth heat.

The zonal control of cloud occurrence and density by solar energy, irrespective of the source of heat generating the water vapor essential for their existence and maintenance, must be kept fully in mind; also the fact that the loci of the zones of the maximum and minimum influences of anti-cyclonic and cyclonic winds are imposed and controlled by the same source of energy, and, that the former were the regions in which the cold of the upper air first reached the surface and produced zonal glaciations, and being also in latitudes of least cloud density, the cloud sphere must have been here first impaired. Land areas in each of these zones chilled prior to the oceans and were therefore exposed to glaciation. Furthermore in cooling oceans each of these impairments occurred at a critical temperature; *first* that degree which could just maintain cloud density in the zones of minimum cloudiness; and *lastly,* that degree which could just maintain cloudiness in the zones of maximum cloud density. Moreover, if, during the existence of either glaciation, the oceans should fluctuate in temperature to points somewhat above or somewhat below these critical temperatures, corresponding variations in the generation of water vapor would necessarily follow, imposing variations in the integrity of the cloud sphere in each latitude. Each fall below this critical temperature would impair the cloud sphere, and each rise above this temperature would restore it, thus alternately exposing the surface to solar energy and shutting off the same until the oceans again chilled below the critical temperature.

Severe zonal glaciation was therefore first imposed in the zones of maximum anti-cyclonic circulation of cold air which glaciated the land areas so exposed. Further chilling exhausted ocean stored earth heat below the critical temperature necessary to maintain the cloud sphere in these latitudes of least density and partial deglaciation followed from exposure to solar energy. Consequent disturbed isostasy and resultant crustal ruptures, with liberation of earth heat, restored the oceans to a few degrees above the critical temperature and thus restored the cloud sphere in these latitudes with its interceptions of solar energy. Repetitions of these actions and reactions followed until crustal stability was attained in these latitudes in so far as their loading by glaciation and unloading by deglaciation would bring about this result.

In the same manner as the final chill of complete loss of earth heat approached, middle latitudes of maximum precipitation and cloud density,[1] were zonally glaciated and deglaciated as in the zones of least cloud density.

Upon the establishment of crustal stability in the temperate zones of cloud belts and rains ocean stored earth heat ceased to be replenished by ruptures, and ocean temperatures fell below the critical temperatures which yields sufficient water vapor to maintain the cloud sphere in regions of its greatest density. Permanent deglaciation followed, and is yet progressing in polar latitudes of least solar efficiency.

Zonal glaciation was thus first imposed in tropical latitudes by reason of exposure to the zonally disposed anti-cyclonic winds of those latitudes; it was zonally disposed in temperate latitudes by reason of these being the zones of the temperate rain belts. The deglaciation of each of these latitudes was effected by solar energy admitted to the surface as the cloud sphere failed first in tropical and later in middle latitudes. Interglacial epochs were imposed upon each of these latitudes under the same conditions, namely, fluctuations of ocean temperatures as their stored heat was lost and restored between crustal ruptures when at critical temperatures of cloud maintenance either in zones of minimum or of maximum cloud density.

Crustal ruptures were caused at these critical stages by reason of alternate overloading by glaciation, and unloading by deglaciation, thus transferring an evenly distributed load upon ocean bottoms to continents as an unevenly distributed load, which, from its low viscosity accumulated to depths of over a mile, imposing crustal loads of over 4½ billion tons per square mile.

SUMMARY OF THE CAUSES AND CONDITIONS OF GLACIATIONS AND DEGLACIATIONS, AND OF INTERGLACIAL EPOCHS

Under these conditions glaciations were the result of the chilling of continental areas to or below 0° Cent, while the oceans were still warm. The two conditions essential for glaciation are—(1) *Cold Continental Areas*—cold from more rapid chilling where remote from ocean influences, from elevation, from exposure to cold anticyclonic winds, and, upon the final loss of effective earth heat;

[1] Probably also equatorial latitudes under the belt of clouds and greater precipitation in that zone. See note 1, p. 34.

(2) *Warm Oceans,* to supply water vapor in sufficient amounts to deeply glaciate and to maintain continuous cloudiness to intercept solar energy.

There were under the causes and conditions which determine the integrity of the cloud sphere three types of glaciation:

(1) Glaciations occurring upon exposed continental areas in any latitude, particularly areas remote from ocean influences and after a long period of crustal stability; such areas were subject to deglaciation either by exposure to solar energy by temporary impairments of the cloud sphere or by an accession of effective heat from crustal rupture.[1]

(2) Glaciations due to exposure to cold anti-cyclonic winds which reached the surface to maximum extents in the latitudes between 15° and 35° North and South, which latitudes are regions of least cloud density. This is a critical stage in ocean temperatures, for having reached a temperature just capable of yielding sufficient water vapor to maintain cloudiness in these regions of least cloud density a slight fall would impair this density and expose the surface to the effects of a tropical sun; crustal rupture at this stage of disturbed isostasy would temporarily rewarm the oceans and restore the cloud sphere in these latitudes with resulting temporary reglaciation, to be followed by the permanent deglaciation of tropical latitudes.

(3) Glaciations due to the final checking of ruptures of the crust as it approached its present stability and ceased thereby to release increments of earth heat.

This is also a critical stage in ocean temperatures and in cloudiness in regions of greater cloud density—slight ocean fluctuations at this stage would impose conditions alternately favorable to glaciation and deglaciation in these regions or result in the interglacial epochs of temperate latitudes.

Final deglaciation was inaugurated at the culmination of Pleistocene glaciation or the Ice Age, and after the interglacial fluctuations, and is yet progressive in polar latitudes.

When we review the cumulative effects of this rewarming; the deglaciation of millions of square miles of continental areas and the establishment thereon of conditions suitable for man's highest development—the rewarming of the surface of the oceans in middle latitudes—the progressive deglaciation of polar wastes, we have a better mental grasp of the work of that fraction of solar radiation which now reaches the surface of the planet; and also of its conserv-

[1] Huronian and Cretacic glaciations are elsewhere cited as types of this class.

ative effects when a large fraction of its power was intercepted by clouds maintained by the cooling crust and heat storing oceans. The limits of this increase are moderate for the heating of the oceans is checked by increasing evaporation and cloudiness, and the impossibility of warming the cold depths of the ocean from surface exposure is a permanent check upon any future rise in mean temperature beyond very moderate limits.

