AN ATTEMPT TO FRAME A WORKING HYPOTHESIS OF THE CAUSE OF GLACIAL PERIODS ON AN ATMOSPHERIC BASIS

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AN ATTEMPT TO FRAME A WORKING HYPOTHESIS OF THE CAUSE OF GLACIAL PERIODS ON AN ATMOSPHERIC BASIS[1]

I.

THERE are hypotheses and working hypotheses. The suggestion that the last glacial period was caused by the passage of the solar system through a cold region of space may be styled a hypothesis, but scarcely a working hypothesis in the geological sense, for it does not form the groundwork or incentive of geological inquiry. An astronomer might be moved to hunt for the cold spot, but it has no inspiration for the geologist. General suggestions of a possible cause do not reach the dignity of working hypotheses until they are given concrete form, are fitted in detail to the specific phenomena, and are made the agents of calling into play effective lines of research. The construction of a concrete working hypothesis suited to stimulate and guide investigation in a wholesome manner, and to take its place in competition with other hypotheses of like working potentialities, thereby inducing a more searching scrutiny of the phenomena and a more varied application of interpretations, represents the higher limit of present reasonable aspiration. It is much too ambitious to hope for a demonstrative solution of the origin of the earth's glacial periods by first intention in the present state of knowledge.

The hypothesis here offered is not worked out into satisfactory detail at all points, but it is hoped that it is sufficiently matured to justify a preliminary statement. In forming it, which has been the work of several years, I have found, or seemed to find, the phenomena of past glaciation intimately associated with a long chain of other phenomena to which at

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[1] A brief statement of the salient features of this hypothesis was given in a paper entitled A Group of Hypotheses Bearing on Climatic Changes, JOUR. GEOL., Vol. V, pp. 653–683, Oct.–Nov. 1897. For earlier history see footnotes on pp. 654 and 681 of that paper.

first they appeared to have no relationship. This chain led on and on until it became connected with many of the most fundamental problems of geology. When once an inquiry into the history of the atmosphere and its possible functions in the past was raised, there seemed no resting place until the origin of the atmosphere — and with it the origin of the earth — was reached. The inquiry raised profound skepticism regarding some of the most firmly accepted doctrines of the original state of the earth, its internal constitution, and the great dynamic forces that have controlled the larger phases of its history. A series of new, or partially new, hypotheses relative to these fundamental phenomena seemed to be necessary to fill out the group of alternative theories requisite to cover the ground of legitimate doubt based on specific reasons for doubt. In other papers I have given a partial expression to the hypotheses framed to cover these points.[1] The exposition of these has not in all cases been sufficiently ample to give them good working form, but has perhaps been sufficient to show their general relationship to an atmospheric hypothesis of glaciation.

The hypothesis here offered is confessedly connected in my own mind with these ulterior and more fundamental hypotheses, but it does not seem to me that it is necessarily so connected. To be sure, if it is assumed, following a prevalent custom of the past, that the original atmosphere was a vast gaseous envelope embracing essentially all the carbonic acid that is now locked up in limestone and other carbonates, and all that is represented by coal and other carbonaceous matter, and that the atmospheric history has been essentially a progressive depletion of this original supply, I do not see how the proposed hypothesis can be entertained, at least for the earlier glaciations. But if it be

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[1] A Group of Hypotheses Bearing on Climatic Changes, JOUR. GEOL., Vol. V, No. 7, 1897. The Ulterior Basis of Time Divisions and the Classification of Geologic History, *ibid.*, Vol. VI, No. 5, 1898. A Systematic Source of Evolution of Provincial Faunas, *ibid.*, No. 6, 1898. The Influence of Great Epochs of Limestone Formation upon the Constitution of the Atmosphere, *ibid*, Lord Kelvin's Address on the Age of the Earth as an Abode Fitted for Life, Science, N. S., Vol. IX, No. 235, pp. 889–901, June 30, 1899, and Vol. X, No. 236, pp. 11–18, July 7, 1899.

assumed that as early as Paleozoic times the atmosphere had some such constitution as it possessed in later geological times, and that its history has been a contest between the agencies of atmospheric supply and the agencies of atmospheric depletion, and that the constitution of the atmosphere at any time has been dependent upon the relative rates of supply and depletion, then the hypothesis may be entertained quite independently of all views of the origin of the earth and the atmosphere and of internal dynamics.

Previous advocacy of an atmospheric hypothesis.—The general doctrine that the glacial periods may have been due to a change in the atmospheric content of carbon dioxide is not new. It was urged by Tyndall a half century ago and has been urged by others since. Recently it has been very effectively advocated by Dr. Arrhenius,[1] who has taken a great step in advance of his predecessors in reducing his conclusions to definite quantitative terms deduced from observational data.[2] The great labor involved in this and the specific results springing from it place his contribution on a much higher plane than the general suggestions of those who had preceded him. Valuable as these general suggestions were, they must still be regarded as falling much short of working hypotheses, since no attempt was made to show that changes in the content of carbon dioxide of such a degree as would be compatible with the continuity of life and with other limiting geological conditions were quantitatively competent to produce the effects assigned them; nor were modes of inquiry into this essential matter suggested. It is one thing to point out a theoretical *causa vera*, and quite another thing to give good reasons for believing that it is quantitatively sufficient, and to open lines of inquiry for demonstrating that it is so. This Dr. Arrhenius has done and apparently with great success. While his results are doubtless to be regarded as subject to modification when more full and exact data are at hand,

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[1] On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground, by SVANTE ARRHENIUS, Phil. Mag., April 1896, pp. 237–276.

[2] See review of his paper in this number of the JOURNAL, p. 623.

it is apparent upon inspection that they can be very largely modified and still fall within the limits of the conditions of the case. This will perhaps appear more evident in the course of the subsequent discussion. In so far as the deductions of Arrhenius and the accompanying views of Professor Högbom[1] fail to definitely postulate operative geological agencies competent to produce the requisite variations in the constitution of the atmosphere, and to give reasons for believing that such agencies were in operation at the times requisite to produce the effects assigned them, they fall short of furnishing an ample working hypothesis from the geologist's point of view. This, of course, is the function of the geologist rather than the chemist and the physicist. Professor Högbom has made a valuable contribution to the general doctrine of consumption and supply.

To form a good working hypothesis in a geological sense, it is furthermore necessary to assign subsidiary agencies working in an oscillatory manner correspondent with the oscillations of glaciation now so well authenticated by observation.

Specific requisites of a working hypothesis.—It is obvious that it is necessary at the outset to assign agencies capable of reducing the amount of the carbon dioxide of the atmosphere at the time of the glaciations. If there were no other glaciation than that of the Pleistocene period, and if there were no kindred phenomena needing to be elucidated at the same time, it might be sufficient to point to the well-known abstraction of carbon dioxide from the atmosphere in the formation of limestones and carbonaceous deposits, and there rest the case, with the implication that further production of limestones and carbonaceous deposits would insure further glaciation, and that the permanent and final winter of the earth is at hand. A very slight computation of the rate at which carbon dioxide is now consumed is sufficient to show that an effective depletion of the atmosphere is near at hand unless there be sources of supply approximately equal to the depletion. But recent depletion touches only the

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[1] SVENSK KEMISK TEDSKRIFT, Bd. VI, p. 169 (1894). Quoted in Dr. Arrhenius's paper, p. 269.

easier part of the problem. Whatever may be thought of the supposed signs of cold periods at other early periods, the evidences of glaciation in India, Australia and South Africa near the close of the Paleozoic era are so abundant, so specific, and so well attested, that they cannot be ignored, and any hypothesis that assumes to account for glacial periods must take serious cognizance of these and must meet the strenuous issues that spring from their early age and from the mildness of the periods following them. It seems to the writer almost equally necessary to take cognizance of the salt and gypsum deposits of various periods, which imply degrees of aridity in relatively high latitudes scarcely equaled at the present day. If the atmospheric line is followed, it seems necessary to postulate a reduction of carbon dioxide near the close of the Paleozoic era — to say nothing of other early times — so effectual as to produce glaciation between 20° and 35° latitude on both sides of the equator, a glaciation the deposits of which aggregate a greater thickness than those of Pleistocene times, and whose oscillations, marked by thick accumulations of coal, were even more remarkable than those of the Pleistocene glaciation. If a depletion of the carbon dioxide of the atmosphere sufficient to produce this glaciation at this relatively early stage in geological history is postulated, it is necessary to assign agencies for the reënrichment of the atmosphere in carbon dioxide to account for the mild climates in high latitudes in Jurassic, Cretaceous, and Tertiary times. In short, it is necessary to assign competent operative geological agencies which shall produce effective depletion alternating with effective reënrichment of the atmosphere from an early period in its history down to the present time. If the salt and gypsum deposits, and the prevailing red beds, with arkose elements, be regarded as the products of exceptional aridity, and if this be assigned to the localization and intensification of heat and moisture due to the removal of carbon dioxide, as subsequently set forth, it is necessary to multiply the oscillations from enrichment to depletion very notably, and to extend the alternating action at least as far back as the close of the Silurian period when the great saline deposits of New York, Ontario, Ohio, Michigan and adjacent regions were laid down.

Primary assumptions.— (1) It is therefore assumed as the working basis of the hypothesis that the carbon dioxide of the Paleozoic atmosphere was at certain stages not essentially greater than it is today, that at the specific epochs of great saliferous deposition and of glaciation it was reduced to a quantity notably less than the present content, while at other and intervening stages its amount exceeded the present content by some multiple —these latter periods being those in which the wide extension of marine epicontinental life took place. For myself, I am disposed to extend the assumption of a measurably limited atmosphere back to the very beginning. To this I am led in part by the conviction that the gravitation of the earth is incompetent to hold an atmosphere very greatly beyond the amount so assumed, and by the much more speculative consideration that the earth may have grown up by slow accretion rather than rapid concentration, and that hence the early development of the atmosphere was controlled by limitations much like those that have affected it in its later history. But, as already remarked, this assumption is not regarded as vital to the hypothesis. (2) Wrapped up in the foregoing postulate is an assumption of the essential correctness of the doctrine of Arrhenius that variations of the atmospheric carbon dioxide falling within limits compatible with life and with other geological phenomena, are competent to effectively change the thermal state of the atmosphere. This needs further statement.

The functions of carbon dioxide.— By the investigations of Tyndall,[1] Lecher and Pretner,[2] Keller,[3] Rœntgen,[4] and Arrhenius,[5] it

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[1] Heat as a Mode of Motion, 6th ed., pp. 345–349, 1892. Contrib. to Mol. Physics, pp. 38. 117, 421, 1888.

[2] Sitzungsberichte des Akad. der Wissenschaften d. Wien (2). Vol. LXXXII, p. 851 (2), Vol. LXXXVI, p. 52.

[3] Am. Jour. Sci. (3), Vol. XXVIII, p. 190.

[4] Poggendorfs Annalen (2), Vol. XXIII, p. 1259.

[5] Phil. Mag., Vol. XLI, pp. 237–279.

A brief statement of the conclusions of these authors is given in the article of Mr. Tolman in this number, p. 586. See also his review of Dr. Arrhenius, p. 623.

has been shown that the carbon dioxide and water vapor of the atmosphere have remarkable power of absorbing and temporarily retaining heat rays, while the oxygen, nitrogen, and argon of the atmosphere possess this power in a feeble degree only. It follows that the effect of the carbon dioxide and water vapor is to blanket the earth with a thermally absorbent envelope. Their absence would leave the surface of the earth essentially exposed to the free impact and free radiation of the solar rays, measurably, though of course not entirely, as if the earth were devoid of atmosphere. A reduction or an increase in these constituents would produce corresponding partial effects. The general results assignable to a greatly increased or a greatly reduced quantity of atmospheric carbon dioxide and water may be summarized as follows:[1]

a. An increase, by causing a larger absorption of the sun's radiant energy, raises the average temperature, while a reduction lowers it. The estimate of Dr. Arrhenius, based upon an elaborate mathematical discussion of the observations of Professor Langley, is that an increase of the carbon dioxide to the amount of two or three times the present content would elevate the average temperature 8° or 9° C. and would bring on a mild climate analagous to that which prevailed in the Middle Tertiary age.[2] On the other hand, a reduction of the quantity of carbon dioxide in the atmosphere to an amount ranging from 55 to 62 per cent. of the present content, would reduce the average temperature 4° or 5° C., which would bring on a glaciation comparable to that of the Pleistocene period.

The amount of moisture in the atmosphere, other things being equal, is directly dependent upon the temperature, and the temperature in turn is dependent upon the amount of moisture in the atmosphere. This reciprocal dependence renders the aqueous

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[1] The action has two phases that in an exhaustive exposition would need separate statement, (1) the absorption of solar rays before they reach the earth, and (2) the absorption of the rays radiated by the earth. The latter have longer wave-lengths on the average and are relatively much more affected by the constitution of the atmosphere.

[2] Dr. Arrhenius, loc. cit.

vapor a vacillating factor subject to the control of any other agency which increases or decreases the atmospheric temperature. Whenever therefore an increase of carbon dioxide raises the temperature, it increases the quantity of water vapor and this by its thermal absorption further increases the temperature and calls forth more vapor and this action and reaction continue in diminishing force until an equilibrium is established. A decrease in carbon dioxide decreases the temperature and thus lessens the water vapor, and this further lowers the temperature and inaugurates a reversed series of actions and reactions. Fluctuation in the quantity of carbon dioxide therefore is attended not simply by its own individual effects, but by these auxiliary effects also. The carbon dioxide becomes therefore the determinative factor, and the question of the thermal absorption of the atmosphere may be discussed for convenience as though it were solely dependent upon the fluctuations in the content of this constituent, although this will not be strictly exhaustive.

b. A second effect of increase and decrease in the amount of atmospheric carbon dioxide is the equalization, on the one hand, of surface temperatures, or their differentiation on the other. The temperature of the surface of the earth varies with latitude, altitude, the distribution of land and water, day and night, the seasons, and some other elements that may here be neglected. It is postulated that an increase in the thermal absorption of the atmosphere *equalizes* the temperature, and tends to eliminate the variations attendant on these contingencies. Conversely, a reduction of thermal atmospheric absorption tends to *intensify* all of these variations. A secondary effect of intensification of differences of temperature is an increase of atmospheric movements in the effort to restore equilibrium. Increased atmospheric movements, which are necessarily convectional, carry the warmer air to the surface of the atmosphere, and facilitate the discharge of the heat and thus intensify the primary effect. In the case of a naked earth, the radiant energy of the sun falling directly upon the tropical belt is concentrated in space, and subject to the minimum reflection; in high latitudes, the rays are spread over greater space, and are subject to greater relative reflection because of the low angle of incidence. In the case of an earth swathed in a thermally absorptive mantle, the direct equatorial ray is absorbed in traversing the atmosphere to a less extent than the ray of higher latitudes because it penetrates a less depth of atmosphere, while the amount of reflection from the atmosphere is small in both cases, so far as the transparent elements are concerned. In so far therefore as the temperature effects are dependent upon the absorption of the incoming rays, the greater depth of atmosphere penetrated in the higher latitudes makes important compensation for obliquity of incidence.

In the case of a naked earth, or an earth clothed with a non-absorptive atmosphere, the solar rays which are tangential to the polar regions have no heating influence upon the earth, while in the case of an earth clothed with an absorbent atmosphere, similar rays are partially absorbed, and serve to warm the earth. In the polar regions, therefore there is a very radical difference between the effects of an absorbent and a non-absorbent atmosphere. The same holds true of the heating effects of the morning and evening sun. With a non-absorbent atmosphere, the tangential morning and evening rays pass through and are lost; in a thermally absorbent atmosphere, they are effectually retained.

In so far as the incoming rays are absorbed in the atmosphere their immediate effects are chiefly felt in its upper strata and their influence upon the surface of the earth is lessened. This is due to the fact that the upper regions are penetrated by rays of all the various wave-lengths that emanate from the sun, while the lower portions are penetrated only by such rays as are left after the selective absorption of the upper atmosphere. The degree of this absorption of the rays of long wave-lengths is such that comparatively little further absorption takes place in the basal portion of the atmosphere, according to the interpretations of Arrhenius. One effect of increasing the absorptive capacity of the upper air by increasing the amount of carbonic acid is an increase in the elevation of the strata chiefly heated by the incoming rays and the consequent reduction of the thermal gradient of a vertical column of the atmosphere. As a result there is less effective tendency to convection and less discharge of heat from the atmosphere.

In high latitudes, besides this effect, it is also to be noted that with an increase of the absorptive capacity of the upper atmosphere, rays that previously passed through the higher strata with little absorption are arrested and contribute heat to the upper air. The same is true of morning and evening rays at high elevations.

In the case of the outgoing rays, which are absorbed in much larger proportions than the incoming rays because they are more largely long-wave rays, the tables of Arrhenius[1] show that the absorption is augmented by increase of carbonic acid in greater proportions in high latitudes than in low; for example, the increase of temperature for three times the present content of carbonic acid is 21.5 per cent. greater between 60° and 70° N. latitude than at the equator. The maximum thermal effects also lie in higher latitudes for the summer months than for the winter months. On the other hand, when the carbonic acid is reduced to 0.67 of the present content, the maximum winter variation is felt between 30° and 40° N. latitude. If the carbonic acid be further reduced, the maximum variation found by extrapolation falls at and below 30°, the latitude of the Carboniferous glaciation. It is not intended, however, to imply that this would be sufficient in itself to produce that glaciation.

An atmosphere having a relatively large percentage of carbon dioxide and water, *i. e.*, an absorptive atmosphere, has a higher heat content than a non-absorptive one, and its circulation in latitude more effectually equalizes the temperature with the same degree of movement.