CLASSIFICATION OF GLACIAL PERIODS, DEGLACIATIONS, AND INTERGLACIAL EPOCHS

We may therefore classify and define glacial periods in accordance with the special conditions under which they occurred:

(1) *Non-Zonal or Minor Glacial Periods* were such as occurred both before and after Permo-Carboniferous time. Those occurring before this period were widely distributed in latitude and dependent upon remoteness from ocean influences and upon elevation; Huronian glaciation may be taken as a type. Those subsequent thereto were due to the same causes but prevailed principally in temperate and equatorial latitudes and possibly extended to polar, the glaciation at the close of the Cretacic may be taken as a type. Glaciations in tropical latitudes subsequent to Permo-Carboniferous time were apparently confined to elevated areas.

(2) *Zonal Glaciations or Major Glacial Periods* were:

(A) In the zones of exposure to cold anti-cyclonic winds;

(B) In the zones of maximum precipitation and cloudiness which were glaciated upon the ultimate failure of earth heat.

Deglaciation.—Deglaciations of non-zonal or minor glaciations were apparently caused: (1) By the increase of temperature inside the constant temperature chamber of moist air and clouds by earth heat which was liberated by crustal ruptures etc., these were in part caused by overloads of glacial ice upon the forming crust; (2) by temporary impairments of the cloud sphere over continents.

Deglaciation of tropical latitudes in Permo-Carboniferous time was caused by exposures to solar energy by reason of the failure of the cloud sphere in these regions of least cloud density.

Deglaciation at the close of Pleistocene time was caused by the final loss of ocean stored heat and the reduction of oceans to that temperature which generated less water vapor than is required to maintain the integrity of the cloud sphere in all latitudes; this permanently exposed the surface to the deglaciating power of solar energy under which no glaciation has been recorded. Fluctuations in ocean temperatures during either of these critical stages would cause alternations of control between the two sources; a temporary local failure of the cloud sphere would cause deglaciation by exposure to solar energy, and a slight rise in ocean temperature would restore the cloud sphere and leave the surface temperatures to the fading effects of earth heat, or would cause reglaciation.

Inter-Glacial Epochs were therefore caused by fluctuations in ocean temperatures during zonal glaciations, and in these phenomena are recorded the alternation of control between the two sources of heat.

The last major glacial period, B, may well be termed *The Ice Age* and may be defined as follows:

The Ice Age was the period just antedating the final loss of ocean stored earth heat and culminated in the final glaciation of land areas in latitudes of maximum precipitation and cloud density.[1]

The decline of The Ice Age was inaugurated as the oceans lost their last effective increment of earth heat and became dependent for any increase of surface temperature upon solar energy, under which exposure sufficient water vapor is not generated, either to maintain cloud density to a sufficient extent to protect glaciated areas or to yield winter snowfall equivalent to summer melting.

THE ESTABLISHMENT OF SOLAR CLIMATIC CONTROL

The change from the dual effects and the climatic control by earth heat to that by solar energy alone was so important a development in the evolution of climates that it is best to review briefly the author's interpretation of the conditions and stages of this change.

It was not effected during any one period, nor in all latitudes coincidently. It was inaugurated just after the culmination of the zonal glaciation of tropical latitudes in Permo-Carboniferous time; and, after short alternations of control, as heretofore explained, ocean-stored earth heat ceased to yield sufficient water vapor to re-establish and to maintain the cloud sphere in the tropical regions of its least density; this permitted a fraction of solar radiation to reach the surface in these latitudes and thereafter to dominate their climates.

So far as the author understands the geologic records, climatic control by earth heat was not re-established in the tropical regions, for this would have required the rewarming of the oceans to that

[1] F. W. Harmer, F. G. S., has discussed "The influence of the winds upon climate during the Pleistocene epoch." Quart. Jour. Geol. Society, Aug., 1901. pp. 405-476.

temperature which would restore the cloud shield and result in another similar zonal glaciation, followed by an alternation of control as it passed away under clearing tropical skies, and permanent solar control of the climates of these zones.

These complex conditions—the glaciation and deglaciation of tropical regions under the zones of anti-cyclonic circulation, while middle, polar and equatorial regions under cyclonic circulation remained mild, present what Professors Chamberlin and Salisbury term "a plexus of problems of unparalled difficulty." Under the assumption of solar climatic control this conclusion is preeminently correct. But these problems appear to present somewhat lighter difficulties and to yield under the interpretation and analysis herein essayed.

During the long interval from and including the Triassic to the establishment of the Modern Era of complete solar climatic control, the two sources appear to have coincidently prevailed—the greater, solar energy, in the tropical zones, in which the integrity of the cloud-sphere had been permanently impaired; and, the lesser, earth heat, in the zones of denser and more persistent cloudiness and in which a lower ocean temperature is capable of maintaining cloudiness than in the zones of its least occurrence.

During the greater part of Triassic time widely distributed mild climates prevailed, but at its close the gradual loss of the available increments of earth heat imposed a milder glaciation during which certain forms of land life deserted the more readily chilled continents and retreated to the milder oceans. Tropical zones under solar control offered more constant mildness and in these a larger proportion of life survived.

Under the influence of the increments of earth heat which were made available by the ruptures near the close of the Cretacic mild conditions were partly restored in regions still under earth heat control. This mildness again gave way near the close of this period, which caused a second permanent migration of land life to milder oceans.

There followed the temperate climates of Eocene and Miocene time, succeeded by the cold temperate climates of the Pliocene.

Pleistocene glaciation succeeded, it marked the final chilling of lands, and oceans chilled to a degree never before attained. "The whole world felt its effects." The great zonal glaciations of this period reached their maxima under the belts of maximum precipitation.

The two great zonal glaciations therefore, reached their maxima under different conditions; both were imposed under earth heat control, but tropical glaciations reached their maxima under the anticyclonic circulations of these latitudes, while Pleistocene glaciations reached their maxima under the cyclonic belts of maximum precipitation; both of these zonal glaciations fluctuated between partial deglaciations and re-glaciations due to alternations of climatic control; and, final de-glaciation, in both cases, was due to solar control—the earlier as the cloud shield failed in its least dense and the later in its densest zones.

Solar control now completely dominates climates, even in the great glaciated areas about the poles; and these and lesser residuals of Pleistocene glaciation are yet slowly and finally disappearing.

THE CLIMATIC TRANSITION ERA

The periods between the culminations of the two major, or zonally disposed, glaciations constitute, therefore, a climatic transition era. During this transition the two sources coincidently prevailed in different zones. The cloud sphere having first permanently failed in the zones of its least density permitted solar radiation to reach the surface and to dominate their climate. Under the belts of densest cloud formation the climates were still dominated by the gradually failing earth heat, which as its final exhaustion approached was too feeble to maintain continental temperatures above 0° Cent.; their glaciation, therefore, followed, reaching maxima under the zones of maximum precipitation. Upon the final chilling of the oceans and the consequent failure of the cloud sphere in its densest zones, deglaciation under solar radiation resulted, and this source remains in the sole control of climates.

PART II

APPLICATION OF THE PRINCIPLES HEREIN SET FORTH TO THE FACTS OF PALEONTOLOGY AND GEOLOGY AS COMPILED AND DISCUSSED BY PROFESSOR CHARLES SCHUCHERT IN "CLIMATES IN GEOLOGIC TIME"

Professor Schuchert's review and presentation of the facts of Paleontology and Geology, bearing upon climatic variations is so accurate, succinct and clear that it is well adapted and lends itself admirably for the application and test of any interpretation of the causes and conditions which controlled Geologic and present climates.[1] Although these facts were compiled under very different conceptions of the causes of climatic variations than is herein presented, the author elects to apply the principles and interpretation herein rendered to Professor Schuchert's masterly presentation.

The temperature curve and the periods of mountain making, or of " changes in the topographic form of the earth's surface," on Professor Schuchert's chart[2] are reproduced on the diagram herewith. The other elaborate data expressed on this chart are not reproduced as they are not essential to the author's presentation of the causes of climatic variations. These variations would have occurred whether the strand lines of continents varied or remained fixed, whether coal or limestone formed or not, and would recur if crustal ruptures should liberate sufficient earth heat to rewarm the oceans.

This temperature curve is manifestly intended for continental variations, but ocean temperatures are mentioned throughout the text; from these an ocean temperature curve is added, and, both curves are extended to indicate the distributions of temperatures during the Modern Era. This requires separate curves to express the mean yearly temperatures of low, middle and high latitudes as neither the existing distribution of ocean temperatures nor of climates conforms to those of geologic time.

[1] The Climatic Factor, Dr. Ellsworth Huntington, Publication No. 192, Carnegie Institution of Washington, Smithsonian Institution, Report 1914, pp. 277-311.

[2] *L. c.* p. 305.

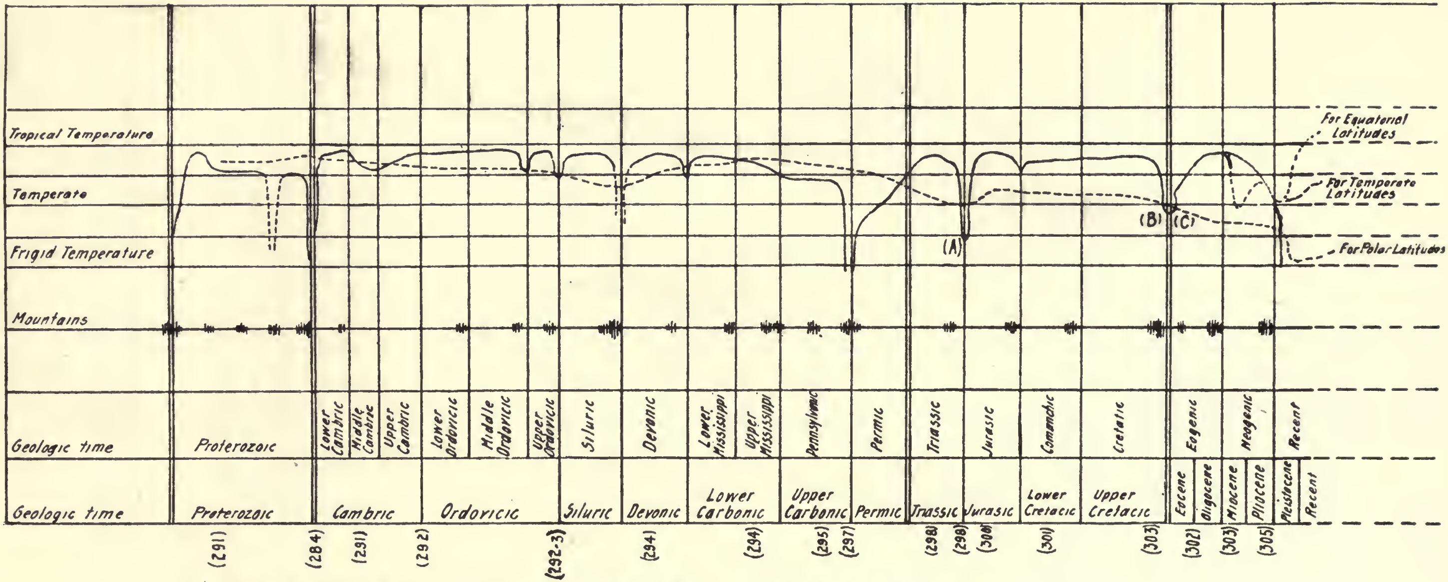

CHART OF GEOLOGICAL CLIMATES.

{ AFTER SCHUCHERT Smitsonian Report 1914 Page 305 }

Land Temperatures ⌒
" Temperatures (recent) .... } Added
Ocean " – – – – – – – – }

(A) Land reptiles retreated to the oceans.
(B) Scaled reptiles and tortoises retreated to the oceans.
(C) Forebears of whales, porpoises, dolphins, seals, sealions etc. retreated to the oceans and became permanently marine in habit.

NOTE:
Numbers in brackets refer to page in report.

THE CLIMATIC FACTOR, pub. 192 Carnegie Institution of Washington. Climates in Geologic Times by Prof. Schuchert p. 285 also Report Smithsonian Institution 1914 p. 305.

An inspection of the curve of continental temperatures shows that there were thirteen (13) short-period depressions, as follows:

(1) *At the dawn of Proterozoic time.*
(2) During Proterozoic time.
(3) *Between Proterozoic and Cambric time.*
(4) During Middle Cambric time.
(5) Between Middle and Upper Ordovicic time.
(6) Between Upper Ordovicic and Siluric time.
(7) *Between Siluric and Devonic time.*
(8) Between Devonic and Lower Carbonic time.
(9) BETWEEN UPPER CARBONIC AND PERMIC TIME.
(10) Between Triassic and Jurassic time.
(11) Between Jurassic and lower Cretacic.
(12) Between upper Cretacic and Eocene.
(13) BETWEEN PLIOCENE AND THE MODERN ERA.

OCEAN TEMPERATURES DURING GEOLOGIC CLIMATES

The following ocean temperatures are noted in the text of Professor Schuchert's review:

Proterozoic (p. 291). "Warm waters teeming with life."

Lower Cambric (pp. 283-4). "The world over tropical and subtropical."

Lower Cambric (p. 291). "Fairly uniform the world over."

Early Cambric (p. 292). "Relatively mild."