Similar considerations are applicable to the effects of land and water areas. In so far as the atmosphere absorbs the incoming rays in passing through it, the amount that reaches the surface of the earth is reduced. To this extent the possibility of

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[1] Loc. cit., p. 266.

differential effects between the sea and land is lessened. On the other hand, in the absence of absorptive and diffusive effects, the tropical rays fall with full intensity upon the surface. On the land they promptly heat the immediate surface, and the heat is as promptly radiated away. On the sea, neglecting reflection, they penetrate deeply into the water until they are absorbed. The upper layer of the sea is therefore heated to a notable depth, and radiates its heat away with relative slowness. The result is an intensification of the differences in average temperature of the land and the sea. This action is quite familiar, but perhaps not the point here urged — that this difference is dependent on the atmospheric effects upon the incoming as well as outgoing rays. If the atmosphere were so far robbed of its absorbent factors, carbon dioxide and water, as to give great intensity to this differential effect, the result might be an average temperature of the land below the freezing point, while that of the sea might be relatively warm. It seems clear that at some point short of an absolute thermal transparency a stage would be reached where the average temperature of the land would sink below zero, while yet the sea, barring convection in latitude, would retain a comparatively mild temperature. There would then apparently arise, even in low latitudes, the conditions of glaciation.

Without following out these lines into greater detail, the more pertinent deductions may be summed up in the following propositions: A reduction of the thermal absorption of the atmosphere would intensify the differences of temperatures between (1) the basal and the upper portions of the atmosphere; (2) low and high latitudes; (3) land and sea; (4) night and day; and (5) the seasons. In short, it would intensify temperature differences generally, and would lead to (1) greater local heat, as well as greater local cold; (2) to greater local dryness, as well as greater local moisture; (3) to more intense movements of the atmosphere in the endeavor to maintain equilibrium; and (4) to lower average temperature. The effect of reducing the absorbent factors is the intensification of differences.

On the other hand, an increase in the absorptive factors renders ineffectual, in a corresponding degree, the variations of altitude, of latitude, of land and sea, of day and night, and of the seasons, and conduces to an equable and mild temperature, to gentle and yet thermally effective circulation, and to higher average temperature. As Arrhenius has remarked, "The geographical, annual, and diurnal changes of temperature would be partly smoothed away if the quantity of carbonic acid was augmented. The reverse would be the case (at least to a latitude of 50° from the equator) if the carbonic acid diminished in amount."[1]

AGENCIES OF DEPLETION AND ENRICHMENT

It now becomes necessary to assign agencies capable of removing carbon dioxide from the atmosphere at a rate sufficiently above the normal rate of supply, at certain times, to produce glaciation ; and on the other hand, capable of restoring it to the atmosphere at certain other times in sufficient amounts to produce mild climates.

These agencies on both sides belong to two classes, the permanent and the temporary, and the distinction has practical importance.

Sources of permanent loss.— Permanent depletion results from the consumption of carbon dioxide in the transformation of the silicates of the original earth, and of volcanic products into the carbonates of the secondary strata. It is fairly safe to assume that the original earth's surface was composed of material of the general class represented by the igneous rocks and the basement complex. These, it is needless to say, consist largely of silicates with which are associated certain quantities of certain gases to be considered more fully hereafter. These silicates, where exposed to the weathering action of the atmosphere, become decomposed and take the form of carbonates (with less quantities of sulphates, phosphates, etc.) and of residual silicates and oxides (kaolin, quartz, ferric oxides, etc.). Neglecting the minor transformations which do not concern us here, the operation may be

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[1] Loc. cit., p. 268.

characterized as carbonation, and consists essentially of the substitution of carbonic acid for the silicic acids. The carbonic acid is derived, in the main, from the atmosphere. In their soluble condition, the carbonates so formed are largely bicarbonates. This is the only form in which calcium carbonate is appreciably soluble, and the same is true in a less degree of magnesium carbonate. The monocarbonates of potassium and sodium are highly soluble, but the bicarbonates also appear in solution. Practically the carbonates of these alkalis usually become changed into other salts (sulphates, chlorides, etc.) and the carbon dioxide that may have been temporarily locked up with them is set free by the change, or enters some other combination. The magnesium and calcium carbonates are also in part changed to other salts. But for the purposes of this discussion, which is concerned chiefly with the final issue and not with the transient stages of these compounds, it is sufficient to note that the chief result of the decomposition of the original silicates is the formation of calcium and magnesium carbonates, which are deposited as limestones and dolomites and thus lock up carbon dioxide at the expense of the atmosphere. The amount so taken from the air in the known geological periods has been variously estimated at from 20,000 to 200,000 times the present content; indeed estimates have gone beyond the last figure. When it is considered that 44 per cent. of all pure limestone and a higher per cent. of all pure dolomite is carbon dioxide, it is obvious that the total quantity is very large, and its computation is dependent upon the estimate of the total amount of limestone and dolomite in the crust of the earth.

A second source of permanent loss consists of the consumption of carbonic acid by plants and the fixation of the carbon in carbo-hydrates, hydro-carbons and other carbonaceous compounds which ultimately take the form of coals, bitumens, oil, gas, and perhaps most important of all, disseminated organic matter in the sedimentary series.

Exceptions.—Some hydro-carbons have probably been produced by inorganic action, notably those derived from carbides

(Moissan) formed within the earth and extruded from it. Some carbonates probably have been formed by carbonic acid contained within the rocks or extruded from the interior. In certain phases of the problem, deduction is to be made for such carbonaceous compounds and carbonates as are formed in the sea by marine plants and other agencies which derive their carbonic acid from the sea water; but in the general discussion of the question, the carbonic acid of the sea must be reckoned in with the carbonic acid of the air, for the two are in equilibrium and constitute essentially and potentially one body. The necessity for this assumption will be more obvious when we come to discuss the function of the ocean in influencing the constitution of the atmosphere.

Sources of permanent gain.—Over against these sources of secular loss there are certain sources of gain. If the assumption that the constitution of the atmosphere has varied through only moderate limits within the known ages be adopted, it is necessary to postulate sources of supply of a competency approximately equal to the sources of loss. The data for such postulation are exceedingly unsatisfactory and a function of the hypothesis should be to stimulate investigation in these lines which have been barely touched by serious inquiry.

a. Gain from the interior.—The crystalline rocks of the surface of the earth have been shown by the recent examinations of Tilden[1] to contain very notable quantities of gas, consisting of hydrogen in preponderance, carbon dioxide and carbon monoxide in large percentages, and nitrogen and marsh gas in small quantities, with water vapor, but with a practical absence of oxygen. Twenty-five analyses, including ancient and modern volcanic and even some metamorphic rocks, gave an average volume of gas equal to about four and a half times the volumes of the containing rocks. A computation on this basis shows that an atmosphere equivalent in mass to the present one would be contained in a very superficial rind of the earth, and that if this volume of

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[1] On Gases Contained in Crystalline Rocks and Minerals: W. A. TILDEN, Chemical News, April 9, 1897.

included gases be constant for the whole body of the earth, it contains potentially a multitude of atmospheres.

It is a familiar fact that enormous quantities of gases are ejected from volcanoes during their active periods. It has been very generally assumed that these gases and vapors, among which steam vastly preponderates, have a surface origin, and there can be no doubt that this is true of some notable part; but, on the other hand, there is abundant ground for the belief that another notable part is brought from the interior and is a real contribution to the earth's atmosphere and hydrosphere. It may not be possible at present to demonstrate this, but inquiry in this direction is invited. There seem to be no means of estimating from present data even approximately the volume of gas which is given forth, but it is certainly large. There are grounds for believing that the gases of the interior escape by other than volcanic vents. The deep rending and sharp shock of the earth in seismic movements, the stresses and fissuring of readjustments, the disintegration of crystalline rocks, and the resources of slow diffusive penetration are among these. So far as the setting free of carbon dioxide by decomposition of the containing rock is concerned, it is to be noted that the chemical action which sets it free involves a consumption of carbon dioxide very greatly in excess of the amount liberated, so that, as computation will show, the total effect of the process is one of loss which the internal gases only very slightly modify. This, of course, is not true of mechanical disintegration.

b. Exterior sources of gain.—The meteorites which are constantly falling to the earth contain included gases, often in great volume. They also contain carbonaceous matter which is partially burned in passing through the air. The nature of the included gases is notably similar to those of the crystalline rocks, hydrogen and carbon dioxide being the leading constituents with nitrogen in very subordinate amount and free oxygen essentially absent.[1] Water vapor appears in both meteorites and

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[1] See numerous papers of A. W. WRIGHT in Am. Jour. Sci., notably Gases contained in Meteorites, Am. Jour. Sci, 3d series, Vol. XII, No. 69, Sept. 1876.

crystalline rocks, but it is impossible to say how far it was absorbed from terrestrial sources. It has even been suggested that all the gases both of meteorites and of the crystalline rocks were simply absorbed from the air and not brought in from without; but their proportions are so different from those of the air that it would be necessary to assume an extraordinary selective power to make this possible; for oxygen must be wholly rejected as a gas; nitrogen, though greatly preponderant, must be almost neglected; carbon dioxide must be absorbed in great quantities relatively; carbon monoxide, though very rare in the atmosphere, must be taken in abundantly; while the hydrogen, which is scarcely detectable in the atmosphere, must be absorbed in superlative amounts. It is difficult to conceive how a meteorite passing rapidly through the air can have absorbed many times its volume of an element which does not appear in the air in detectable quantities. However, I am unable to say that the analyses were made sufficiently soon after the fall of the meteorites to make this point conclusive. But, at any rate, the hypothesis of selective absorption is confronted with grave difficulties and the alternate hypothesis that the gases are brought to the earth in the meteorites seems the more probable. The emanations from comets support the view that meteorites are charged with gases in extra-terrestrial regions. Here again inquiry is needed and experimental tests are obviously suggested.

If gases are brought in with meteorites, it is probable that independent molecules are flying through space and are caught up by the earth. The modern doctrine of molecular velocities, which holds that gases are liable to escape, and presumably are escaping constantly, from planetary bodies, carries the presumption that individual molecules are flying through space with some degree of frequency. Astronomical phenomena, to be sure, seem to indicate that the quantitative value of these cannot be very great, but as definite data are yet wanting and we are dealing with vast lapses of time and slow processes of depletion, making need for slow processes of accretion only, this agency may deserve a place among the undetermined sources of atmospheric material.

It is among the possibilities that the sun itself may be a direct source of atmospheric feeding. The speed at which the solar prominences are projected from the sun has been observed to exceed the parabolic velocity of the sun;[1] that is, the rate of projection is such that if the outer atmosphere of the sun does not effectually interfere, the gases are shot away beyond even the sun's control. A much less speed could carry the gases to the earth, so that, unless the outer atmosphere of the sun interposes effectual barriers, it is not improbable that gases are thrown as far out as the orbit of the earth. The earth probably cannot hold hydrogen, the chief gas of these prominences, permanently as such, but it may do so when combined with oxygen. The shooting of solar hydrogen through our atmosphere would lead to the formation of water, because, even at ordinary temperatures, such of the molecules of oxygen and hydrogen as collided with the requisite velocity would enter into union. There seem therefore grounds for placing this among the possible but undetermined sources of supply for our atmosphere and hydrosphere. When the mystery of the zodiacal light and the gagenshein shall be solved, it is possible that demonstrative evidence of our relations to the extreme projections of the solar atmosphere may be available.

In the present state of extreme uncertainty relative to all these possible sources of supply, a hypothesis which necessarily involves them proceeds with uncertain steps and must perforce wait patiently for more definite determinations, but the pressing of a hypothesis which lays emphasis upon them is but giving effect to the fundamental mission of all working hypotheses.

VARYING RATES OF ACTION

By the terms of the hypothesis the state of the atmosphere at any time is dependent upon the relative rates of loss and gain.

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[1] The Story of the Sun, by SIR ROBERT BALL, pp. 185–188; The New Astronomy, LANGLEY, p. 61.

It is of supreme importance therefore to consider irregularities in the action of the sources of loss and gain.

Varying rates of gain.—The constancy or irregularity of the sun's contribution—assuming it to make a recognizable contribution—is quite unknown. It would presumably be dependent upon the internal explosive action of the sun concerning which all thought is as yet highly speculative. So far as its relations to geological periods are concerned, it would probably be either an essentially constant factor or one which would not fall in systematically with any special phase of geological progress, and could not be regarded as a coöperative factor in any definite phase. It might be progressively increasing, as the sun concentrates, or progressively diminishing.

Much the same is to be said with regard to possible sources of supply from meteoric and similar extra-terrestrial sources.

The extrusion of gases and vapors from the interior has been presumably periodic, because the conditions of molten eruption and of mechanical disruption have probably been periodic rather than constant. No specific determination of the periodicity of volcanic action has yet been made out, but the testimony of present geological data is to the effect that vulcanism has been more frequent and intense at certain periods than at others. This is clearly true for individual grand divisions of the earth, and seems to be true of the earth at large, notwithstanding the fact that vulcanism was a more or less local phenomenon. While a definite periodicity, specifically connected with other phenomena, cannot now be affirmed, the tentative proposition that vulcanism has been more abundant in great periods of readjustment than in periods of quiescence may be entertained. The connection with those periods seems sometimes to have been very intimate and immediate, and at other times more remote. So far as disruption of the rocks constitutes a means of escape for internal gases, there should obviously be a close connection with periods of readjustment. In a rather general and uncertain way, then, it would seem necessary to assume, in a working hypothesis, that the enrichment of the atmosphere from internal sources has proceeded more rapidly at or about the periods of crustal disturbance. This, as we shall see, coincides practically with the periods of depletion from atmospheric action on the surface, and hence, so far forth, the two processes tend to neutralize each other and preserve the constancy of the earth's atmosphere. The hypothesis must therefore recognize that it was only when one agency fell behind the other in its competency that its specific results became manifest, and then only by the difference in their respective effects.

Varying rates of loss.—The rate of chemical action of the atmosphere on the surface of the rocks is believed to have been intimately connected with the extent and height of the land area, considering the earth as a whole. There were qualifying conditions, as we shall see, but notwithstanding, this is regarded as an important law. It is made a fundamental postulate of the hypothesis, and the vitality of the hypothesis as a working instrument of investigation hangs very largely upon it. It is obvious that the greater the surface area of rock exposed to the effective action of the atmosphere, the more rapid will be the rate of disintegration, other things being equal, and the more rapid the consumption of carbon dioxide.[1]

The rate of carbonation of the rock is dependent upon elevation as well as superficial area. The disintegration of rock is the most active by far in the zone lying between the surface and the level of permanent underground water, technically the water table. It is in this zone that the atmosphere and the moisture of the earth combine to give the greatest chemical

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[1] Oxygen is also consumed in the decomposition of average rock, but in less amount than carbonic acid, and as the amount of oxygen in the air is very much larger than that of carbon dioxide, the part consumed is far less critical. In an exhaustive study of the constitutional history of the atmosphere, the loss and gain of oxygen must be considered, and certain very interesting and important phases of atmospheric variation are probably connected with the production and consumption of the oxygen, but, as indicated, they are much less immediate and critical in the consideration of thermal problems with which our hypothesis is more especially concerned, and for the sake of simplicity the oxygenation of the rocks may be temporarily neglected; and for like reasons the many minor reactions may also be ignored and attention confined to the carbonation.

activity. It is established by the most ample observation in mining, that below the permanent water level disintegration has made slow progress compared with that in the zone above the water level. Now the thickness of the zone between the surface and the permanent water level is intimately dependent upon the general altitude. In a continent reduced approximately to base level, this zone is exceedingly thin. In a region much elevated and deeply dissected by erosion, the thickness of the zone is very much greater. As between a continent with an average elevation of 2000 feet, at the climax of dissection following a crustal readjustment, and a continent of similar area with an average elevation of 300 feet, during a period when it is approximately at base level, the average depth of the aërated zone above the water level, probably varies more nearly with the square of the elevation than as a direct multiple of it. It is improbable, however, that the chemical action is augmented at so great a ratio. Probably greater warmth and more abundant vegetation are correlated with the lower altitudes, and both these aid chemical action. This in turn is somewhat offset by the greater mechanical disaggregation which results from changes of temperature and from gravitative influence in the more elevated condition. Making all allowances that seem required for the offsetting factors, it would still appear that the elevated condition increases the activity of decomposition in a very notable degree.

Below the permanent water level, the advantage probably also lies greatly with the higher elevation. The action of surface water upon the deeper rock is dependent upon the unbalanced hydrostatic pressure which promotes underground circulation and forces the water through the crevices and pores of the rock. If the underground water stands near sea level, there is little unbalanced hydrostatic pressure to promote active circulation and thereby carry the surface waters, enriched with atmospheric gases, down into the lower strata and bring them into action. The atmospheric waters precipitated upon the surface run away chiefly at the surface, and fail of the contact necessary for action. On the other hand, in an elevated region there is a potential hydrostatic pressure measured by the difference of altitude of the surface of the ground water and the surface of the sea which tends to cause the waters to flow through the rock and thus find a tortuous way to the equilibrium of the sea level. A deep underground circulation is therefore a function of high altitude, and, correlated with that circulation, is chemical activity proportionate to the enrichment of the surface waters with chemically active agencies, in the present instance, carbon dioxide in particular. This deeper circulation, correlated with hydrostatic pressure, is enhanced by the greater degree of fissuring of the rock which attends elevated tracts, for in the process of elevation, writhing and cracking are notable incidents, and, in addition to this, the gravitative tensions which necessarily attend an elevated position lend their aid in the production and opening of crevices. Precisely the opposite conditions prevail at low levels. The protruding superficial portion of the land is the most fissured part and when it has been cut away by erosion the basal remnant is normally less open to the penetration of water. It would appear from a consideration of these several associated influences that disintegration and decomposition are facilitated by elevation in a very important degree.

If, therefore, there were times in the history of the earth when there were general readjustments of its bodily form to accumulated internal stresses, resulting in extensive elevations, embracing not only the formation of mountains and plateaus, but the general warping outwards of the continental platforms, and the bowing downwards of the ocean basins, attended by the withdrawal of the sea, so that the land area was extended and, at the same time its average elevation increased, and a portion of it rent and crushed, it is believed that the carbonation of the rocks must have been accelerated by some notable multiplier and that the rate of consumption of the carbon dioxide of the atmosphere must have been correspondingly promoted ; and this is made an important postulate of the hypothesis.