Ordovicic and Siluric (pp. 292-3). "Mild and uniform."

Devonic (pp. 293-4). Cooler oceans and local continental glaciations.

Middle Devonic (p. 294). Warmer conditions.

Late Devonic and Carboniferous (p. 294-5). World wide warm waters.

Upper Carbonic (p. 295). Relatively uniform and mild, sub-tropical in places and extending into the polar circles.

Permic (p. 297). Marine life much like that of the coal measures.

Triassic (p. 298). Nearly uniform distribution of warm waters over a great part of the globe.

Between late Triassic and earliest Jurassic (pp. 298-9). Cooler climates, not local but of a general nature, local continental glaciation.

Middle and Upper Jurassic (p. 300). Warm throughout the greater part of the world, cooler but not cold waters in the polar areas.

Cretacic to Eocene (p. 303). No marked climatic change but a reduction in temperature marked in marine life.

Middle Miocene (p. 303). Temperate waters, Atlantic and Pacific.
Late Pliocene (p. 304). Polar waters were cool.
From this data the curve of ocean temperatures is laid out.[1]

COMPARISON OF THE CURVES OF CONTINENTAL AND OF OCEAN TEMPERATURES

These curves distinctly mark two significant facts:

(1) That continents fluctuated between tropical and glacial temperatures, the depressions being short and of varying intensity with two distinct minima: Between upper Carbonic and Permic time, (9), and, between Pliocene and Recent Time, (13).

(2) That oceans fluctuated between more moderate limits, and reached glacial temperatures only once in geologic history, namely: Near the close of Pleistocene time.

The distinct periods of zonal glaciation were notably different in locality, in succession and significance: The earlier, Permo-Carboniferous time (9), was preceded and succeeded by periods of universally warm climates, and was accompanied throughout with warm oceans. The glaciations were localized in the zones between latitudes 15° and 35° north and south, or they occupied the north and south tropical zones of minimum cloudiness and rainfall of the Modern Era. Judged by depth of tillite they were the severest recorded. They gave place to the succeeding widely distributed milder conditions of Triassic time after a series of deglaciations and reglaciations.

The last Pleistocene time (13) was as distinctly localized in the middle latitudes of the temperate rain belts of the Modern Era, and extended into polar latitudes. Both middle and Polar latitudes escaped in the former period of maximum glaciation; or, the zones of maximum glaciations in either period escaped in the other. This glacial period was preceded by the cold temperate oceans of Pliocene time when "polar waters were cool"; *it was accompanied by glacial oceans,* in middle and polar latitudes, and, was succeeded by the zonally distributed temperatures of today, ranging between the torrid climate of equatorial latitudes and the glacial climate of polar latitudes. It merged into these conditions after short periods of deglaciation and reglaciation in middle latitudes, gradually receding to the progressive deglaciations of polar latitudes and the upward retreat of the snow line in all latitudes and a rewarming of the surface of the oceans in middle latitudes, which is greater in the narrow Atlantic than in the broad Pacific ocean. This deglaciation and re-

[1] See Also *White and Knowlton.* SCIENCE, N. S., Vol. XXXI, p. 360.

warming of both continents and oceans marks a decided amelioration of climates since the culmination of The Ice Age, or a warming earth.

The chill of this glacial period extended over the entire globe, continents as well as oceans—it was severest in middle latitudes, notably in the Northern Hemisphere, where there were land areas to receive it, and affected tropical and torrid latitudes by the lowering of the snow line at least several thousand feet, and *for the first time the two curves of land and ocean temperatures reached the inferior limit practically concurrently, all other continental depressions of moment causing intersections with the ocean temperature curve.* THESE PHENOMENA MARK THE GLACIAL PERIOD OF PLEISTOCENE TIME, OR THE ICE AGE, AS THE CLIMACTERIC PERIOD OF THE GEOLOGIC HISTORY OF THE EARTH.

In which Age solar control of surface temperatures, inaugurated in Permo-Carboniferous time in tropical latitudes, was finally effected, and earth heat ceased to be a sensible factor in climatic control. The fluctuating climates incident to this local factor passed into geologic history and glaciation ceased to be a recurrent or a probable progressive condition, and the earth became a heatgathering or warming body.

THE PERIODS OF MOUNTAIN MAKING OR OF "CHANGES IN THE TOPOGRAPHIC FORM OF THE EARTH'S SURFACE"

Nearly or quite coincident with each period of sharp depression and rise in the curve of continental temperatures there is a period of crustal adjustment and rupture, except in the latter part of the rise in temperature now in progress and as noted in slow glacial retreat and the corresponding advance in life. There were other adjustments which do not appear to have been accompanied by such marked temperature changes, but these are less in number. The connection between these changes in temperature and crustal rupture is threefold—First, the long interval of stability preceding each permitted continents to cool and be partly loaded by glaciation; second, this glaciation disturbed the isostasy of the forming crust and caused conformable adjustments; and finally, the heat thus liberated tended to restore continental temperatures and the stored heat of the oceans. During the two periods of maximum glaciation, these readjustments seem to have been repeated and were accompanied by several short epochs of deglaciation and reglaciation.[1]

In these, consequent actions and reactions is manifestly offered, an answer to Professor Schuchert's question: "What is it that forces

[1] The Great Ice Age, Professor J. Geikie, p. 790, (ed. 1894).

the earth's topography to change with varying intensity at irregularly rhythmic intervals"?[1]

There were doubtless other causes, but non-uniform glacial overloadings and the restorations of these loads uniformly distributed over the ocean bottoms must have imposed serious disturbances to isostasy; these made themselves manifest at the close of each period of crustal stability which preceded the several glaciations.

From the earliest Proterozoic to the close of Pleistocene time Professor Schuchert notes thirteen (13) periods of depression of continental temperatures and one of ocean temperatures. These have been previously recited and are indicated on the diagram.

Two of the glaciations accompanying these depressions were of notable extent and severity and were distinctly zonal in their occurrence and maxima; they were also characterized by Interglacial epochs, and by the escape of the latitudes glaciated in one during the glaciation of the other. The first was Permo-Carboniferous and the latter Pleistocene glaciation.

All of the other depression of continental temperatures do not appear to have been accompanied by glaciation—at least of marked extent, but most of them recorded their occurrence by deposits of tillite in various latitudes, so that there can be little doubt of the action of ice over considerable areas.

The two zonal glaciations were of such striking characteristics and significance that they will be considered separately; the occurrence of interglacial epochs were incidents common to both, and their similarity was manifestly imposed by similar causes and conditions acting at widely separated periods and latitudes, and marked alternations of conditions first favorable to glaciation and then to deglaciation before finally yielding to the latter.