At least two periods of such very general and notable elevation appear to be well authenticated by present geological data, imperfect as they are for certain quarters of the earth. These periods occurred near the close of the Paleozoic and of the Cenozoic eras respectively. Closely connected with these two periods are two well authenticated glacial periods.

If, on the other hand, there were periods of prolonged quiescence of the earth's body during which the lands were cut down well towards base level, they would be accompanied by a progressive slackening of the rate of disintegration, and a corresponding reduction in the rate of atmospheric loss of carbonic acid, giving opportunity for the agencies of repletion to overtake and surpass the agencies of depletion. It is believed that there was a series of such periods among which the Cretaceous is best authenticated.

During a prolonged period of relative quiescence the encroachment of the coast lines upon the land, if elevated, becomes notable. In addition to this, the material removed from the land and deposited in the sea raises the water level, and when the degradation is notable this rise amounts to an appreciable factor. This aids the coast action by lifting it above the restraining influences of its own products, which, by shoaling the water off shore, tend to break the force of wave action. The notion is also entertained that during periods of readjustment the continental masses are apt to be lifted beyond the plane of perfect isostatic equilibrium, and that there follows a tendency to slowly creep back into equilibrium, accompanied by a general tendency of the continental platform to flatten out under gravitative stress. The continental platforms are to be regarded as having elevations above the abysmal ocean bottom of perhaps 12,000 feet, and, as their average gravity is two and a half to three times that of the water which surrounds them, there remains a large excess of gravitative stress tending to cause the continents to spread laterally.

The combined effects of these agencies is a transgression of a thin edge of the sea upon the land. Now, such extensive transgression took place on all the great continents in the Upper

Cretaceous period, and this fact may be taken as indicating that the planation which reached so pronounced an expression on the American continent at that period affected nearly or quite all the continents in some similar measure. An inspection of the whole range of geological history shows periods of similar transgression accompanied by the development of luxurious and cosmopolitan marine faunas of the shallow-water type which in themselves imply the conditions here postulated.[1]

If this be a correct view it is obvious that at such periods the areas of land exposed to atmospheric action were notably reduced by sea encroachment, and that at the same time the lowness of the land greatly limited the depth of atmospheric activity by reducing the zone between the surface and the water-table and by reducing the hydrostatic penetration of surface waters. As already remarked, there is to be counted in offset probably warmer temperature, a higher degree of moisture, and a more abundant vegetation, but it is not believed that this approaches, even remotely, to a full offset to the reduction due to low elevation and reduced area.

If the foregoing views are correct there were certain periods in the history of the earth when carbonation proceeded with multiplied activity, separated by other periods during which its activity was greatly reduced. The intensification and the reduction differ by some notable multiplier of the average rate.

In working application, the hypothesis tentatively recognizes as periods of land extension attended by rapid carbon dioxide consumption, (1) the close of the Silurian and the opening of the Devonian, (2) the Permian and early Triassic, and (3) the Pliocene and Pleistocene. To this category may perhaps also belong, though the evidence at present is less adequate, (4) the early Cambrian, (5) the closing Ordovician and opening Silurian,

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[1] For further statement of these views, see The Ulterior Basis of Time Divisions and the Classification of Geologic History, JOUR. GEOL., Vol. VI, No. 5, July–August, 1898, pp. 449–462; A Systematic Source of Evolution of Provincial Faunas, JOUR. GEOL., Vol. VI, No. 6, Sept.–Oct., 1898, pp. 597–608; The Influence of Great Epochs of Limestone Formation upon the Constitution of the Atmosphere, *ibid.*, pp. 609–621.

(6) the close of the Jurassic and the opening of the Lower Cretaceous, and (7) the transition period between the Cretaceous and the Eocene. In these periods there are evidences of declared intensifications of climatic influence expressed in widespread and thick deposits of salt and gypsum and in great series of red sandstones and marls, and, in the two most notable cases, by pronounced glaciation in middle and low latitudes.

On the other hand, it regards the following as periods of sea extension attended by the active freeing of carbon dioxide through the agency of prolific lime-secreting life, as hereafter set forth: (1) the middle Ordovician, (2) the middle Silurian, (3) the sub-Carboniferous, (4) the late Jurassic, (5) the Upper Cretaceous, and (6), less notable, the later Eocene and earlier Miocene. During these periods there is evidence of extensive limestone deposition spreading out widely on the continental platforms, attended by very mild and equable climates very nearly uniform for all latitudes.

SOURCES OF TEMPORARY LOSS AND GAIN

The discussion has thus far taken note of the original carbonation of the silicates of crystalline rocks only. These crystalline rocks, according to Dr. Tillo,[1] occupy something over 20 per cent. of the surface of the land. There remains nearly 80 per cent. occupied by secondary rocks which now claim attention.

Sources of temporary loss—The function of the secondary deposits.—To a large extent the material of the secondary deposits underwent chemical decomposition and carbonation preliminary to its deposition, indeed as a prerequisite to its derivation. In so far as this process was incomplete in the earlier stages, it was continued during any subsequent state of exposure, but this action belongs under the preceding head of original carbonation.

In the erosion of tracts of secondary rocks the limestones and dolomites are dissolved and carried down to the sea essentially as bicarbonates. In the strata they existed as monocarbonates. Their solution involves the taking up of a second

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[1] Berghaus Atlas.

equivalent of carbonic acid to render them bicarbonates, and this second equivalent is derived essentially from the atmosphere. There is herein a source of temporary loss, temporary because the second equivalent of carbon dioxide remains associated with the bases in the sea only until deposition takes place, when it is set free. It is to be noted that a second equivalent is also taken up in the formation of original carbonates if they are dissolved. As the crystalline rocks occupy only a little more than 20 per cent. of the land surface and are probably not removed as fast as the secondary rocks, not more than about one fifth, probably not more than one tenth, of the bicarbonating carbon dioxide is associated with original carbonation. The remaining four fifths or more are occupied in bicarbonating and dissolving the calcareous and magnesian portions of the secondary rocks. It follows that the ratio of carbon dioxide now taken out of the atmosphere as second equivalent in any unit of time, to that taken out as first equivalent, is probably fully five to one, and not unlikely as high as ten to one. This ratio would not necessarily hold for past periods, but in all those under consideration the second equivalent was undoubtedly very much greater than the first.

Accepting, for the purposes of a rude estimate, the data of T. Mellard Reade,[1] the amount of carbon dioxide removed annually by original carbonation, reckoned by proportional area, is 270 million tons, the amount temporarily removed as the second equivalent of the bicarbonates is 1350 million tons; the amount simply transferred from the land to the sea as the first equivalent of the carbonates previously formed is 1080 million tons; the total mass taken from the atmosphere annually being therefore 1620 million tons, and the total mass removed to the sea 2700 million tons. Besides uncertainties in the original estimate of Reade, the first item is subject to correction (probably large) for the slower rate of disintegration of the crystalline rocks. This is, however, somewhat offset by weathering action on the silicates that remain undecomposed in the secondary rocks, and on

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[1] Addresses, Geol. Soc. of Liverpool, 1876 and 1884, quoted in Dana's Manual, p. 191.

the late volcanics which are not all included in the 20 per cent. of the land area reckoned as crystalline. The second item is subject to correction to the extent that the salts were normal carbonates and not bicarbonates.

Reciprocal sources of temporary gain.—The second equivalent of the carbonates in the ocean is subject to easy removal under suitable conditions, and reënriches the atmosphere by diffusion into it from the ocean. The conditions under which this is set free are of critical importance to our hypothesis. We have to consider (*a*) saturation, (*b*) chemical reactions and dissociations, and (*c*) organic action.

a. Absence of general saturation.—In the absence of other agencies of removal the accumulation of calcium bicarbonates in the ocean would go forward to the point of saturation, if there were a sufficient amount producible. It would then be deposited as limestone, and the second equivalent of the carbon dioxide would be set free. There is little reason to think, however, that general saturation has been reached during the known portion of the earth's history. In local basins subject to peculiar conditions, saturation certainly has been attained, as the marls of the great saliferous deposits testify. The present approach to oceanic saturation in calcium carbonate is apparently only about 40 per cent. If the ocean in former times had reached saturation in calcium carbonate and any notable precipitation had followed, the precipitate should appear as a distinctive constituent of the clastic deposits. While calcareous matter which might be so interpreted occurs in some of these deposits, there is a notable absence of anything of the kind in many others where it might be expected, and the general character of the sandstones and shales seems more concordant with the accepted view that they were laid down in waters that did not, except in special cases, directly deposit calcareous matter. In view of the probable presence of lime-secreting organisms, the problem is generally rather to account for the paucity of calcareous matter than its abundance in the clastic deposits. The explanation is doubtless found in the undersaturation of the sea water and its ability to dissolve calcareous relics. This view is supported by the partially dissolved condition in which calcareous fossils are so commonly found in the sediments of practically all the ages. The inference, therefore, to be drawn from the character of the sediments, and from the partial solution of calcareous fossils, is that the ocean, as a whole, has not generally been saturated with calcium bicarbonate during its known history. Murray has made us aware that at the present time the greatest depths of the ocean dissolve calcareous relics so freely as to prevent their accumulation.

b. Inorganic chemical reactions.—Viewed comprehensively the sea water consists of such solutions as have been carried down from the land in past times, modified by concentration and deposition. No important constituent has been totally removed. The land and sea waters have therefore the same fundamental constitution, but the salts of the former enter the sea in a more dilute form and in different proportions from those contained in the latter. Aside from organic action, and from exceptional inorganic agents such as may arise from submarine volcanic action and like incidental sources, essentially all occasion for chemical reaction when land waters are added to sea waters, is limited to a readjustment of the equilibriums of the common constituents of the two commingling waters. Following the simple doctrines of the old familiar "chemistry of results," the addition of a dilute solution of salts of the alkalis and alkaline earths to a more concentrated but not saturated solution of the same salts would neither occasion precipitation nor the evolution of gas, for every acid is mated with a base, and all are much below the point of saturation. According to the old interpretation the bases of the sea salts are, in the main, mated to stronger acids than those of the land waters, and these combinations will not be changed on the entrance of the latter. So, also, the small amounts of strong acids of the land waters are already mated with the strong bases in the main, and largely form the same combinations as those of the sea waters. Such interchanges as follow involve a double reaction essentially without the freeing of acid or base. Under the old method of interpretation the sea salts, according to Dittmar, consist of—

	Percentage	Total Tons
Sodium chloride	77.758	35,990 x 10^{12}
Magnesium chloride	10.878	5,034 x 10^{12}
Magnesium sulphate	4.737	2,192 x 10^{12}
Calcium sulphate	3.600	1,666 x 10^{12}
Potassium sulphate	2.465	1,141 x 10^{12}
Calcium carbonate	0.345	160 x 10^{12}
Magnesium bromide	0.217	100 x 10^{12}
	100.000	46,283 x 10^{12}

A rude average of the composition of land waters and of the amounts of salts carried to sea annually, founded on the estimates of T. Mellard Reade, is here given for comparison.

	Approx. percentage	Tons annually
Calcium carbonate	50	2,700 x 10^6
Calcium sulphate	20	1,080 x 10^6
Magnesium carbonate	4	216 x 10^6
Magnesium sulphate	4	216 x 10^6
Sodium chloride	4	216 x 10^6
Potassium and sodium, Sulphates and carbonates	6	324 x 10^6
Silica	7	378 x 10^6
Other substances	5	270 x 10^6
	100	5,400 x 10^6

These tables do not embrace the second equivalent of carbonic acid.

From these data it appears that it would require only a little over eight and one half million years for the land waters to bring in a gross amount of salt equal to that of the ocean, but it would require very different periods to bring in the individual constituents. It would take 166 million years to bring down the sodium chloride, but only about 1.5 million years to bring down the calcium sulphate, and only about 60,000 years to bring down the calcium carbonate. It appears therefore that there must be agencies constantly removing the calcium carbonate and the calcium sulphate at relatively high rates. These particular figures are subject to all the uncertainties involved in

Reade's primary estimate, but they probably represent approximately the relative ratios, and show the general nature of the eliminations that are requisite to change accumulating land waters into sea waters.

While these general statements of the nature and limitations of chemical action, based on the more familiar doctrines of the older chemistry, are doubtless essentially true, the refinements of modern chemistry teach that there is an intricate series of dissociations and exchanges of acidic and basic factors, and of the various ions, in an effort to establish and maintain a new equilibrium between the salts, required by their new proportions and their new states of dilution. As the land waters contain a relatively large percentage of bicarbonates of calcium and magnesium, the readjustment affects these especially, with the result that probably a minor percentage of the second equivalent of carbon dioxide is set free. It seems necessary to state this with qualification on account of the extreme complexity of the reactions, and the incompleteness of existing data; but the Challenger, and similar investigations show that the quantity of second equivalent of carbon dioxide is less than sufficient to raise all of the carbonates into bicarbonates. This deficiency is apparently limited to 20 per cent. or less of the theoretical amount required. More rigorous experimental determination is, however, greatly needed.

It is probable that the second equivalent of the land waters is deficient in some like degree, but this has not been experimentally determined. If this be true, it must reduce the estimate of the carbon dioxide brought down to sea, and also the amount set free by dissociation. The total amount of carbon dioxide which may be supposed to be set free by inorganic reaction in the sea in its present state of concentration, is therefore probably much less than 20 per cent. It is obvious from the preceding considerations, and others that will follow, that to maintain the atmospheric status even approximately there must be a nearly or quite complete return of the second equivalent of carbon dioxide by some means. This is also implied by the fact that the oceanic deposits are not bicarbonates in any notable degree. The chief agencies of this return are held to be organic, and will be considered presently.

The chief compounds of both the land and sea waters are sodium, potassium, magnesium and calcium chlorides and bromides ; sodium, potassium, magnesium and calcium sulphates; sodium, potassium, magnesium and calcium carbonates and bicarbonates ; in other words, every combination which may take place between the acids and bases involved. Besides these salts there are, theoretically at least, the several acids and bases and a complete series of ions as well. There is a continuous dissociation and reunion in the effort to maintain equilibrium. The extent of the dissociation is dependent, among other things, notably upon the degree of concentration of the solution and upon its temperature. In an especial degree the extent of the freeing of the second equivalent of carbon dioxide is believed to be dependent upon this dissociation as influenced by temperature, and it is thus a vital consideration in realizing the function performed by the ocean during glacial episodes when its temperature was greatly changed. This function is made the subject of a special study in the paper of Mr. Tolman in this number of the JOURNAL.[1]

Mr. Tolman's studies have been founded upon Dittmar's experiments, and seem to show that the amount of carbonic acid freed from the bicarbonates by dissociation is very sensibly influenced by such changes of temperature as are necessary, according to the deductions of Dr. Arrhenius, to produce extended glaciation, on the one hand, and a mild climate in the arctic regions, on the other. In this he finds support for the suggestion which I made in a previous paper[2] that the ocean during a glacial episode instead of resupplying the atmosphere, in the stress of its impoverishment, would withhold its carbon dioxide to a certain extent, and possibly even turn robber itself. On the other hand, when the temperature is rising after a glacial

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[1] Pp. 585–618.

[2] A Group of Hypotheses Bearing on Climatic Changes, Vol. V, No. 7, 1897, p. 682.

episode, dissociation is promoted, and the ocean gives forth its carbon dioxide at an increased rate, and thereby assists in accelerating the amelioration of climate.

c. Organic action. — The elimination of the vastly preponderating percentage of calcium salts in the land waters, involving a reduction from 70 per cent. in these to less than 4 per cent. in sea waters, is assigned mainly to marine life. With the calcium sulphate we do not seem to be specially concerned here except so far as indirectly it may become involved in the reactions which eliminate the calcium carbonate. It would appear obvious, however, from the fact that its ratio is reduced from about 20 per cent. in the land waters to about 3.6 per cent. in the sea waters that it suffers much secular loss. The reduction of the calcium carbonate from about 50 per cent. in the land waters to about one third of 1 per cent. in the sea waters is a fact of prime importance.

The amplest and most familiar geological observation shows that the elimination takes place mainly as normal carbonate of lime in the form of shells and skeletal parts of various marine animals, and of some plants. The gross fact of observation is the disappearance of great quantities of calcium bicarbonate from the water, and its reappearance as the secretions of animals and plants in the form of normal carbonate. Whatever may be the specific steps involved in their life economies, it seems essentially immaterial to consider here whether the animals and plants take their lime directly from the calcium carbonate, and set its surplus carbonic acid free, or whether they take it from calcium sulphate, and by using carbonic acid, derived ultimately from the waters also, convert it into carbonate, setting free the sulphuric acid to attack in turn the calcium carbonate of the sea, and thus by circuitous process free its carbonic acid, or whether the procedure follows any other indirect course; for the final result, when balanced all around, seems to be essentially the same. It may even trench on the organic cycle without essentially changing the final result. The important thing to be observed is that the process is dependent upon sea life, and varies with its activity. There is no free supply of any competent discharging agency independent of sea life.

Variations of lime-secretion by sea life.—The amount of lime-secreting sea life is greatly influenced by the temperature of the sea and by favorable habitat. Lime-secreting sea life, both plant and animal, is greatly favored by high temperature and reduced by low. In support of this the following statements from the Challenger Report[1] and other sources may be offered, in which I have italicized the significant parts:

> Species of algæ which secrete carbonate of lime are abundant in the *shallow waters* of the ocean. In the *tropical regions* especially there are massive species of *Lithothamnion*, *Lithophyllum*, *Halimeda* and other genera that make up a large part of some coral reefs and of the surrounding coral sands and muds. *Two hundred fathoms* is probably the extreme limit at which any of these organisms live in the ocean.
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> Rhabdospheres are especially developed in *equatorial* and *tropical regions*, and are *rarely* met with in regions where the temperature of the surface water falls below 65° F. (18.3° C.). Coccospheres, while abundant in tropical waters, are found further north and south than the Rhabdospheres; they are present even where the temperature on the surface is as *low as 45° F.*, (7.2 C.); indeed, Coccospheres attain their greatest development in *temperate regions*. These organisms are absent or *rare in coast waters* affected by rivers; they especially flourish in the pelagic currents of the open ocean. . . . In *Arctic and Antarctic waters* Coccospheres and Rhabdospheres are replaced by similar minute algæ *which do not, however, secrete rods and disks of carbonate of lime on their outer surfaces.*
>
> Rhabdoliths and Coccoliths—the broken down parts of Rhabdospheres and Coccospheres—play a most important part in all deep-sea deposits, *with the exception of those laid down in polar and subpolar regions.*
>
> Of all the organic remains met with in marine deposits, by far *the most frequent are the shells of Foraminifera;* it may be safely said that these organisms or their fragments are present in every average sample of marine mud, clay, ooze or sand. . . . *Nearly all the species are confined to tropical and subtropical waters; they gradually disappear from the surface-nets as the polar regions are approached*, the dwarfed forms *Globigerina pachyderma* and *Globigerina dutertrei*, being the only species met with in Arctic and Antarctic waters. . . . *In the calcareous oozes from tropical regions, the shells of all the species inhabiting the surface waters are observed in enormous abundance, but these same species are never met with in deposits from polar regions.* . . .