The non-zonal or minor glaciations, if we may call them such, occurred both before and after Permo-Carboniferous glaciation and there were no especial features nor conditions differentiating one from the other. They range in time from the earliest to the latest era, in latitude throughout the temperate, tropical and torrid zones of today, possibly into the polar.

Applying the principles herein advocated these depressions in continental temperatures were caused by the failure of earth heat to maintain the temperature of continents above freezing during the intervals between the ruptures noted on the diagram, which from time to time made increments of earth heat available as climatic

[1] *L. c.* p. 311. Carnegie Institution, Pub. 192, p. 298.

factors, and restored more genial conditions inside the cloud-sphere, and replenished the stored heat of the still warm but slowly cooling oceans. Each of these glaciations recorded the fact that solar energy was not available to prevent it although in latitudes which would have been exposed to its power unless intercepted by an effective agent—for there is a significant absence of any evidence which would show entire solar control of the temperature and ice distributions during any of the eras prior to the present, except those solar influences which manifestly imposed a zonal distribution of ice in Permo-Carboniferous and Pleistocene glaciations, without being able to prevent their occurrence in latitudes which could not have been glaciated under exposure to its heating effects; and, in the deglaciations of these latitudes. In this respect all glaciations, even the short period reglaciations following interglacial epochs, distinctly record the fact that they were independent of direct solar heat control and not ascribable to variations in solar energy, by reason of the contradictions and anomalies involved in any assumption or hypothesis assuming or predicating such control.

In all particulars both the non-zonal, minor glaciations and the greater zonal glaciations and accompanying interglacial epochs contradict any assumption of solar control. They however answer and agree in every particular as phenomena occurring inside a constant temperature chamber of moist air and clouds, practically impenetrable to radiations from either source of heat and enclosing a globe with surfaces of different specific heat which were both dependent upon the interior supply—which was not only intermittently made available and slowly lost through the walls of moist air and clouds, but conserved in the fields of its actual loss in the outer atmosphere by the practically constant and far more powerful source, solar energy.

As the more quickly cooling, lighter and weaker portions of the crust and the atmosphere lost their heat, exposed areas in any latitude were glaciated and the materials composing tillite were shifted by glacial erosion and flow, until the isostasy thus disturbed and the resistance of the crust being overcome its rupture followed with the consequent liberation of the interior heat supply, acceleration of denudation and exposures of radio-active materials. The repetition of these reactions is recorded at the close of long periods of crustal stability by the coincident occurrence of glaciations closely followed by a general increase in temperature, due to the setting free of increments of earth heat.

There were specific conditions imposing more severe glaciations along zonal lines, first in the tropical and later in the temperate latitudes of today, with accompanying interglacial epochs which must be dealt with under separate headings, although their prime causes were the same—a failure of earth heat inside the constant temperature chamber. But in the cases of interglacial epochs, these failures were complicated with the cooling of the oceans to certain critical temperatures which must be fully considered.

A COOLING AND A WARMING EARTH

Professor Schuchert's perplexity, "Further a cooling earth is yet to be demonstrated,"[1] appears to be demonstrated by the Geologic record of climates which registers first a cooling and later a warming earth.

A COOLING EARTH

A cooling earth during long eras of fluctuating continental temperatures, varying inside its heat retaining and protecting walls of moist air and clouds between approximate limits of 50° and minus 5° Cent.

During these eras the heat held in the non-conducting and forming crust was slowly and intermittently liberated so that the worked over materials which at one time or another were in contact with water, probably measure scores of miles in thickness. This heat, conserved by effective processes imposed by itself through water in its various forms, and under partial replacement from solar radiation in the fields of its actual loss, has performed nearly all the work recorded during geologic climates.

Cooling oceans record a loss of heat more slowly and within fluctuations of narrower limits; but none the less wide and effective when the extreme temperatures of Proterozoic or early Paleozoic oceans are compared with Pleistocene and modern oceans. The former were tropical and warm temperate and no colder in their deeps than the coldest surface temperatures. The latter are, with the exception of the surfaces of temperate, tropical and equatorial oceans, still near the freezing point of water, or at the temperature of polar oceans.

The successive cooling of continents as the forming crust lost its heat is recorded in several minor and two major glaciations. The glaciation between latitudes 15° to 35° north and south and the subsequent glaciation of middle and high latitudes brought the greater portion of the land surfaces into contact with ice. The final chilling of the oceans brought over 70 per cent of the crust into contact with water at its minimum temperature, which with polar oceans and continents yet remain at about 4° Cent.

[1] Report Smithsonian Institution 1914, p. 311.

Thus nearly the entire surface of the lithosphere has been brought into contact with ice or with water at its lowest temperature and about 80 per cent is yet at this temperature.[1]

A WARMING EARTH

Professor Schuchert did not extend his continental temperature curve into the Modern Era so as to note the amelioration of surface temperatures which solar radiation has wrought since the vast glaciations of the Ice Age. The same energy and conditions which brought the deglaciations recorded since Pleistocene time are yet active and their effects are yet cumulative.[2] A cooling, and, later a warming earth could not be more clearly recorded nor more impressively demonstrated.

This rewarming was inaugurated by a new control which itself provides a moderate limit against excessive heating, under this new control have been and are being developed higher, nobler types of life, at the head of which stands the human race.

PERMO-CARBONIFEROUS AND PLEISTOCENE GLACIATIONS AND INTER-GLACIAL EPOCHS

There are, therefore three important and notable chapters in geologic history which demand attention not only by reason of their analogies and apparent anomalies, but because they furnish crucial tests of any explanation or interpretation of the causes and conditions which controlled geologic climates and the period during which they " merged without abrupt change " into those of the Modern Era.

These chapters are:

(1) Permo-Carboniferous Glaciation.

(2) Pleistocene Glaciation.

(3) The Inter-glacial Epochs.

PERMO-CARBONIFEROUS GLACIATION

This glaciation was distinct in locality, extent and occurrence. " It lies in the midst of geologic history with periods of great uniformity and remarkable polar geniality both before and after it."[3]

[1] The author has not had an opportunity to observe extended areas within the torrid zone; but the topographic forms and physiographic features described by others indicate to him, and he has expressed the probability, that continental areas under the equatorial cloud-belt were glaciated in Pleistocene time.

[2] Science, N. S., Vol. 47, No. 1200, pp. 639-640, and authorities there quoted or referred to; *ib.* Vol. XLVII, No. 1220, pp. 487-488.

[3] Geology, Chamberlin and Salisbury, Vol. II, p. 656.

The glaciations of this period were distributed in the latitudes of the tropical arid zones of today, or between latitudes 15° and 35° north and south.[1]

No cold temperate climates of wide extent, such as that of Pliocene time, preceded them, although a cold temperate flora was locally developed adjacent to the glaciations and gave way to the milder forms of life of Triassic time. Warm temperate and tropical life apparently flourished between the zones of glaciation in a broad equatorial zone some 30 or more degrees wide and north polar latitudes were " frequented by ferns, corals, figs and magnolias.[2] The data for determining Antarctic climates of Permo-Carboniferous time are meagre, but inferentially they were also temperate.

Temperate latitudes, which later in Pleistocene time were deeply glaciated, also escaped in the period of maximum glaciation of tropical latitudes.

There are therefore presented in Permo-Carboniferous time zonal glaciations, deglaciations and reglaciations in latitudes which could not have been glaciated under direct solar control; the absence of complete solar control is made manifest by the fact that polar and middle latitudes which, under such control should have also been glaciated remained mild. Repeated partial deglaciations and reglaciations of tropical latitudes, assumed to have been under solar energy, are recorded, but without evidence of a zonal arrangement of climates; these conditions merged into the universally mild climate of the Triassic, such as that which in Carboniferous time, preceded these glaciations—an admittedly complex set of conditions, not explicable under solar control, and not possible of assignment entirely to earth heat control.

Of these conditions Profs. Chamberlin and Salisbury remark:

> Between a marvelous deployment of glaciation, a strangely dispersed deposition of salt and gypsum, an extraordinary development of red beds, a decided change in terrestrial vegetation, a great depletion of marine life, a remarkable shifting of geographic outlines, and a pronounced stage of crustal folding, the events of the Permian period constitute a climateric combination. Each of these phenomena brings its own unsolved questions, while their combination presents a plexus of problems of unparalleled difficulty.[3]

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[1] Compare plates 17 and 18 and p. 16, BARTHOLOMEW'S PHYSICAL ATLAS, Meteorology; and, Schuchert's chart of early Permic Glaciation, Smithsonian Report, 1914, p. 281.

[2] Sir A. Geikie, Geology, Vol. II, p. 1081. Chamberlin and Salisbury, Geology, Vol. II, p. 677.

[3] Geology, Vol. II, p. 655.

Under the controlling principles and conditions outlined in Part I, the first regions to be subjected to zonal glaciation were the anti-cyclonic zones of cold descending winds. Lands in these zones were exposed to glaciation from warm oceans until they chilled to that degree which impaired the cloud sphere in the bands of its least density. As heretofore held this a critical ocean temperature, readily fluctuating from increments of earth heat between that degree which would fail to sustain or that which would restore the cloud sphere. Each failure would expose the surface to the deglaciating power of solar energy, and each restoration would intercept this energy and leave surface temperatures to the effects of the fading supply of earth heat. Crustal ruptures might liberate sufficient earth heat to partially deglaciate, but the ultimate effect would be to restore glaciation until more slowly cooling oceans again sufficiently lost their stored portion of this increment of earth heat to again permit the clearing of tropical skies and reimpose deglaciation under solar energy, and finally establish its control.

These phenomena were therefore not manifestations of short period variations of solar energy, but of alternations of control of surface temperatures, first by the slow loss of earth heat liberated by crustal ruptures, etc., and then by solar energy admitted to the surface by failures in the continuity of the cloud sphere. In these climatic complications are presented the dual and the alternate effects of the two sources of heat. The one being gradually exhausted and put into temporary effect through crustal ruptures, denudations, exposures of radio-active materials, chemical and physical actions and reactions etc., the other, a practically constant source, intermittently and finally permanently admitted in control in these zones of least cloudiness, by temporary and later final failure of the cloud sphere in these latitudes. They have not since been subjected to severe glaciation, although the final chill of the oceans in the subsequent Ice Age of Pleistocene time may have extensively lowered the snow line in tropical and equatorial latitudes. Partial and later final deglaciation of tropical latitudes is therefore recorded in the phenomena of Permo-Carboniferous glaciation and deglaciation as recited by Professor Schuchert.

CLIMATIC CONDITIONS BETWEEN PERMO-CARBONIFEROUS AND PLEISTOCENE TIME

Following this period of maximum glaciation in tropical latitudes and up to the succeeding one in temperate and polar latitudes there lies a group of periods embracing fluctuating climates; these were principally tropical and warm temperate of wide distribution, but broken by short glaciations of less marked extent than the others; and closed with the widely distributed cold temperate climate of Pliocene time.

The oceans, throughout these periods, remained tropical or temperate until the Pliocene and early Pleistocene when cold temperate oceans succeeded.

As in the minor glaciations prior to Permo-Carboniferous time so on elevated regions, on the interiors of continents, where cold air could descend to the quickly cooling land and on the easterly shores of continents minor glaciations occurred. These were similar to those preceding Permo-Carboniferous, with the restriction that they were not so common in tropical latitudes, as these apparently remained under solar control.

PLEISTOCENE GLACIATION

This, the last and widest glaciation in latitudinal effects reached its maxima in temperate and polar latitudes. Its greatest deployment was under the widest extent of continental areas between latitudes 40° and 60° North. Corresponding land areas in the southern hemisphere were also deeply glaciated but their extent was restricted by the limited areas of the southerly part of South America, South Australia, Kerguelen, New Zealand, and smaller islands. These glaciations were under the temperate rain belts of the Modern Era.

The zones from which glacial dispersion took place in the widest land extents under the north temperate rain belt were not the mountain divides, but a line of maximum precipitation which corresponds with the track of maximum storm frequency of the present era.[1]

From this belt glacial dispersion, modified by orographic features, appears to have reached latitude 38° in the valley of the Mississippi, latitude 65° in that of the MacKenzie, latitude 48° in that of the Volga, and into the Arctic Ocean and the White Sea.

Polar latitudes, which escaped in the Permo-Carboniferous, were deeply glaciated for the first time in Pleistocene time. Their maxima were reached probably later than those of temperate latitudes and deglaciation has and is proceeding more slowly, as they are least exposed to solar radiation and yet remain deeply glaciated. Deglaciation is, however, progressing under solar control in both Arctic and Antarctic regions, which, taken in connection with the corresponding

[1] See Plates 28 and 29, Bartholomew's Physical Atlas, Vol. III.

deglaciation of temperate latitudes, calls for ultimate and corresponding deglaciation of polar regions.[1]

Oceans for the first time in geologic history reached glacial temperatures in middle and polar latitudes—but such low temperatures do not appear to have been imposed upon oceans in tropical latitudes, as these shared in the ameliorating influences of solar energy, which reached these latitudes after the oceans fell to that temperature which depleted cloudiness in these anti-cyclonic zones of least cloudiness.