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[1] Challenger Report, Deep Sea Deposits, pp. 257, 258–261, 263, 31 and 266.

There are not more than twenty or twenty-two species of pelagic Foraminifera, yet so numerous are the individuals of the species that they usually make up over 90 per cent. of the carbonate of lime present in the calcareous oozes of the abysmal regions of the ocean. . . .

The bottom-loving Foraminifera—those belonging to the Benthos—*are more abundant in the shallow water*, than in the deep-sea deposits, and occasionally a single species may occur in such abundance in shallow depths in some regions as to make up the greater part of a deposit. . . .

The presence of large numbers of Pteropod and Heteropod shells indicates tropical or subtropical regions, and relatively shallow depths. Abundance of the shells of pelagic Forminifera indicates the same regions, but when found without the shells of pelagic mollusks they indicate a greater depth than when these latter are present. . . . . The presence or absence, and the size of Rhabdoliths, Coccoliths and Coccospheres *give important indications as to latitude and depth*—the first predominating in tropical regions, the two latter being better developed in temperate regions, and *all disappear from the deposits as the polar waters are approached.*

A large number of these pelagic mollusks (Pteropod and Heteropod) *secrete carbonate of lime shells, and this is especially the case in tropical waters.* In *polar* regions the place of the shelled species is taken, with the exception of one or two small species of Limacina, by a *shell-less species.* The shells of the tropical species make up a large part of some tropical and subtropical deposits from moderate depths, in which there is a relatively small quantity of land débris. *Like the pelagic Foraminifera these pelagic* Mollusca attain their greatest development in the warm oceanic currents, *and diminish both in the number of species and the size and mass of the shells as the colder currents of the polar regions are approached.*

Reef-forming corals are confined to waters which, through even the coldest month, have *a mean temperature not below 68° F.* Under the equator the surface waters in the hotter part of the ocean have the temperature of 85° F. in the Pacific, and 83° F. in the Atlantic. The range from 68° to 85° is, therefore, not too great for reef-making species.[1]

An isothermal line crossing the ocean where this winter temperature of the sea is experienced, one north of the equator, and another south, bending in its course toward or from the equator, wherever the marine currents change its position, will include all the growing reefs of the world; and the area of waters may be properly called the *coral-reef seas.* . . .

Over the sea thus limited coral reefs grow luxuriantly, yet in greatest profusion and widest variety through its hottest portions.[1]

I have found no specific statements relative to the dependence of common mollusks on temperature, but the enumeration of the

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[1] DANA: Corals and Coralline Islands, p. 83.

species in different latitudes clearly indicates that they are less abundant in the arctic provinces than in the tropical, from which it may perhaps be safely inferred that the lime-secreting function of the mollusks is increased by warm temperature.

In the foregoing quotations references are made to the preference of certain forms for shallow waters. The great preponderance of lime-secreting species on the shoal areas—100 fathoms or less—is too familiar to need emphasis.

In other articles[1] I have endeavored to show that there were certain stages in the earth's history when the seas were extended widely over the continental platforms, affording conditions extremely favorable to the multiplication of lime-secreting shallow-water life. I endeavored to connect these, on an observational basis, with the great limestone-producing epochs of geological history and to show that these were correlated with genial climates over high and low latitudes alike. On the other hand, I endeavored to show that there were other periods during which the land area was increased and the sea restricted, resulting in a great reduction of this normal habitat of the chief lime-secreting forms of life. I endeavored to show that so far as the lime-secreting life is concerned, the freeing of carbonic acid was promoted during periods of extended seas and that it was retarded during periods of extended land. This holds good when considered simply from the standpoint of available area, but it becomes still more true if, as this hypothesis maintains, the extension of sea-area was correlated with favorable temperature, while the restriction of sea-area was correlated with adverse temperature. The only pelagic life that enters much into the problem is that which occupied the superficial waters of the open ocean. The area of this increased and diminished concurrently with the extension and contraction of the sea.

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[1] A Systematic Source of Evolution of Provincial Faunas, JOUR. GEOL., Vol. VI, No. 6, pp. 597–608.

The Influence of Great Epochs of Limestone Formation upon the Constitution of he Atmosphere, JOUR. GEOL., Vol. VI, No. 6, pp. 609–621.

THE FORMATION OF ORGANIC COMPOUNDS AS AN AGENCY OF ENRICHMENT AND DEPLETION

The familiar fact that plants produce complex carbon compounds at the expense of the carbonic acid of the air, and that animals, aided by plants, by combustion, and by decay, decompose these compounds, and return a portion to the air as carbonic acid need not be dwelt upon. These reciprocal processes constitute a cycle which, in so far as it is mutually compensatory, affects the constitution of the atmosphere only in temporarily locking up carbon in the transient organic matter. The cycle, however, is not complete at any time, and has fallen far short of being complete at certain times. A portion of the carbon compounds are not reconverted into carbonic acid, and this residuum has been sealed up in the strata, and represents so much of depletion of the atmosphere. When this residuum was large there was a hastening of the process of robbing the atmosphere. When it was small it put less tax upon the agencies of supply. In its concrete application, the hypothesis recognizes one notable period of residual accumulation, the Coal Measures. Subordinately it recognizes others, as the Huronian and the late Cretaceous. Perhaps the Coal Measure period is the only one in which the excess of carbon composition over decomposition was so great as to seriously influence the constitution of the atmosphere, considered by itself alone, though this is open to question. A computation of the carbonic acid locked up in coal and similar carbonaceous deposits compared with that locked up in the limestones shows that the former is greatly inferior to the latter, from which it is inferred that the organic factor has been much the less influential in producing variations of atmospheric constitution, *per se*, than through its relations to the carbonates.

Respecting the organic cycle itself, it is obvious that when the sum total of vegetable and animal life increases, the amount of carbonic acid locked up in the living organisms is increased, and *vice versa*. The total mass of all the vegetable and animal living matter on the earth is some small fraction of the total amount of free carbon dioxide. It does not seem possible now to arrive at any closely approximate estimate of this ratio. Johnson[1] expresses the belief that the growth of plants would exhaust the carbonic acid of the atmosphere in 100 years if there was no return. The average length of time during which plant products remain as living tissue is probably greater than one year, and much less than ten years, which would make the total amount of the carbonic acid so locked up a quite small per cent. of that in the air. The amount of carbon locked up in the tissue of marine life which probably was not embraced in Johnson's estimate, would somewhat notably increase the figure, but if oceanic life is considered, the free carbonic acid of the ocean must be considered also which would greatly reduce the ratio.

A study of the life of the geological periods seems to indicate that there were very notable fluctuations in the total mass of living matter. To be sure there was a reciprocal relation between the life of the land and that of the sea, so that when the latter was extended upon the continental platforms and greatly augmented, the former was contracted, but notwithstanding this it seems clear that the sum of life activity fluctuated notably during the ages. It is believed that on the whole it was greatest at the periods of sea extension and mild climates, and least at the times of disruption and climatic intensification. This factor then acted antithetically to the carbonic acid freeing previously noted, and, so far as it went, tended to offset its effects.

THE FUNCTION OF THE OCEAN AS AN ABSORBENT OF CARBON DIOXIDE

The atmosphere penetrates the ocean by simple diffusion according to the laws of gas diffusion, modified slightly by hydrostatic pressure, and this must be considered in close computations, but is too small a factor to seriously affect the larger issues.

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[1] How Plants Feed, p. 47.

Absorption of carbonic acid.—Independently of this the ocean has a specific power of absorbing carbonic acid. It is important to note that this power of absorption is greatly affected by temperature, as shown by the following table of the variations for *pure* water:[1]

1 volume of water at	0°	dissolves	1.7967	volumes of carbon dioxide.
1 " " " "	5°	"	1.4497	" " " "
1 " " " "	10°	"	1.1847	" " " "
1 " " " "	15°	"	1.0020	" " " "
1 " " " "	20°	"	0.9014	" " " "

The precise rates of absorption for sea water are not accurately determined, and, indeed, are determinable with difficulty because, experimentally, they are complicated with the "loose" carbonic acid of the bicarbonates which is liable to be constantly freed by dissociation. The rates appear to be something less than those that obtain in pure water. Mr. Tolman has discussed this factor in his paper already referred to.

Release of absorbed carbonic acid.—Theoretically both the carbon dioxide diffused through the ocean and that dissolved in it should be in equilibrium with that of the air. Its quantity is dependent upon the temperature of the ocean and upon the partial pressure of the carbon dioxide of the air. Whenever the temperature of the ocean is raised a portion of its dissolved carbon dioxide is given forth. Whenever the partial pressure of the carbon dioxide of the air is reduced a portion of the free carbon dioxide in the ocean diffuses forth to reëstablish the equilibrium. The tendency to equilibrium is always present, though the constant variations of temperature and partial pressure prevent its complete realization at any particular time. If there were no counteracting influence the free carbon dioxide of the ocean would act as though it were a part of the air, and as the carbonic acid of the latter was consumed, that of the former would come forth into it.

But with loss of atmospheric carbon dioxide there is a reduction of temperature, and this increases the absorptive power of

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[1] Treatise on Chemistry, Vol. I. ROSCOE and SCHORLEMMER, p. 724.

the ocean, which then tends to prevent the escape of the carbonic acid. Low temperature is, therefore, antagonistic to atmospheric resupply. Mr. Tolman has attempted to ascertain the relative value of increased absorptive power and reduced partial pressure, and, though the data are insufficient for final conclusions, finds them about equal. The withdrawal of carbon dioxide from the air does not therefore call forth a proportionate amount of free carbonic acid from the sea. Indeed, it calls forth so little that the rate of atmospheric depletion is probably not appreciably retarded by it.

Summation.—Before proceeding to make special application of the hypothesis to the recognized glacial periods it may be serviceable to bring together into briefer statement the fluctuating features of atmospheric gain and loss.

1. Of the agencies of original or permanent supply, the internal group have probably fluctuated in some rude proportion to the disruption of the crust of the earth; the external group are beyond tangible treatment, but for aught that appears may be regarded as essentially uniform.

2. Of the agencies of permanent depletion, the conversion of silicates into carbonates (the chief factor) is assumed to have fluctuated essentially with the extension and restriction of the land; the formation of carbonaceous deposits fluctuated with the well-known conditions that presided over coal accumulation.

The agencies of permanent supply and of permanent loss are both regarded as rather slow in action and as being on the whole mutually compensatory, and indeed as being in some degree self-regulative since increase of supply naturally increases consumption and reduction of supply ultimately reduces the consumption; but these relations are believed to be subject to sufficient fluctuation to give a basis for pronounced climatic changes.

The sources of temporary supply and waste are much more rapid in action and apparently more intense and voluminous in results within any brief period.

1. The sources of temporary loss are: (*a*) the locking up of carbon dioxide in bicarbonates while in solution as their second

equivalent (the great factor); (*b*) the absorption of carbon dioxide in sea water; and (*c*) its consumption in forming organic matter.

The first and greatest of these is definitely connected with extension and elevation of the land, and the second is largely a sequel to it, dependent upon the temperatures it induces, while the third does not usually coöperate with these two, but rather, to the extent of its limited competency, offsets them.

2. The sources of temporary enrichment embrace: (*a*) the discharge of the second equivalent of carbon dioxide in the sea by life action (the great factor), and (*b*) by dissociation; (*c*) the diffusion into the air of carbonic acid absorbed in the sea water due to higher temperature antagonized by reduced partial pressure, and (*d*) the freeing of carbonic acid both in the air and the ocean by the decomposition of organic matter.

These sources of fluctuation are definitely correlated with the elevation and extension of the land, on the one hand, and the extension of the sea and the reduction of the land, on the other. During an extensive elevation of the land, silicates are converted into carbonates at an increased rate and the limestones and dolomites are dissolved and carried to the sea more rapidly, both processes involving an acceleration of the consumption of carbon dioxide. Correlated with this extension of the land is a reduction of the sea area attended especially by a lessening of the area of the continental shelves which are the habitat of the chief lime-secreting life, while the area available for pelagic surface life is also lessened. Reduction in the lime-secreting life retards the incidental process of freeing carbonic acid and returning it to the atmosphere. The result is a reduction of temperature which in turn increases the ability of the ocean to absorb carbon dioxide and reduces the dissociation of the second equivalent of carbon dioxide, thus further reducing the returning process and increasing the capacity of the ocean to hold carbon dioxide notwithstanding the reduction of the partial pressure in the atmosphere. The reciprocating processes are thus temporarily affected in opposite directions so as to conjoin their results.

In periods of sea extension and of land reduction (base-level periods in particular), the habitat of shallow water lime-secreting life is concurrently extended, giving to the agencies that set carbon dioxide free accelerated activity, which is further aided by the consequent rising temperature which reduces the absorptive power of the ocean and increases dissociation. At the same time, the area of the land being diminished, a low consumption of carbon dioxide both in original decomposition of the silicates and in the solution of the limestones and dolomites obtains. Thus the reciprocating agencies again conjoin, but now to increase the carbon dioxide of the air.

These are the great and essential factors. They are modified by several subordinate agencies already mentioned, but the quantitative effect of these is thought to be quite insufficient to prevent very notable fluctuations in the atmospheric constitution. As a result, it is postulated that geological history has been accentuated by an alternation of climatic episodes embracing, on the one hand, periods of mild, equable, moist climate nearly uniform for the whole globe; and on the other, periods when there were extremes of aridity and precipitation, and of heat and cold; these last denoted by deposits of salt and gypsum, of subaërial conglomerates, of red sandstones and shales of arkose deposits, and occasionally by glaciation in low latitudes.

II.

SPECIAL APPLICATION OF THE HYPOTHESIS TO THE KNOWN GLACIAL PERIODS

It now remains to specifically apply the hypothesis to the recognized glacial periods. At present only those at the close of the Paleozoic and Cenozoic eras are sufficiently determined to require discussion.

The mapping of the Pleistocene glacial deposits is sufficiently complete to show their great features, and reveals a strong development in the northern hemisphere, and at the same time a quite peculiar localization. The analysis of the deposits has progressed far enough to show that the glacial period was marked by pronounced oscillations of both the major and the minor kind. Interglacial epochs of a declared character may be assumed to be fairly demonstrated, while the glacial epochs themselves were attended by rhythmical stages of progress, as most pointedly brought out by recent detailed field work in the Mississippi and St. Lawrence valleys, notably that of Mr. Leverett and of Mr. Taylor. These rhythmical features are made the subject of a special discussion by Mr. Taylor in a paper entitled "Moraines of Recession and their Significance in Glacial Theory."[1]

To be really applicable to Pleistocene glaciation a working hypothesis must therefore not only postulate agencies capable of producing a glaciation covering the American plains down to

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[1] JOUR. GEOL., Vol. V., No. 5, 1897, pp. 421–465. See also "The Great Ice-Dams of Lakes Maumee, Whittlesey, and Warren," American Geologist, Vol. XXIV, No. 1, July 1899, pp. 6–38, and the review of this paper by MR. GILBERT in the last number of the JOUR. GEOL.

37° north latitude, and mantling also the plains of middle Europe and high altitudes quite generally, but it must assign agencies for the oscillations which attended it.

General cause.—The atmospheric hypothesis finds a general cause for the Pleistocene glaciation in that notable extension and elevation of the land which reached a climax near the close of the Pliocene period. It is not, however, through its direct topographic influence that this was accomplished, though this may have been incidentally tributary, but through its effects on the constitution of the atmosphere. The recently named Ozarkian or Sierrian period embraces the specially effective stage of this great land area, and it is with much pleasure that I support the emphasis laid upon the significance of this period by Professor Le Conte in his paper in the last number of the JOURNAL,[1] though I interpret that significance in different terms. The wide extent and high elevation of the land at that time are so strongly set forth by Dr. Le Conte as to leave no need for additional emphasis here.

A rude estimate of the land area in Middle Tertiary times, when the climate was mild far to the north, gives about 44 million square miles. A similar estimate for the Ozarkian or Sierrian period gives about 65 million square miles, while the received estimate of present land is about 54 million square miles. Taking the Middle Tertiary area as a basis of comparison, the land was increased in the Ozarkian period about 47 per cent., and afterwards fell off to the present area, which is 23 per cent. greater than that of the mid-Tertiary. It is probably conservative to estimate that the average elevation of the Ozarkian land was at least two or three times, perhaps three or four times, as great as that of the mid-Tertiary. Combined in the light of the suggestions previously made regarding elevation, these indicate a very great change in the effective contact of the atmosphere with the earth. If we measure the actual contact by the surfaces of the grains, pores, fissures, and minute crevices with which the air and the atmospheric waters come in contact

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[1] Pp. 525–544.

—and this is the true contact area—the increase will appear impressive.

As in other cases, there was here also a self-accelerating action. As land was elevated, its underground water level was at first carried up measurably with it and lay near the surface. Trench-cutting accompanied it, to be sure, but at a slower rate. As the declivity increased the cutting and transportive power of the drainage increased, and as the dissection of the land proceeded, the water level was lowered and the effective zone of atmospheric contact augmented. The very process of degradation, up to a certain stage, increased the facilities for the chemical action of the atmosphere. In general it may be observed that degradation reacts upon itself favorably for a time. The cutting of certain of the western plains into "bad lands" and the gullying of the cultivated fields in certain parts of the southern states are striking examples of current self-accelerating processes of the more mechanical sort.