Glaciation was therefore more extended in Pleistocene time than at any other period of geologic history.[2]

These conditions " shaded without abrupt change of any kind into what is termed the Human or Recent Period." (Geikie).

There is therefore presented in the glacial phenomena of the Pleistocene period, or Ice Age, the culmination of a series of remarkable climatic phenomena merging into present conditions after two widely separated periods of zonal glaciations, and of periods of minor glaciations, all laid down unconformably to the climates into which they have shaded and which are distinctly under solar control.

INTER-GLACIAL EPOCHS

The merging of one condition into the other was accomplished through a remarkable series of minor changes from conditions favorable to glaciation into those unfavorable thereto, characterized as *inter-glacial epochs.* Of these and their causes Professor Schuchert remarks, " The causation for the warmer interglacial climates is the most difficult of all to explain, and it is here that factors other than those mentioned may enter." [3]

The explanation which the writer offers for these complicated conditions involves three factors:

(1) *Solar Energy,* to which the earth, whatever its conditions, has been exposed throughout its cosmic existence, and which has been nearly constant, so far as our knowledge goes, during geologic time.

(2) *Earth Heat,* locked during geologic time in a practically nonconducting crust from which it has been released by the various pro-

[1] Science N. S. Vol. XLVI, No. 1200, pp. 639-640, Dec. 28, 1917. Proc. 10th Session International Geol. Congress, Mexico, 1906, *ib.,* 11th Session Stockholm, 1910, p. 1102.

[2] " The distinguishing feature of the Pleistocene period is its phenomenal glaciation."

Chamberlin and Salisbury, Geology, Vol. III, p. 327.

" The whole world felt its effects." *Ib.*

[3] *L. c.* p. 311.

cesses of rupture, denudation, the exposure and transformation of radio-active substances, volcanism, etc.

(3) *The conditions under which these two sources of heat have acted,* and which were imposed through the functions of moist air clouds and warm oceans, these shut in the interior supply as liberated from the forming and non-conducting crust, inside a constant temperature chamber of moist air clouds and outer media, into which was brought into available use the several increments of earth heat as freed by various processes, here it acted as the controlling temperature factor in whole or in part until its final loss was recorded by glacial ocean. Upon the outside of these walls solar energy wrought its constant effects and was zonally admitted first in the bands of least cloudiness and later in those of greater cloud density, each zone being subjected to a fluctuating admittance of this source of energy by reason of slight fluctuations in ocean temperatures when at critical stages in the generation of sufficient or insufficient water vapor to maintain cloudiness in the zones of its varying densities.[1]

The author realizes that he may have somewhat broadened the masterly presentations of Professor Schuchert and that his record of geologic facts has been prepared under conceptions of the control of geologic climates totally different from that herein presented. It is hoped, however, that the reasons for this radical difference as given in Parts I and II are justified upon the basis therein recited; and, that the marvelous records of geologic climates and their gradual change into those of the present will be found to fit into the present interpretation better than they have into the assumption of solar control.

[1] These changes have been discussed on pp. 33 *et seq.*, 39 *et seq.* and 46. It is not necessary to repeat the views there expressed.

PART III

RECAPITULATION OF CONCLUSIONS AND THEIR GENERAL APPLICATION

SUMMARY OF CONCLUSIONS

These studies have resulted in the conclusion that a logical application of the known principles of atmospheric physics; of the heat conserving functions of water in its various forms and their action upon radiant energy, the intermittent liberation of heat from the non-conducting crust by ruptures and its exposure to denudation and to the setting free of radio-active energies, together with the further conservation of this heat through the utilization of solar energy in and beyond "the true radiating surface" of the planet are competent to explain the variations and developments of geologic and present climates without resort to assumptions or "working hypotheses" of any kind; and, that all climatic phenomena come within reasonable explanation upon the rejection of the assumption of solar climatic control prior to that era during which this control is distinctly demarked in zones of climate.

These conclusions are so radically at variance with those reached by all others who have essayed these problems that it may be well to specifically recapitulate these conclusions.

1. The assumption that solar control alone prevailed during any period of geologic time is rejected. The basis of this rejection is, the complete failure of any and all attempts to fit the facts of geology thereto and the contradictions and anomalies which this control cannot meet. This carries with it the rejection of mathematical calculations limiting the time and effects of earth heat influences, which are used to fortify the assumption of solar control. The basis of the rejection of these results is the inadequateness of the assumed factors and the omission of the larger and more important ones, which controlled the conservation of earth heat; and also, because these calculations were made before the sources of heat rendered available by the exposure and transformation of radio-active materials were discovered.

2. It is held that this heat, conserved by a non-conducting crust, stored in the oceans and liberated as a climatic factor by slow denudations and exposures of radio-active materials, by faults, fractures,

ruptures, volcanism, and other changes of its topographic forms, was a factor in temperature conditions until the exhaustion of its last effective increments from the oceans in Pleistocene time.

3. That the supply of ocean stored heat replenished from time to time by the above processes kept the oceans warm until near the close of geologic climates as attested by the character and distribution of fossil marine life by the distribution of temperatures and of ice; they fluctuated through very moderate limits and fell to glacial temperatures only in Pleistocene time.

4. That oceans at these temperatures do not generate sufficient water vapor to maintain more than the present 52 per cent of cloudiness which admits solar energy to the lower and denser strata of the atmosphere and to the surface, which it warms. The earth then emits long wave length radiations which are trapped or absorbed in the atmosphere. This process, within certain reasonable limits is cumulative, and results in a gradual amelioration of the conditions of Pleistocene time.

The oceans at the higher temperatures of pre-Pleistocene time maintained a far denser and more continuous cloudiness, which shut in earth heat and intercepted and utilized solar energy in the upper atmosphere as a further conservative influence.

5. That the interposition of this cloud sphere imposed two highly conservative conditions upon the further conservation of earth heat: (a) The moist air and clouds are practically impenetrable to the radiations emitted by the planetary surface, and the loss of this heat through these media was restricted to the interchange of water in its various forms in the atmosphere and of the action of cyclonic and anti-cyclonic circulation as fixed by solar radiation; (b) solar radiation as a source of heat was restricted to the part of a conservator of earth heat by its absorption and utilization upon and above the cloud sphere, and was admitted to the lower regions of the atmosphere and to the planetary surface as a controlling factor by reason of impairments in the cloud sphere.

6. That continents thus protected from solar radiation, and by reason of low specific heat and elevation frequently reached glacial temperatures during the intervals between outbursts of earth heat from the forming crust, during which intervals adequate earth heat was not available to prevent glaciation, nor was solar radiation available by reason of the intercepting cloud sphere. They were also exposed under the same condition to two periods of maximum glaciation, first in the regions of cold downcast currents of anti-cyclonic

latitudes, and later to the chill of final refrigeration in Pleistocene time.

7. That during geologic time, as now, the functions of solar radiation prevailed in fixing zones or belts of cyclonic and anti-cyclonic circulation, of maximum and minimum barometric pressure of consequent cloud densities and belts of maximum and minimum precipitation, but its heating or temperature effects were intercepted by clouds maintained by warm oceans and the available supply of earth heat inside the constant temperature chamber of moist air and clouds. Under these conditions the *supply* of water vapor was dependent upon the stored heat of the oceans and its *disposition* as a circulating agent in the form of vapor, clouds, rain and snow was fixed by solar radiation acting on the spheroid of air and clouds, these effects in no material way differing from the present dispositions, except more uniformity in the exposed surface than at present offered by land and sea and variability in clouded areas.

8. That upon the acquisition of a stable crust by the slow processes of cooling, and, by the overloading of continents at various periods with glacial ice and the removal of these overloads under the effects of solar energy the liberation of increments of heat ceased, and the oceans chilled to their point of maximum density. This degree is too low to generate sufficient water vapor to maintain continuous cloud density at any latitude, and leaves surface temperatures under the control of solar radiation. Under this control glaciation is not possible until this source of energy shall decline to an effectiveness less than that now reaching polar latitudes. That should this period arrive a type of glaciation not yet recorded would follow.

9. Under the rewarming effects of solar energy temperatures must continue to rise until the surface of oceans shall rewarm to a degree which will increase evaporation therefrom and impose a check to farther rise in temperatures by increased cloud extension and density.

POSSIBILITY OF FUTURE GLACIATIONS

Within the field of speculative cosmology future glaciations of the earth are possible from two causes:

(1) In the progress of stellar evolution, at some remote eon of time solar energy may decline to a maximum efficiency less than that now deglaciating polar latitudes and less than that now seasonally melting off the polar snow caps of Mars. The ensuing glaciation would be unlike any yet recorded—it would be inaugurated in polar

latitudes and it would be light, since cold and freezing oceans do not yield sufficient water vapor for severe glaciations.

(2) A cataclysmic rupture of the crust which would liberate sufficient earth heat, now locked within its non-conducting crust, to re-warm the oceans. This would re-inaugurate geologic climates and the ultimate chilling of land masses with still warm oceans and resultant dense clouds would give a corresponding series of climatic events to that recorded within the reach of the geologist.

It is not improbable that such phenomena may have characterized pre-geologic eras; and that the eras of geologic history are only the last chapters of the formation of the fully tested and stable crust.

Under neither of the above possibilities may future glaciation be regarded as an impending event.

APPLICATION OF CONCLUSIONS

As stated in the Preface, the object of this work is to offer an interpretation of the causes, conditions and controlling principles of the climates which the earth has manifestly undergone during geologic and present time.

It was indicated that the conclusions would be applied to the analogies apparently offered by other planets. Such application can now be made only under a broad interpretation of the features presented by the planets which are selected for this purpose.

If the principles herein used for the interpretation of the climates of the earth have been rightly selected and applied and the conclusion correctly reached and found to fit the geologic record and present conditions, these conclusions have certain general applications to the other members of our system. This is brought out in the quotations from Herschel, Chamberlin and Salisbury, Barnard and Campbell.

During the greater part of geologic time, it is held that the earth was swathed in clouds ranged in zones parallel with the equator. This cloud sphere was practically continuous and presented a surface of high albedo—that of clouds, or about .60. At present this surface is broken and the albedo has been lowered by the exposure of about 48 per cent of its dark surface. Moreover, it is known that the violet end of the spectrum is utilized to a greater extent than the red end, and hence this end controls the color of the reflected ray.[1]

It follows that a planet in this or in a later stage of climatic development has a low albedo, and the color of its reflected light is that of

[1] Hence the copper red of the "earth shine" on the new moon, which reflects greatly reduced but normal light from the crescent.

the least utilized end of the spectrum. The earliest of these stages must be presented by the larger planets, whose masses have imposed a longer period of cooling and they present a cloud-banded surface of high albedo.

The latest stage must have been reached by the smaller planets which, having cooled more rapidly, have reached a more advanced stage and present a surface of low albedo, utilize the violet end of the spectrum and reflect light deficient in this color.

The first stage appears to be presented by the great planet Jupiter, which seems to be shrouded in dense clouds maintained by its own heat, and exposes a surface of high albedo 0.62, with banded zones and spots having varying tangential velocities and moving freely in its atmosphere. The heat emanating therefrom is about of that intensity which should be derived from reflected solar energy. The reflected light is normal and white, which shows that neither end of the spectrum is utilized or trapped to a greater extent than the other, as is the case with the earth and Mars. All the conditions are similar to those which a densely clouded earth would present to an observer in interplanetary space.

Mars, on the other hand, presents a clear or slightly cloudy atmosphere, through which the features of the surface are faintly observed, notably the alternate formation and melting away of polar snow caps as these are seasonally turned away from or towards the sun. The albedo is low, only .26, the violet end of the spectrum is manifestly utilized to a greater extent than the red end and hence this latter color prevails in the reflected light.

Polar ice caps are lacking and in their stead polar snow fields form in winter and melt off in summer, foreshadowing the conditions of the earth's polar regions when energies and conditions now active shall have deglaciated, first the north polar regions in the land hemisphere and later the ocean bound regions of Antarctica.

Three distinct stages of climatic evolution are therefore apparently presented by these three planets. Jupiter, in the stage through which the earth has passed; the earth in the stage of the gradual development of solar controlled climates; Mars in a more advanced stage towards which our present developments are tending.

If the eras of climates through which the earth has manifestly passed and the changes now passing before us have herein been referred to their proper principles and correctly interpreted, the "intricate problems which have hitherto baffled the geologist" may prove grander by reason of their simplicity and unity.

But the conclusions herein reached traverse those which are reached by able scientists and which are taught in the great universities.

The principles upon which they rest are believed to be sound and the prime question is *are these applications of them correct?* They will therefore have to be judged with severe caution, attacked and hammered from every standpoint, and accepted only after sound judgment shall determine that they fit and correctly interpret the wonderful records in the crust of the earth. Aye, more, that they yield analogies of use in correctly judging the conditions apparently reached upon other members of the family of planets to which the earth belongs.