Concurrent with this increase of the atmospherie contact-area on land there was a reduction of sea surface, the habitat of lime-secreting life, and *nota bene*, an almost complete obliteration of the epicontinental seas and sea-shelves which were the parts of the sea bottom that were by far the most prolific in carbonic-acid-freeing marine life. Shallow-water marine life must have been very generally driven down on the abysmal slopes and on to such limited deeper shelves as may have been brought within reach by the lowering of the seas. The consequent lessening in the rate of freeing of carbon dioxide is assumed to have been great, and this coöperated with the accelerated consumption on the land to hasten the depletion of the atmosphere.

Besides this, when any appreciable reduction of temperature followed these coöperating agencies, it tended of itself to check the lime-secreting life of the ocean, and at the same time to give the oceanic waters greater absorptive power and less dissociative activity, thus calling into operation a group of secondary agencies which intensified the effects of the primary agencies.

Now the task assigned this remarkable combination of agencies is not a formidable one. If we take the largest of the current estimates of the present atmospheric content of carbon dioxide, viz., .06 per cent. by weight (comparable to .04 per cent. by volume), the mid-Tertiary atmosphere should have contained .15 per cent. to .18 per cent. of carbon dioxide, and that of the glacial period .03 per cent., following Dr. Arrhenius' estimates. That is to say, for the reduction of the carbon dioxide of the Tertiary atmosphere from the assigned .15 per. cent. or .18 per cent. to the assigned .03 per cent. of the glacial period, we have an estimated increase of land area of 47 per cent., and an increase of elevation 100 per cent. or 200 per cent., and perhaps more. To produce the present amelioration we have a falling off of about one half in each of these items.

Numerical data, which will be given later, indicate that something like $\frac{1}{2000}$ of the carbonic acid of the air is now taken out annually. If the same amount is returned, the constitutional status is preserved. But if the foregoing agencies that coöperated in late Pliocene and early Pleistocene times to disturb the balance between removal and return were effective to no more than 10 per cent. of the total rate, it would have been capable of reducing the assigned mid-Tertiary content of .18 per cent. carbonic acid to the assigned glacial content of .03 per cent. in 50,000 years. It is not, of course, supposed that the rate would be constant as the state of enrichment changed, and note of this will be taken later, but the computation serves to show how effective a disturbance in the relative rates of supply and removal becomes when such action bears so high a ratio to the total mass of carbon dioxide in the air. It may also serve to show that the hypothesis is assigning agencies whose supposable quantitative competency is abundantly adequate to the results imputed to them.

ASSIGNED CAUSES OF GLACIAL OSCILLATION

It has been already noted repeatedly that the assigned causes of glaciation are self-accelerating in certain significant phases. The salient effect of this, reasoning on general principles, must be to push results to an extreme from which reaction is inevitable. Let us consider this in detail. It is thought that there were three dominant agencies concerned in this, modified by several subsidiary ones.

1. A necessary consequence of the accelerated rate of transmission of carbon dioxide to the sea, combined with a slackened rate of release in the sea, was an accumulation of oceanic carbon dioxide. The primary form of this was an increase of the carbonates.

2. The cooling of the sea waters which attended the process reduced the dissociation, and hence the carbonates were more nearly full bicarbonates than before. *There were, therefore, not only more carbonates, measured by the bases, but they carried more carbon dioxide in proportion to the bases.*

3. With the growth of the snow-fields attendant on the progress of glaciation, there was an increase of reflection of the sun's radiation and a reduction of its absorption. Computation shows that the albedo is an important factor.

Subsidiary to these there were the following:

4. There was an increase in the absorption of carbonic acid in the ocean, resulting from the lowering of the temperature. This, however, was offset by the declining partial pressure of the carbon dioxide in the air, and, as the two seem to be of the same order of magnitude, they may be set aside for the present.

5. With increasing cold there was a less rapid decay of organic matter and a less complete release of carbon dioxide. Over against this, however, there was a reduction in the amount of carbon locked up in living organic matter. It is difficult to form a trustworthy estimate of either, but it may be provisionally assumed that they belong to the same order of magnitude and may be set aside together. At any rate, any residual difference would not be a notable factor.

6. The majority of chemical authorities state that the solubility of calcium carbonate in water saturated with carbonic acid increases with a lowering of temperature through ordinary

ranges. Unfortunately there is not complete unanimity on this point. But, if this be true, as the temperature fell the solvent action of the carbonic acid of the land waters upon the limestone was increased. Over against this was a probable reduction of the action of organic acids. Probably the decomposition of the silicates went on at a lower rate, but, as it was much less than one fifth of the whole action, its reduced rate is not very material here.

As the carbonic acid of the air was diminished, its action on the land surface declined—though not at a proportional rate—but long before it could offset the enlargement of the contact area aided by the sea action, glaciation would be far advanced, if the previous estimates hold good.

Setting aside, as being measurably balanced, or as being of minor or uncertain value, all but the first three items, which are clearly factors of great potency, we find at first a strong disposition toward the acceleration of the depleting process.

But this, although a pronounced influence in the early stages of refrigeration, could not continue indefinitely, for the process involved the conditions of its own arrest.

The arrest of the depletion and the inauguration of the reaction.—With the development of glaciation, the agencies that tended to counteract atmospheric depletion received a powerful ally in the ice-sheet itself. The spread of the ice over the surface prevented further effective weathering of the area so covered and correspondingly arrested atmospheric depletion. The total area covered by glaciation at its maximum was probably not far from 8 million square miles, or nearly 15 per cent. of the land surface.

Besides this, the area outside of that actually covered by the ice-sheets was probably affected by prolonged freezing during the winter stages, and was perhaps to some extent permanently frozen beneath the surface, and this arrested solvent and chemical activity. If the modest figure of 5 per cent. be assigned for this supplementary effect, 20 per cent. of the functional area would be withdrawn from action. Whether this numerical estimate be correct or not, it may be assumed that if a given amount of withdrawal, combined with associated agencies, were not sufficient to arrest the progress of glaciation, the glaciation would have continued to extend itself until the point of balance was reached. It is, perhaps, not too much to assume that the extension of glaciation and its concurrent agencies mark in themselves the measure of preponderance of the depleting agencies at the stage when glaciation began. That is to say, after the depleting agencies had brought the air's carbonic content down to the point at which the glacial centers were inaugurated, these agencies were still preponderant over the repleting agencies to some such extent as 20 per cent., more or less.

While it does not seem necessary to our general purposes to consider the associated agencies of arrest, if these views be correct, they possess an interest of their own, and may be mentioned briefly.

With little doubt the lowering of the temperature lessened the rate of decomposition of the silicates, though frost action aided in disaggregating them mechanically and in thus increasing the atmospheric contact. On the other hand, while the authorities are not altogether agreed, the weight of the latest opinion supports the view that the limestones would be dissolved by cold water saturated with carbon dioxide faster than by warm water, other things being equal. The cold waters would quite certainly contain more absorbed carbon dioxide than warm ones. Probably other things were not equal, for the vegetable action and the organic acids probably lent less and less aid as the temperature fell. It is not clear what the balance of these influences combined would be. Whichever way it leaned, it does not seem to have been of decisive moment.

As previously remarked, the progressive removal of carbon dioxide from the air reduced the amount of its action, but not proportionately. While this lessened the depleting action it does not seem to have reached decisive moment, at least not until a late stage in the process of depletion.

Meanwhile, in the ocean, conditions favoring reaction were gathering force as the result of the processes in action there. The ocean was accumulating carbonates and augmenting their degree of bicarbonation with the increase of cold. Now it is obvious that if the loading of the ocean with carbonates were to proceed to the point of saturation, inorganic processes of precipitation and dissociation would come into play to an extent that must necessarily balance all further accessions of material. It does not appear, however, that there is enough, or even nearly enough, carbon dioxide in the air to bring about a condition of full saturation of the ocean with bicarbonates, even if it were all to take that form, and were to be conveyed completely to the sea. But the movement toward saturation should increase in some degree, probably small, the efficiency of inorganic agencies tending toward precipitation, although it could become notably effective only after prolonged accumulation.

The concentration of carbonates in the ocean was somewhat aided by the removal of water required to form the great ice-sheets. On a rather large estimate of the mass of the ice-sheets, this extraction might possibly reach 5 per cent. of the volume of the ocean.

There would probably be a progressive evolution of lime-secreting life adapted to the cool waters, and this would increase the rate of carbonic release and contribute to a reversal of action.

None of these subsidiary agencies, nor all combined, seem to have been controlling factors.

It is notable that some of these subsidiary agencies, on both sides, are final in themselves and quite without retroactive possibilities. When once their work was done there was no resilience. It was quite otherwise with the ice mantling and the ocean loading. Far from being final, these contained in themselves the potentialities of reaction and gave vigor to the reaction when it took place.

Agencies that precipitated reaction.—When once the reactive agencies had reversed the relative rates of enrichment and depletion and there began to be an increase of carbon dioxide in the air, the following influences would coöperate to hasten and intensify the reactive movement.

1. The dissociation of the second equivalent of carbonic acid associated with the carbonates of the ocean would be increased, and as the temperature rose from the diffusion of the freed carbon dioxide into the air this would be still further augmented by its own reactive effects. This is one of those interesting agencies whose effects at once become causes of further like effects.

2. The increased warmth would call forth more lime-secreting life in the ocean, and thus also hasten the freeing of carbon dioxide, and this again would react favorably on itself.

3. The increase of water from melting ice would some what extend the shallow-water zone and favor lime-secreting life. If the land were depressed by the load of ice, as some suppose, this would increase the sea area and favor lime-secreting life. With this may be associated the falling of the water level in the high latitudes (to which it had been drawn by the gravitation of the accumulated ice mass) and a corresponding rise of the water level in lower latitudes. Since the lower-latitude life is more abundant than the high-latitude life, and more effective in extracting lime, the shift would involve a gain in lime-secreting potency.

4. The increased decay of organic matter attendant on the warmer temperature would develop carbon dioxide; but over and against this must be set the increased carbon locked up in the augmented living matter. These, as before, are set aside, as perhaps mutually offsetting each other.

5. The increase of temperature arising from the preceding causes would increase the water vapor in the air and thereby add to the thermal capacity of the atmosphere, and this would react favorably upon itself and upon the other agencies favored by high temperature.

Thus the reaction once started would be self-augmenting, until the fundamental conditions were changed or the reaction was checked by its own ulterior consequences. The sequences may be easily followed. The carbonates of the sea, which had been augmented during the epoch of glaciation were now diminished and limestone was more actively deposited. The ocean, previously fattened in carbonates now became lean. So also the carbonates themselves, that before were quite plump bicarbonates, now became degraded to a mixture of normal and acid carbonates. In short, the ocean holds less free and feebly-combined carbon dioxide and the air holds relatively more. As the ocean is now estimated to contain from eighteen to twenty-five equivalents of atmospheric carbonic acid in the free and feebly-combined states, a moderate fluctuation in its content would cover the full range of atmospheric variation required to produce the climates under discussion, according to Arrhenius. On the supposition that the glacial epoch was produced by a reduction of the carbonic content of the atmosphere to one half the present amount, it would only be necessary for the ocean to release 2 or 3 per cent. of its releasable carbon dioxide to restore the atmosphere to the present condition. If the ocean gave up 4 or 5 per cent. of its releasable carbon dioxide the climate would be notably milder and more equable than the present. Assuming the correctness of Dr. Arrhenius' conclusions, it would seem from these considerations that there is nothing forced or violent in the supposition that an effective interglacial epoch might be brought about by the reactive agencies indicated.

Recrudescence of glaciation.—If the land area of the globe as a whole remained large and high notwithstanding such local depressions as have been attributed to the weight of the ice and the effects of low temperature; or, more precisely, if the atmospheric contact area remained large, the conditions for a renewal of glaciation would again prevail because the renewal of warm temperature, the enrichment of the atmosphere, and the depletion of the ocean would restore the original action. So soon as the ice had retreated from the land, the weathering of the uncovered area would be renewed. This, of course, would begin so soon as the retreat began, and increase in a corresponding measure; but it is a slow process, while the reactions of the ocean are relatively rapid—indeed they should keep close pace with the rise of temperature which they induce. There should be no appreciable lag. After the retreat of the ice a new surficial factor would come into play, the sheet of drift spread over the surface. In so far as this consisted of undecomposable matter blanketing decomposable matter, it would interfere with the progress of decomposition, but in so far as it consisted of limestones and silicates ground to a flour and exposed to the atmosphere, it would facilitate chemical action and expedite a second depletion of the atmosphere and through it a second term of glaciation. Aside from the effect of this mantle of drift and such changes of topography as might have occurred, the conditions for the renewal of glaciation would be, so far as I see, as effective as they were at the outset. Assuming that they were equal to the preceding, a second glaciation equal to the first is to be postulated, and a corresponding reaction at length, as in the previous case, due to like agencies. Thus a series of glaciations and deglaciations should follow each other until the general causes lying back of glaciation had disappeared.

In so far as the land, on the whole, settled back toward sea level or was worn away, or, by any other agency, lost its degree of effective exposure to the atmospheric action, in so far the conditions of glaciation would disappear. Pursuing the normal history which follows a period of great land elevation, it is to be presumed that there would be a gradual reduction of the land surface and land elevation, and that hence the conditions productive of glaciation would gradually pass away. On such an assumption it is presumed that the recurrent glacial advances and retreats would become more and more feeble until the series vanished. Nominally, then, the glacial and interglacial epochs should form a rhythmical series declining from large oscillations at the maximum to lesser and lesser oscillations as the series disappeared. This seems to correspond with the observed oscillation of glaciation in both Europe and America.[1]

INTERCURRENT AGENCIES

Without question the normal series of glacial oscillations just postulated would be subject to intercurrent influences which would be liable to disturb, perhaps quite seriously, its regularity and symmetry.

1. Any notable movement in the land which affected the sum total of the atmospheric contact area would disturb the symmetry of the series.

2. Any notable change in the original supply of carbonic acid through volcanic action or other agency would produce obvious modifications. The deformation of the body of the earth out of which the conditions of glaciation are assumed to have sprung would doubtless be favorable to volcanic action, and if this reached a degree of intensity sufficient to add appreciably to the carbon dioxide of the atmosphere, it would radically affect the ongoing of the process. That there was extensive vulcanism nearly or quite concurrent with glacial action has been urged by some geologists; indeed, glaciation has even been attributed to volcanic action.

3. The precession of the equinoxes has been regarded by many thoughtful students of glaciation as an influential agency. If effective, it would superpose a rhythm of its own upon the rhythm postulated by this atmospheric hypothesis. For specific illustration the extensive series of moraines which marked the later stages of the Wisconsin epoch of glaciation are referred by Taylor to precessional influence, while the Wisconsin glaciation itself would, under the atmospheric hypothesis, be referable to atmospheric depletion. The most serious question which here arises is the compatibility of the prolonged period implied by Taylor's interpretation with the rate of reaction implied by the

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[1] The Classification of European Glacial Deposits, JOUR. GEOL., Vol. III, No. 3, pp. 241–269, JAMES GEIKIE; The Classification of American Glacial Deposits, *ibid.*, pp. 270–277, T. C. CHAMBERLIN; editorial, *ibid.*, Vol. IV, No. 7, October-November 1896, pp. 873–896.

atmospheric hypothesis.[1] This will be more evident as we touch on the time rates.

4. The change in the eccentricity of the earth's orbit which Croll has made the foundation of his beautiful hypothesis of glaciation, if not found competent to produce general glaciation itself, might still be effective in producing climatic changes of less degree, and might superpose important modifications upon the series postulated by the atmospheric hypothesis. It may be remarked in passing, however, that the computed variations of eccentricity of distant periods of the past do not rest on so firm a mathematical basis as is currently supposed.

It is obvious that these and other possible agencies might work concurrently with the atmospheric influences, or antagonistic to them, in either case distorting and masking the normal rhythmical expression which a purely atmospheric series would assume.

DO THE TIME RATES FALL WITHIN WORKABLE LIMITS?

The working capabilities of a glacial hypothesis are somewhat severely conditioned by its time factors. It must not only present a satisfactory correlation between the time of occurrence of glaciation and that of the assigned cause, but the rhythmical action of the cause must be consonant with the rhythmical history of glaciation. That the Pleistocene glaciation followed the Ozarkian or Sierrian stage of elevation at an appreciable distance, I hold to be demonstrated by the relations of the glacial deposits to the eroded topography of that period. On the other hand, there is no evidence of a prolonged interval, geologically speaking. The atmospheric hypothesis demands that the accelerated erosion due to elevation (or rather to the dissection that followed elevation) should have continued long enough to remove about three times the present atmospheric content of carbon dioxide before glaciation could begin, following Arrhenius computations. This removal could only be accomplished by the *excess* of consumption of carbon dioxide over supply and there is

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[1] See GILBERT'S review in last number of this JOURNAL, p. 621.

reason to believe that the rate of supply from the interior was greater than the average on account of crustal disruption and volcanic action. There seems, therefore, little ground to think that the glaciation should have followed closer after the elevation than it seems to have done. It would seem rather that the hypothesis was happy in this time relation at least.

With most geologists, I doubt not, the chief question will be whether the postulated agencies could cause the glacial oscillations, involving the removal and reproduction of the ice, in large part or in whole, as rapidly as the field evidence requires. Present measures of glacial rates and times are quite uncertain but not indefinitely so. Some rude approach to their value may be attained. Recently expressed opinions regarding the time since the last ice retired from the site of Niagara River, and inaugurated the erosion of its gorge, lie between 7000 and 33,000 years, which we may average at 20,000 years. I place no special confidence in this figure, but it is rudely representative of the average order of magnitude of expressed opinion. This represents only a part of the time since the beginning of the deglaciation that removed the Wisconsin ice-sheet. According to Taylor's views it would be only a very small part. I doubt if any careful geomorphic geologist familiar with all the phenomena involved would seriously consider an estimate that made it much more than one half at the most; so that it would apparently not be straining the evidence to take 40,000 years as a rude measure of the time since the beginning of the retreat from the outermost moraine of the Wisconsin stage. However, this may probably be cut in half and halved again without over-straining the possibilities of the hypothesis.

This is the time of retreat. An interglacial epoch involves not only the time of retreat, but the time of interglacial mildness and the time of re-advance. The best specific data now available in America for estimating these elements are undoubtedly those afforded by the excavations about Toronto which have been so fruitfully cultivated by Hinde, Coleman and others.[1] (1) The time occupied in the ice retreat is there almost without record. (2) The duration of the mild climate is recorded in thirty-five feet of clays and sands. It is also implied in the time necessary for the migration of the Paw Paw, Osage Orange and other trees from more southerly regions to this rather northern locality, and also for the migration of the clams and other mollusks from the Mississippi waters to this rather distant region. Both of these migrations were probably rather slow processes. (3) The initiation of the returning cold is recorded in 150 feet of fine stratified peaty clays and sands. (4) Following this there was an unknown period occupied in the transition from the conditions of deposition, during which the preceding series had been formed, to the conditions of effective erosion which followed. To suppose that this transition was due to the removal of an ice-dam that had lingered in the lower St. Lawrence seems quite untenable for a long, mild period and a long, cool, but not glacial, period had intervened. It was probably due to the cutting down of the drainage outlet, or to a surface movement, or the two combined, and hence probably occupied an appreciable time. (5) There then followed a period of erosion comparable to that since the last ice invasion. Succeeding this came the re-invasion of the ice-sheet.[2] These data seem to fairly imply that the interglacial epoch represented at Toronto was several times as long as the postglacial epoch.

While nowhere else has so complete a record been found, many estimates of the differences of erosion of the several till sheets in the Mississippi valley, where the formations are well deployed and happily suited to such studies, have been made

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[1] GEORGE JENNINGS HINDE: Glacial and Inter-Glacial Stages of Scarborough Heights. Can. Jour. 1878, p. 388 *et seq.*

A. P. COLEMAN: Am. Geol., Vol. XIII., February 1894, pp. 85–95. Ditto. JOUR. GEOL., Vol. III., No. 6, 1895, pp. 622–645.

[2] Canadian Pleistocene Flora and Fauna: Report of the Committee consisting of Sir J. W. Dawson (chairman), Professor D. P. Penhallow, Dr. H. M. Ami, Mr. G. W. Lamplugh and Professor A. P. Coleman (secretary), appointed to further investigate the flora and fauna of the Pleistocene beds in Canada.—British Association for the Advancement of Science.

by experienced glacialists, and their concurrent judgment is that the least of the notable interglacial intervals was at least two or three times as great as the postglacial interval. It would not be exceeding current judgment, therefore, to assign from 80,000 to 120,000 years as the duration of a typical interglacial epoch.

But in the interest of conservatism let the postglacial interval be taken at 10,000 years and the interglacial at 20,000 or 30,000 years. This seems to me excessively conservative. If the assigned agencies can affect a reënrichment of the atmosphere in carbon dioxide to an amount somewhat exceeding the present content and then again a depletion of one half within 20,000 or 30,000 years, the hypothesis will not be excluded by time limitations.

We have the following pertinent data based in part on Reade's[1] estimates of the present rate of removal of carbonates:

Total mass of the atmosphere	5×10^{15} tons
Mass of atmospheric CO_2 (reckoned by weight at .0006)	3×10^{12} tons
Total mass of CO_2 taken annually from the atmosphere	162×10^{7} tons
Mass of CO_2 consumed annually in original carbonation (reckoned by area at 20 per cent. of the land)	27×10^{7} tons
If reduced one half on account of the slower rate of decomposition of crystallines it will be 13.5×10^{7} tons, in which case the other half is to be added to the following item, if Reade's estimates are correct.	
Mass of CO_2 consumed annually in forming bicarbonates	135×10^{7} tons
Time required at this rate to consume total atmospheric CO_2, assuming no return	1852 years
Time required at this rate, without return, to consume one half atmospheric CO_2 (the reduction requisite for glaciation.)	926 years
Time required to consume half the "free" and "loose" CO_2 of the ocean (estimated at 18 times that of the atmosphere) without return	16,668 years
Time required to consume half the CO_2 of the atmosphere and the ocean combined, without return	17,594 years

The last items which involve the reduction of the carbon dioxide in the ocean as well as in the atmosphere are not really

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[1] Loc. cit. on p. 569.

pertinent to the discussion, if the foregoing doctrine relative to the mode of action of the ocean during a glacial period is correct, for it is there maintained that the ocean does not give up its carbonic acid with increasing depletion of the atmosphere, but, on the contrary, increases its content. They have some interest, however, in connection with it and with other phases of the atmospheric hypothesis which the reader may possibly wish to consider. They also have some pertinency to the discussion of Paleozoic glaciation, to be taken up presently.

We are here concerned especially with the rate at which atmospheric carbonic acid may be consumed to the amount of one half the total content. For convenience, no account has been taken of the return of carbonic acid from the ocean or through organic action. We reach the rather startling result that if there were no return, the decomposing and solvent actior on the present contact area would consume one half of the atmospheric carbon dioxide in less than 1000 years. This result, based on Reade's estimate, may be checked by independent computation on a more familiar basis and by different modes of computation. For example, by assuming the average rate of degradation of the land surface to be one foot in 5000 years, and that the carbonates constitute 15 per cent. of the material removed, one half of the carbonic acid of the atmosphere would be consumed in 1248 years, if there were no return; or in 1000 years if the degradation was one foot in 4000 years.

The actual depletion must, of course, depend upon the excess of this rate of removal over the rate of return. I have already endeavored to show that there was a very large fluctuation in the conditions that determined the relative rates of consumption and return, notably that the land of the Ozarkian time was more than 20 per cent. greater in area than the present land, and that its elevation was probably 100 per cent. or 200 per cent. greater at the maximum stage of protrusion. And this was correlated with coöperating conditions in the ocean. Both of these estimates, however, must be considerably reduced to give a safe measure of the area which was operative at the time of the interglacial epochs, or at least some of them, for there is abundant evidence that the land was not then so greatly elevated as in the Ozarkian or Sierrian period.

Instead, therefore, of combining 20 per cent. increase of land area with 100 per cent. increase of elevation, and these with the coöperating 20 per cent. reduction of sea area, the destruction of sea-shelves, and the restraining effects of lowering temperatures, as we are entitled to in bringing down the rich Tertiary atmosphere to the lean conditions of the glacial period, let us content ourselves with some modest fraction of these intensifying combinations. If we only assume that the agencies of depletion were superior to the agencies of return by the amount of 10 per cent., the depletion requisite to bring on a glacial epoch, starting with atmospheric conditions like those of the present, would be effected in less than 10,000 years. If, therefore, we over-generously allow as much time for deglaciation as for reglaciation, an interglacial epoch might not require the operation of the postulated agencies for more than 20,000 years, so far as they themselves are concerned. The development of the ice-sheet might take more time, but we have little or no data for estimating this. If 10,000 years additional is allowed for this the total remains at the modest figure of 30,000 years.

It would not seem to be pushing the data previously given to extremes to postulate a larger percentage of difference between depleting and repleting agencies than 10 per cent., which would make the requisite atmospheric depletion possible in a shorter period. It is probably not extravagant to assume that the difference might rise to 20 per cent., in which case the requisite time would be brought down to extremely modest limits. It is difficult to see how anyone who studiously considers the phenomena of the Toronto interglacial epoch could assign to it a duration less than is compatible with these agencies, as here interpreted. It would seem, therefore, that the hypothesis is not excluded from the working category by inadaptability to the time rates of the phenomena which it seeks to elucidate.

There is not likely to be any serious question respecting the time rates at the other extreme, that is, that the agencies necessarily act too rapidly to correspond to the phenomena. Of course, in the final adjudication of the hypothesis, it will be necessary to show that its time rates not only might correspond to the time rates of the phenomena, but that they did so, but this is a labor of the future, and is obviously dependent upon a very notable extension of precise knowledge, which it is the purpose of the hypothesis to aid in calling forth. It is sufficient here to show that reasonable postulates, based on a reasonable estimate of the phenomena, fall within compatible limits.

III.

LOCALIZATION OF GLACIATION.

THE problem of localization is in some sense independent of the fundamental hypothesis offered in this paper, and the suggestions which follow may be accepted or rejected without carrying necessarily an approval or disapproval of the main hypothesis.

The remarkable distribution of the great ice-sheets.—The chief centers of the Pleistocene ice-sheet lay on the north-northeastern plains of North America, and on the northwestern quarter of Europe. On the northwestern Cordilleras there was also a notable center, though it does not appear to have equaled the others in rank.[1] The north-northeastern American centers are properly regarded as chief because the spread of the ice-sheets from them

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[1] This statement is perhaps open to some question. It is quite certain from field observations that the glaciation of the Cordilleran plateau in the United States and in British Columbia as far north at least as 51° Lat. was much feebler than that of the Mississippi basin at corresponding latitudes and much lower present altitudes. It seems also clear that the ice of the north Cordilleras did not creep out upon the plains to an extent at all comparable to the spread of the Scandinavian ice-sheet upon the plains of Europe. Considered from these points of view, and they seem to be the important ones, the statement can scarcely be questioned seriously. The evidences of glaciation on the mountainous border facing the Pacific from 48° northward are, however, quite impressive. They find their climax perhaps in the 4000 or 5000 feet of glacial débris which Russell reports in the foothills of the St. Elias range. In view of this it may perhaps be insisted that the glaciation of this region was exceptionally concentrated on the Pacific border, because of the abrupt rise of the surface and the height of the mountains, and that the glacial discharge toward the Pacific was also exceptionally effective because the high gradient; so that, taking this intensification into account, the sum total of ice formation and ice action in this region may not have been so much inferior to that of the European area as the surface distribution might seem to imply.

was much more extensive than from the other centers, and because they were not aided essentially by mountainous points of origin, for neither the Labradorean nor the Keewatin centers appear to have been initiated by mountainous elevations. It was a development of glaciation on plains, or at most on plateaus. This fact renders the American ice-fields conspicuously chief among all that developed in Pleistocene times. The glaciation of Europe was centered upon mountains; and remnants of glaciation still linger on the mountain heights of most of the old glacial fields, giving ground for the belief that the local topographic features were there important factors. The glaciation of northwestern Europe would possibly have been rather scant if it had received no greater topographic aid than was afforded in the Keewatin field, but apparently it would not have been absent.

It has often been remarked that the Pleistocene glaciation was gathered about the north Atlantic, but it can scarcely be too much emphasized that the greatest of the glacial areas, and by far the most phenomenal, because of its plain topography, lies on the *western*, or what we are accustomed to regard as the *windward*, side of the Atlantic.

It is further to be noted, that on the western side of America, the glaciation, though notable, was still seemingly much inferior to that of the great northeastern plains; and this in spite of its mountainous character and its adjacency to the great Pacific Ocean, a topographic and hydrographic conjunction which expresses itself now in the most vigorous glaciation outside of the polar circles.

More or less nearly contemporaneous with the growth of the foregoing great ice-sheets, local glaciation developed on nearly all the mountain heights of the earth, whether in the northern or the southern hemisphere, and whether in high or low latitudes. This seems to imply an intensification of glacial conditions generally, but at the same time to indicate that the great ice-sheets were dependent on some special agency of localization. In saying that these scattered areas of glaciation were approximately contemporaneous, no dogmatic assertion is intended relative to the exact contemporaneity of glaciation or to its alternation in the northern and southern hemispheres, nor respecting the doctrine of migration of glaciation in longitude. Observational data are yet insufficient to decide these questions. It is obvious, however, that the hypothesis under consideration postulates essential contemporaneity throughout the globe.

The constructive pole of the winds.—As a possible factor in the localization of glaciation, I venture to offer the suggestion that the axis of the earth's rotation and the axis of the atmosphere's circulation, constructively interpreted, are not identical. By the constructive axis of the winds I mean that ideal line about which the general currents of the atmosphere would be found to revolve if all minor movements were eliminated or equated and the aggregate east-west components only were regarded. In other words, it is suggested that the planetary system of circulation is obliquely adjusted to the planet. This was first suggested to me by a study of the peculiar courses of the arctic ice-drift. The polar ice-bearing currents are regarded by experienced arctic navigators as concrete expressions of the average movements of the atmosphere. To be sure, the ice-drift is affected by the ocean currents, but these are also, in the main, the results of the average direction and force of the winds, though they do not so immediately and definitely express it as the ice-drift, because they are also influenced by more remote agencies.

If the axis of the currently postulated "circumpolar whirl" of the atmosphere coincided with the axis of the earth, and if it were the poleward incurving spiral of the winds that swept the surface of the polar sea, the average ice-drift should assume, or tend to assume, a corresponding incurving spiral. The ice should crowd in toward the pole and rotate upon itself in a direction opposite to the hands of a watch. If this were true, the current which carried Nansen from east to west should have flowed from west to east.

If the axis of the "circumpolar whirl" coincided with the axis of the earth, and it were the *outward-running* spiral that swept the surface of the sea, the ice-fields should rotate in the opposite direction with a centrifugal tendency which should carry the ice outwards and press it against the adjacent continents and give a voluminous discharge down the north Atlantic. An attempt to drift *toward* the pole in such a system would be an absurdity, and Nansen's feat would be inexplicable.

Observed ice-drift.— Neither of these are the phenomena observed. On the contrary, as now abundantly demonstrated, particularly by the remarkable drifts of the Jeannette and the Fram, the average movement near the coast of northern Asia and Europe is westward and slightly northward. This course is held until Greenland imposes itself as a barrier. The outer margin of the ice flow is then forced southward, but immediately it reaches Cape Farewell it curves closely about the point (at least during the summer months) and flows northward and westward to the vicinity of the arctic circle. It here encounters a new barrier in the islands of the American Arctic Archipelago and again moves southward.

On the north coast of Greenland, so far as known, the ice presses hard upon the land, as though its normal course were southward. It flows persistently into the channel between Greenland and Grinnell Land, and gives rise to that strenuous ice-pack which has again and again been assailed by arctic navigators with such great daring and such little success. The recent adverse experiences of the Windward and the Fram are but a renewed expression of the persistence of this south-southwestward drift of the ice currents.

On the north side of the Arctic Archipelago, west of Greenland, the ice crowds hard against the shore, and has thus far prevented the full penetration of Jones Sound or any of the other straits between the northern range of islands. The blocking of Jones Sound appears to be the result of an eastward as well as southerly crowding of the ice.

Farther to the west Banks Strait and McClintock Channel together form a continuous and rather broad water way, beginning in longitude 130° west and stretching southeasterly to longitude 95° west. This channel is always tightly jammed with ice pressed in from the northwest. So persistent and strenuous is the pressure of this ice-pack that it constitutes an effectual barrier to the northwest passage, and has thus far mocked all attempt to force it. This implies a definite and persistent movement from the northwest to the southeast.

It appears, then, that from far east of Greenland to the western limits of the northern archipelago there is a definite convergence of the ice currents toward a point located somewhere north of Hudson Bay, *i. e.*, a point lying to the north of the two great centers of Pleistocene glaciation, the Labradorean and the Keewatin, and on a meridian that runs between them.

It is interesting to note that the point of convergence lies in the general vicinity of the magnetic pole. and this obviously leads to the further suggestion that there may be some genetic connection between the two as yet undetermined.

Concurrent in import with this is the fact that on the opposite side of the north pole the coasts of northern Asia and Europe become partially free of ice each season. This, although doubtless partly due to the effects of the fresh water borne in by the great rivers of those coasts, is probably none the less an expression of the fact that the polar ice is not crowded down upon those coasts; for if it were, its great mass would completely overwhelm the effects of even the great Siberian rivers. This phenomenon, taken in connection with the direct observations of the ice-drift made by De Long, Nansen, and others, leaves little room for doubt that the great polar ice-field drifts away from the Eurasian coast and crowds toward Hudson Bay. The meridian of 90° may be taken as rudely representing the axis of this converging ice-drift. It is interesting to note that this same meridian bisects the Mississippi valley and crosses the southern apex of the great American glacial field.

Distribution of arid zone.—Correlated with this remarkable phenomenon is an equally remarkable distribution of the great desert tracts of the eastern hemisphere. Commencing on the Atlantic coast of Africa between 10° and 30° north latitude, the arid belt stretches north of east across Africa and Asia until in Mongolia it lies between 30° and 50° north latitude. That is to say, in this stretch of 70° or 80° in longitude it has advanced 20° in latitude. If now we select the meridian at 90° east, at or about which the desert area reaches its northern culmination, and follow this through the pole to a point 20° beyond on the meridian of 90° west, we are in the vicinity of the point towards which the arctic ice-drift seems to concentrate. And if we follow the same meridian southward we reach the point in the Mississippi valley where the ice-sheet had its southernmost extension. It is to be noted further that this last point coincides with the region where a large percentage of the cyclones which descend from the northwest curve about and take northeasterly courses.

If there were space here to enter into other particulars, additional coincidences of an apparently significant nature might be found. The inference drawn is that the axis of the main polar whirl, if indeed the polar movement can be called a whirl, is not coincident with the axis of the earth, but lies at some point southward from it in the vicinity of the meridian of 90° west longitude and 20° more or less distant from the pole.

Indications of meteorological data.—As just implied, the idea entertained is not that there is a simple polar whirl whose axis is located here, but that the rather complex movements of the polar atmosphere, when combined and correlated, give a theoretical or constructive pole in this region. What is meant by this will appear more specifically from a study of the available meteorological data. Unfortunately these are yet quite imperfect and partially uncorrelated, and hence I have given precedence to the natural correlation expressed in the ice-drift. The International Circumpolar Commission has not yet combined and discussed its data. It may therefore be most convenient to have recourse to Buchan's[1] or Hann's[2] meterological maps for

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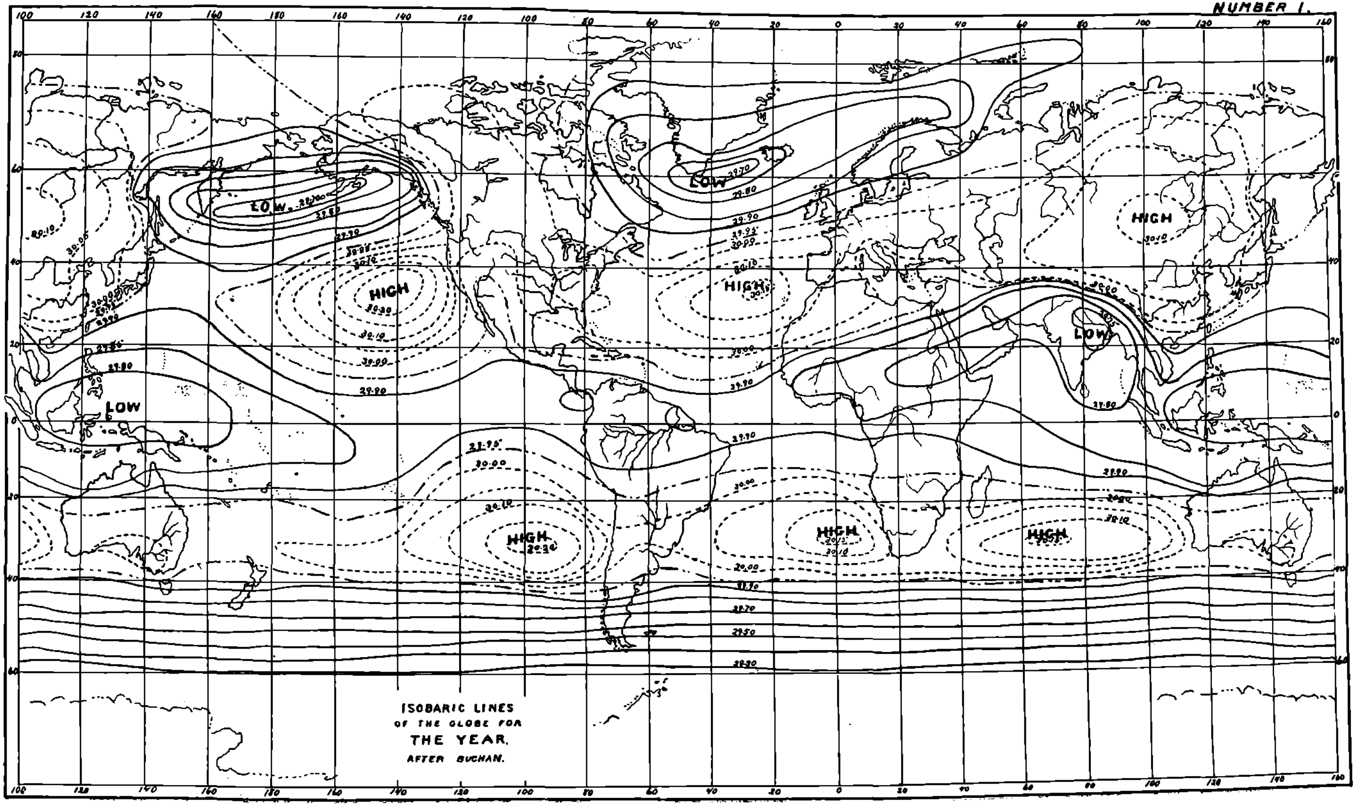
[1] Challenger Reports. Physics and Chemistry, Vol. II, Atmospheric Circulation. Maps 51 and 52. These include the main data gathered by the International Circumpolar Stations.

[2] Berghaus Physical Atlas.

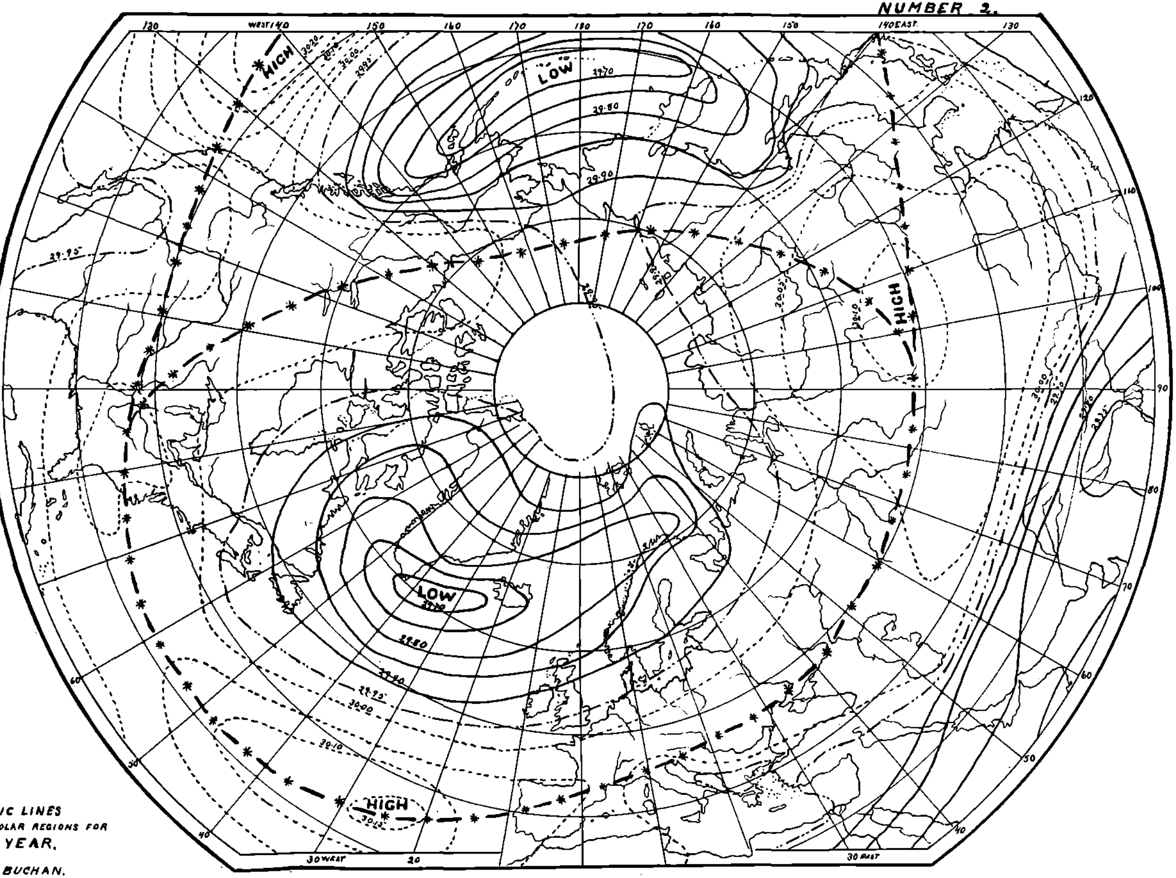
the general features of atmospheric pressure and circulation. An inspection of Buchan's isobaric maps shows that there are, north of 45° north latitude, two nearly permanent areas of *low* barometer and one of *high* barometer. (See accompanying sketch maps 1 and 2, based mainly on Buchan's.) The area of high barometer is located in Asia on the meridian of 100° east longitude. It may perhaps be regarded as one of the normal high areas that theoretically belong to the parallel of 30° north latitude, but which has been displaced 20° to the northward by the topographic conditions of the great Eurasian continent. Its two chief companions under this view lie, the one in the east Atlantic centering near the Azores, about 30° north latitude and 25° west longitude, the other in the east Pacific, off the coast of California, in about 35° north latitude and 140° west longitude. But the Asiatic area of high pressure seems to combine in itself also the function of a polar center, for no other center, high or low, lies between it and the pole. Moreover, it is above mid-latitude, and is nearer the parallels of the two permanent areas of low pressure of the arctic region than to those of its 30° correlatives, for it lies itself in 50° north latitude, while the arctic "lows" lie in 55° and 60° north latitude respectively.

Furthermore, as shown on Buchan's map 52, these high-latitude centers are arranged about the pole at nearly equal distances from each other, the Asiatic "high" being in about 100° east longitude, the north Atlantic "low" in about 35° west longitude, and the north Pacific "low" in about 170° west longitude, *i. e.*, their successive distances from each other are 135°, 145°, and 140°. While these centers shift somewhat during the seasons, they are essentially fixed, the above statements being based on the isobaric averages for the year. These centers are therefore to be distinguished from the familiar moving cyclonic centers and are to be regarded as enduring factors which express the essentially permanent circulatory features of the circumpolar atmosphere. The Asiatic "high" is a permanent anti-cylonic area characterized by descending outward-flowing currents, attended by low precipitation and clear air. The north Atlantic

NUMBER I.


ISOBARIC LINES
OF THE GLOBE FOR
THE YEAR.
AFTER BUCHAN.
LOW
HIGH
LOW
HIGH
HIGH
LOW
LOW
HIGH
HIGH
HIGH
29.80
29.90
29.95
30.00
30.10
30.20
29.70
29.50
29.30

NUMBER 2.



ISOBARIC LINES
OF THE NORTH POLAR REGIONS FOR
THE YEAR.
AFTER BUCHAN.

and north Pacific "lows" are permanent cyclonic areas with inflowing ascending currents attended by high precipitation and prevalent fogs.

Of the two "lows" that of the north Atlantic is the broader and more northerly, and appears to be the more influential factor now, as presumably it was in Pleistocene times. The north Atlantic "low," according to both Buchan and Hann, centers near the apex of Greenland; the north Pacific "low" centers on the Aleutian islands.

It is not difficult now to understand the peculiar behavior of the ice-drift of the polar seas. The Asiatic "high" with its outflowing currents pushes the ice off the Asiatic coast, while the currents inflowing toward the two "lows" impel it toward a point between the two. The Asiatic "high," however, develops more to the northeast of its center than to the northwest, and the North American area of moderately high barometer extends a tongue to the northwest between the two "lows," so that the two high areas approach each other north of the north Pacific "low" and reduce its influence upon the high latitude currents. These are therefore directed disproportionately toward the north Atlantic "low," and give to it a dominating influence. Buchan's maps of wind-directions for the winter months (when local influences are reduced to the minimum) show that the prevailing wind currents flow concentrically about the north Atlantic center from the Lena on the east to the MacKenzie on the west, a stretch of 220° longitude.

Correlation of circumpolar currents.—But in considering the circumpolar circulation as a whole, it is necessary to combine all the movements about all these centers to find the true dynamic center or the constructive pole of the winds. While such a combination cannot be accurately made from present data, it is obvious that it must place this constructive pole somewhere to the northward and westward of the north Atlantic "low" and nearer to it than to either of the other centers. The point toward which the ice-drift converges satisfies these conditions, and may be taken as nature's own practical correlation. Possibly the magnetic pole may prove to be another expression of the same correlation, made indirectly through the agency of electric and magnetic dynamics springing from atmospheric circulation.

One-sided location of "lows."—As already noted, the two areas of permanent low barometric pressure are located on the American side of the globe and have their centers, according to Hann and Buchan, less than 140° Long. ($\frac{7}{18}$ of the total 360°) apart. They are notably elongated in a general east-westerly direction, the north Atlantic area being especially extended easterly and northeasterly, and somewhat curved and reniform. If the isobaric line of 29.95 inches, which represents the average pressure for the globe, be taken as defining the low areas, their borders are only about 40° Long. apart on the American side, while they are 115° Long. apart on the Asiatic side in about the same latitude. In other words, the distance between the borders of the low areas on the American side is about one third of the distance on the Asiatic side. The distance between the borders of the "lows" is only about one half their own longitudinal diameters. The tract between the borders of the "lows" on the American side being thus relatively narrow, it might naturally be anticipated that the currents within it would be much influenced by those of the adjacent depressions, and this seems to be in a large measure realized, for the winds on the northern American plains east of the Rocky Mountains flow in the main concentric to the north Atlantic depression. On Buchan's map 52, which has a polar projection, the isobaric line of 30 inches describes nearly a circle about a point not far from the center of Greenland's ice-field. (See sketch map 2.) In a rude way the prevailing winds within this circle and for some short distance without it whirl about the Greenland center with inward tendency. The influence of the north Pacific depression does not appear to be appreciably felt east of the mountains.

Relation of moving cyclones.—It is interesting to note in this connection that many of the moving cyclones that traverse the mid-latitudes of our continent seem to take their origin in the tract between these two permanent cyclonic areas, or in the region immediately to the south of it, and that possibly they are but secondary eddies generated by the action of the great fixed ones. As before noted, the migrant eddies swing concentrically about the north Atlantic depression.

Location of present glaciation.— Coming closer home to the glacial problem, it is important to note that the two great areas of present arctic glaciation are intimately related to these two permanent cyclonic areas. The Alaskan and Greenland ice-fields not only lie within these areas of barometric depression, but are peculiarly related to them. It is, at first thought, not a little singular that, while the Alaskan ice-fields lie on the *northeast* border of the Pacific "low," the ice-fields of Greenland lie in the *northwest* quarter of the north Atlantic "low;" that is, the chief glaciations lie *between* the centers of the two permanent cyclonic areas. The apparent anomaly of maximum ice accumulation in the northwest quarter of the Greenland "low" probably finds its explanation in the following considerations:

1. The maximum precipitation (which is normally found in the southeast quarter of a "low") and the maximum ice accumulation should not theoretically be coincident; for the ice accumulation is not a true measure of the precipitation, but merely a measure of that *part* of precipitation which is frozen when it falls and survives melting and evaporation. Now in the north and west quarters a larger percentage of the precipitation is snow than in the south and east quarters, where the sum total of precipitation is greater. Moreover, the melting in the north and west quarters is obviously less than in the opposite quarters. The annual isotherms for the southeast quarter range from 35° up to 50° F., while those of the northwest quarter range from 35° down to 0° F. The ice-fields of Greenland and the lands west of it lie in the tract whose annual average is below 32° F. Iceland, whose precipitation is greater, but whose glaciation is less, lies between isothermals 35° to 40° F.

2. The configuration of the water area which wraps about Greenland gives special snow-precipitating efficiency to the winds that swing about the depression on its north side and

cross Greenland from the east and northeast. *The nature of the circulation is such that Greenland is really on the leeward side of the north Atlantic.* This is shown by the following tables of prevailing winds. The first is from the prolonged observations recorded at Godthaab and Upernivik, by Dr. Rink; the second, from those taken under the direction of General Greeley at Fort Conger in the years 1882 and 1883:

PERCENTAGES OF TIME DURING WHICH GREENLAND WINDS BLOW FROM THE DIRECTIONS NAMED

	At Upernivik Lat. 72° 47′. Long. 55° 35′				At Godthaab Lat. 64° 11′. Long. 51° 43′			
Direction	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn
N.	25.5	33.9	31.9	28.8	33.1	37.4	30.3	25.5
E.	34.3	23.1	16.2	36.5	38.4	24.8	8.6	33.6
S.	15.5	20.3	28.0	18.1	16.1	21.7	32.9	22.9
W.	1.8	2.5	6.4	4.4	4.9	5.7	15.1	6.2
Calms	22.9	20.2	17.5	12.2	7.5	10.4	13.1	11.8
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

FREQUENCY AND VELOCITY OF WINDS AT FORT CONGER,
LAT. 80° 44′ N., LONG. 64° 45′ W.

Direction	1881-2		1882-3	
	Times	Miles	Times	Miles
N.	393½	1522	420	2401
N. E.	761	3061	1022	4613
E.	1151½	4843	1369	4061
S. E.	678½	3605½	862	3650
S.	683½	3864½	775	4214
S. W.	678	2011	900	3059
W.	371	949	343	997
N. W.	296	731	387	1142
Calm	3408	1282	2682	50

The winds of the summer months are much influenced by local features, especially by the sea, the naked earth and the ice fields, respectively, while in the cold months a nearly uniform mantle of snow or ice covers the whole surface in common, and removes essentially all sources of variation except those of relief. Including the data of the summer months, the preponderant direction is shown by the above tables to be easterly. Omitting them, it becomes northeasterly. But in either case the dominant winds come from the north Atlantic, and justify the statement that Greenland is on the leeward side of the high north Atlantic and the adjacent part of the Arctic Ocean.

In the eastern part of the Arctic Archipelago as far south as Hudson Straits the winds are very variable, a fact quite consistent with their physiographic surroundings, and with their location well toward the interior of the north Atlantic depression.[1]

The paths of the moving cyclones.— Besides the general fact that the prevailing atmospheric currents from the Mackenzie to the Lena form a great eddy, with maximum conditions of glaciation on the north and west of its chief center near the apex of Greenland, it is to be noted that the paths of the moving "lows" are greatly influenced by the permanent depression at the center of the eddy. This is graphically shown for the north Atlantic portion of the region by Hann's map No. 36[2] herewith reproduced (sketch map 3), in which it is shown that nearly all the moving "lows" curve to the northward in courses more or less rudely spiral or concentric to the permanent "low." The larger number of paths run spirally in toward the permanent center, which suggests the conception that the great fixed cyclone is in some sense an aggregate of numerous small in-running migrant cyclones. If data were sufficient to permit the following of the complete courses of all the migrant cyclones from their origin to their extinction, a dominant system of great interest would probably be shown. As already remarked, a considerable number of these migrant cyclones originate in the American northwest.[3] These show a notable habit of sweeping southeasterly

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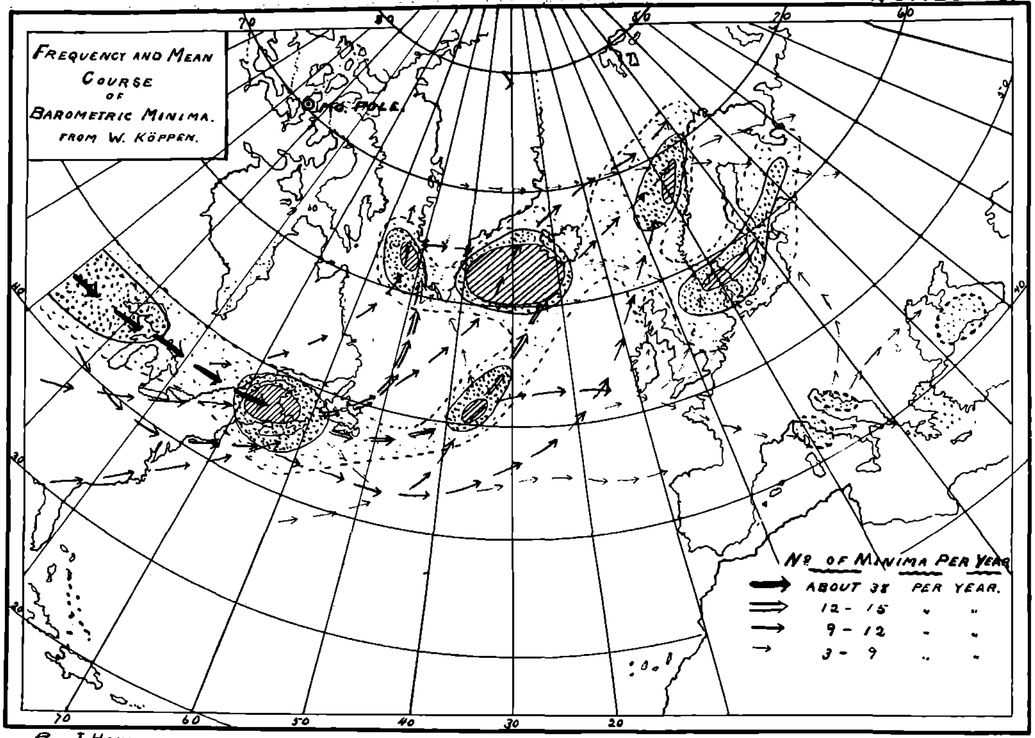
[1] I am greatly indebted to the Hon. Willis L. Moore, Chief of the United States Weather Bureau, and to Professor R. F. Stupart, of the Canadian Meteorological Service for transcripts of data relative to various high latitude stations not otherwise at my command.

[2] Berghaus' Physical Atlas.

[3] "The North American continent is the region where cyclones form in large numbers, and Europe and Asia the region where they dissipate." F. H. BIGELOW: Am. Jour. Sci., Vol. VIII, December 1, 1889, p. 443.

NUMBER 3.



FREQUENCY AND MEAN COURSE OF BAROMETRIC MINIMA. FROM W. KÖPPEN.

BY J. HANN.

into the Mississippi Valley, where they curve about and follow the courses shown on Hann's chart. These courses seem to fall into two classes, the one running spirally inward toward the center of the great fixed eddy, the other spirally outward with dispersive tendencies. A suggestion relative to the possible reason for this last feature will be given in another connection.

A more general view.—While all generalizations now entertained must be held very tentatively, because of the imperfection of present data, a general conception of the circulation of the northern part of the northern hemisphere, which will serve to bring together and give coherence and unity to the more special features which have been discussed, may be pardoned.

The whole temperate and polar region is divisible into areas of high pressure (annual average above 29.95 inches, 760 mm) in which the dominant currents are downward and outward, and areas of low pressure (annual average below 29.95 inches, 760 mm) in which the dominant currents are inward and upward. The mutual disposal of these gives a basis for a general view of the atmospheric circulation.

The high pressure loop.—In tracing the former we may start, for convenience, on the 30° latitude tract at its Atlantic node near the Azores, where it lies between 30° and 40° north latitude. Tracing it thence easterly, it inclines notably to the north, and at the meridian of 100° east, has made a northerly gain of 20° latitude. Thence onward it continues to gain in latitude, at first more rapidly and then less rapidly to about the meridian of 180°, when its course is nearly normal to the meridian, and its latitude may be roughly taken as 75°. Thence onward its course is south of east to the Mackenzie basin, and thence more southerly over the Canadian plains east of the Rocky Mountains until it again joins the high tract that normally lies near 30° latitude. It thus makes a great loop swinging around the pole, and passing near it at its climax in latitude, and enclosing the great north Atlantic eddy (see sketch map 2). The tract is accentuated by nodes of an anticyclonic nature. The chief of these is the great "high" of Asia. This protrudes to the southeast, and is constructively connected in that direction with the 30° belt, which develops a strong anticyclonic node near the California coast, beyond which it connects with the main tract which crosses the United States and the Atlantic near its normal position. Between this connection across the Pacific and the main loop before traced lies the Aleutian depression.

The high tracts of the northern hemisphere therefore form (1) a great loop embracing the great north Atlantic depression and, (2) incidentally, as it were, a minor loop embracing the north Pacific depression. The great loop is not conceived as a current, much less a whirl, but as a tract along which the upper atmosphere habitually descends with outflowing tendencies. The enclosed area of low pressure is a tract over which the lower atmosphere habitually ascends with inflowing tendencies.

Now the main loop and the main enclosed eddy lie on one side of the northern hemisphere and embrace the chief area of Pleistocene glaciation. This main loop and its enclosed eddy embrace about three fourths of the hemisphere north of 30° N. Lat. In the area left vacant, so to speak, the secondary Aleutian eddy is developed and covers the main area of the Cordilleran Pleistocene glaciation.

There can be no question that this peculiar configuration is due to physiographic influences, particularly the oblique attitude and peculiar oceanic circulation of the Atlantic, and the similar obliquity of the main body of the eastern continent. To realize the full force of this obliquity one should trace on a globe the great axis of the eastern continent from Cape Verde on the protruding portion of Africa to Cape East at the extremity of Asia, an immense spiral, and then, starting from the coast of South America near the lesser Antilles, trace the axis of the North Atlantic to the heart of the Polar sea in a similar great spiral, essentially parallel to the former. With these primary influences many secondary ones are joined, some acting concordantly to intensify the obliquity of the circulation, and others acting discordantly and tending to destroy its symmetry, and modify its configuration.

This discussion of the present circulation, too protracted for this place, yet too brief for its purpose, has seemed necessary to make clear the conception entertained respecting the agencies of localization. It has previously been urged in this paper that a reduction of the carbonic acid in the atmosphere and the consequent reduction of its heat-absorbing capacity must intensify the influence of all surface features. In the discussion of existing glaciation I have endeavored to connect the present great ice-fields genetically with the two great areas of low pressure, and to associate them with an oblique disposal of the great circulatory features. The chief centers of present glaciation lie on the borders of the American continent. The chief Pleistocene glaciations, were concentrically arranged about these centers. As has been pointed out by other students of Pleistocene glaciation, the great northeasterly ice-sheet had its western, southern and southeastern limits almost coterminous with the predominant paths of northern migrant cyclones. To complete the hypothesis of localization it is therefore only necessary to assume an intensification of the present oblique system of circulation, with a further shifting of the centers of depression in the direction of the present displacement, accompanied by a sufficient depression of temperature. And these are the effects assigned to a reduction of the atmosphere's thermal capacity due to loss of carbonic acid.

Suggestion relative to migrant cyclones.—One further feature deserves notice. If the constructive pole of the winds lies somewhere between the earth's pole and the American continent, the frictional action of the earth will affect the two sides of the eddy in opposite senses. On the western side (from the American point of view) the friction will tend to drag the bottom air toward the cyclonic center and crowd the isobars upon each other. As the lines of the wind circulation and the earth rotation cross each other obliquely, a predisposition to form gyratory or cyclonic eddies may be inferred, and this may be one of the sources of migrant cyclones which may be regarded as small eddies in the grander cyclonic movements.

On the eastern side of the pole of the winds, the earth movement tends to drag the bottom air away from the center and this is perhaps one of the reasons why the moving cyclones on that side show a tendency to dispersal, both in course and in force, as previously noted.

Possible relation to terrestrial magnetism.— It is scarcely appropriate to this paper, if it were in my power, to discuss the relations of this oblique system of atmospheric circulation to the oblique system of terrestrial magnetism. Crudely stated, the notion entertained is that an atmosphere charged with electricity, circulating obliquely about a rotating earth which is inset with magnetic and magnetizable matter, might give rise to a magnetic system which should express the dynamic resultant of the atmospheric circulation. A comparison of the magnetic and atmospheric charts shows so many points of resemblance, some of which are striking *peculiarities*, as perhaps to justify this tentative notion until the mystery of the earth's magnetism be solved. Connected with terrestrial magnetism are auroral manifestations whose distribution is notably similar to that of the chief Pleistocene glaciation, as was remarked many years ago when first the progress of exploration outlined the extent of the glacial deposits. It can hardly be presumed that either terrestrial magnetism or auroral displays have in themselves any causal connection with glaciation, but if they are dependencies of atmospheric circulation they become eminently serviceable to glacial students by affording a tangible concrete expression of the dynamic correlation of the atmospheric circulation, free from the intricate complexities of the latter; in short, a natural resultant at easy command. The verity of the notion must, of course, depend wholly on the outcome of magnetic investigations on their own lines, which happily are now being vigorously prosecuted.

SUGGESTIONS RELATIVE TO MINOR GLACIAL OSCILLATIONS

It has already been noted that besides the oscillations of epochal order there were subsidiary ones which left their record in a series of concentric moraines which corrugate the individual sheets of glacial débris. The latest drift sheets show this best. That designated Wisconsin is accentuated by nearly a score of peripheral ridges. In a recent admirable paper by Keilhack[1] it is shown that similar lines of halt, and perhaps of minor advance, mark the corresponding European glacial sheet as deployed on the plains of north Germany; indeed, even in some of the greater details, a striking correspondence is traceable between the two series, whose general identity in age and kind were long since noted by Salisbury.[2] These minor oscillatory phenomena seem, therefore, sufficiently general and sufficiently important to require an explanation, and this explanation is not necessarily connected with the fundamental cause of glaciation. The preceding discussion carries in itself a suggestion which is worthy of note in passing. If the localization of the great ice-sheets was dependent on the general circulation of the atmosphere, any periodic shifting of the circulation of moderate magnitude might be competent to cause a shifting of the ice-sheets of corresponding nature. There are historical facts that give some color to the notion that such shiftings have taken place within the period of human records. The oscillations of existing glaciers point in a similar direction. There is clearly a secular shifting of terrestrial magnetism, but the nature of its cycle is yet undetermined. Current opinion gives it a periodicity which would quite well satisfy the demands of the concentric moraines.

GLACIATION NEAR THE CLOSE OF THE PALEOZOIC ERA

While the occurrence of extensive glaciation in India, Australia and South Africa near the close of the Paleozoic era may be regarded as fully established, a specific discussion of its origin along the lines of an atmospheric hypothesis presents formidable difficulties, because the exact date of the glaciation, its

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[1] Die Stillstandslagen des letzten Inlandeises und die hydrographische Entwickelung des pommerschen Küstengebietes. Separatabdruck aus dem Jahrbuch der königl. preuss. geologischen Landesanstalt für 1898. Berlin.

[2] Terminal Moraines in North Germany. Am. Jour. Sci., Vol. XXXV, p. 401. Series 3.

immediate antecedents and the nature of contemporaneous conditions in other parts of the world are not yet satisfactorily determined. No embarrassment attends a merely general application of the atmospheric hypothesis set forth in this paper, and perhaps it would be wise in the present state of knowledge to be content with such general application. But the main purpose of the paper — to develop a *working* hypothesis, helpful in the promotion of investigation — would be measurably defeated thereby, for a general theory merely supposed to be applicable in some indefinite way, not even specifically thought out, much less shaped to promote definite inquiry, falls short of working qualities. Were the Paleozoic glaciation a high-latitude phenomenon which could be referred to the same category as the Pleistocene glaciation, we might well leave specific discussion until further data were afforded, for few additional doubts as to the verity of the hypothesis and probably few new lines of inquiry would be raised. But the Paleozoic glaciation presents characters so extraordinary as to render it the supreme problem of glaciation. In it every hypothesis finds its severest test. No hypothesis that does not, in some remote way at least, approach an elucidation of this supreme case can have serious claims to acceptance as a working theory. It is, therefore, imperative to frankly and fully recognize this crucial problem and deal with its difficulties as well as existing data permit. A really satisfactory discussion is quite impossible in the present nature of the case. The attendant atmospheric and geographic conditions must be postulated, consciously or unconsciously, but the data for such postulates are imperfect and their interpretation is at best not more than probable. It is hoped, however, that fairly good reasons can be assigned for everything assumed in this paper.

The essential facts that make the Paleozoic glaciation a peculiarly strenuous problem are these:

1. It occurred in an early stage of the earth's history. No appeal can, therefore, be made to an advanced state of secular cooling leading on the "final winter" nor to any senile condition

inherent in an aged earth. If the traditional view that the primitive atmosphere constituted a vast store that has been gradually drawn upon throughout the ages in the formation of the coals and carbonates, and was their chief source, the atmosphere at the close of the Paleozoic era must still have been rich, deep and dense to a degree far surpassing the present atmospheric state, for vast deposits of coal and carbonates have since been made through its agency. One of the most conservative as well as most competent estimates of the consumption of carbonic acid since the Paleozoic era places it at 5000 times the present content. To be conservative, let this be halved and halved again, and still the content of carbonic acid is 1250 times that of the present. This atmosphere was so different from that of the Pleistocene and present period as to render uncertain, if not inapplicable, all arguments founded upon the phenomena of the latter. The question of the constitution of the Paleozoic atmosphere is, therefore, fundamental, because it affects the substratum of all arguments based on present or recent experience. Even with the above excessively reduced estimate, do we reach an atmospheric environment in which any known agency applicable to the case can be reasonably postulated as competent to cause general glaciation? In such an atmosphere, or in any atmosphere greatly richer than the present in heat-absorbing and heat-retaining qualities, are there any sufficient grounds for seriously supposing that any of the putative causes of Pleistocene glaciation, whether topographic, geographic, latitudinal or astronomical, could produce such a glaciation as is recorded under the tropics of the far Orient. It is not a part of the purpose or the method of this paper to antagonize other hypotheses, but rather to invite their development into working coöperation and competition with that herewith advanced; but a wholesome interaction of hypotheses will be best attained by eliminating wholly untenable grounds and by bringing all hypotheses within the limital conditions of competency. It is, therefore, no transgression of my purpose to urge the question whether all hypotheses are not required, for their own conservation, to accept so much of the fundamental postulates of the atmospheric hypothesis as are needful to give an atmosphere compatible with glaciation under such other conditions as prevailed in India, Australia and South Africa in the later Paleozoic.

2. The localization was most extraordinary. The chief areas lay under the tropics — the Indian, under the Tropic of Cancer and the Australian and South African, under the Tropic of Capricorn. The Indian area stretched southward to 17° 20′ N. Lat. and northward to the vicinity of 35°. The Australian area stretched north to 20° 30′ S. Lat. and southward (in Tasmania) to 42°. The extent of the South African area is less well known, but centers about 30° S. Lat. It appears then that on both sides of the equator glaciation reached two or three degrees within the tropics, while in the opposite direction general glaciation has not been traced beyond 42° To the south this signifies little because of the prevalence of the sea. To the north the apparent limitation is very singular and doubtless very significant. It cannot, however, be positively asserted that glaciation did not prevail in the higher latitudes, but no decisive evidence of it has yet been discovered. At the same time it must be recognized that many evidences of remarkable transportation and of unusual bowlder accumulation, and indeed of occasional striation have been reported, and that these have been attributed to glacial agencies by geologists of high standing. It cannot be affirmed at present that these phenomena were precisely contemporaneous with the glacial deposits of the oriental tropics, but they were nearly so.

In the southern portion of Brazil there are deposits strikingly similar to the glacial beds of Africa and Australia, but no striation or distinctive marks of glaciation have yet been authoritatively reported.

The southernmost extent of the lowland Pleistocene glaciation was about 37° N. Lat. The Paleozoic glaciation, therefore, reached 20° farther.

The altitude of the glaciation.—Respecting the altitude at which the Paleozoic glaciation took place, it is to be remarked that in some cases there is so intimate an association with marine deposits as to indicate that the ice reached the sea level and discharged icebergs. The associated marine fossils do not seem susceptible of explanation by mechanical admixture through the action of the ice, because of their condition and their position in the embracing sediments. Oldham[1] reports that certain bowlder-bearing mudstones "contain delicate Fenestellæ and bivalve shells, with the valves still united, showing that they had lived, died, and been tranquilly preserved where they are now found, and proving, as conclusively as the matrix in which they are preserved, that they could never have been exposed to any currents of sufficient force and rapidity to transport the blocks now found lying side by side with them. These included fragments of rock are of all sizes from a few inches to several feet in diameter."

These and other evidences leave little room to doubt that a part of the glaciation at least affected low horizons. On the other hand, most of the glacial beds are so related to their own glaciated floor as to show that they were formed by land ice. This is confirmed by the nature of the striæ, the relations of the transported blocks to their source, and the association of the glacial beds with fresh-water deposits. At present some of the glacial beds are 3000 to 3500 feet above sea level (Tasmania), but in general they are much lower. How much of this altitude is due to subsequent changes I do not know. There is, however, much evidence that the glaciation was not of the alpine type, or at least not simply of the alpine type. It spread over broad areas of moderate slope.

In kind of glaciation and in topographic relations the Paleozoic phenomena seem to have been of the same class as the Pleistocene.

Approximate age.—Professor David and other cautious writers of recent date do not attempt to locate the horizon of this glaciation nearer than Permo-Carboniferous. It is certain that in the Salt Range in northwestern India a Productus fauna overlies the

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[1] R. D. OLDHAM: Rec. Geol. Surv. India, XIX, 1886.

bowlder beds. From this and other paleontological evidence it would seem that the lowest of the glacial deposits at least antedated the disappearance of the Permian faunas from the seas.[1] It is unfortunate that the peculiar nature of the formation, and the not less peculiar nature of the associated flora, make it impossible at present to fix its exact horizon in terms of the European and American standards, so that the contemporaneous conditions in these regions could be determined. However, for the application of the atmospheric hypothesis the foremost question is the relationship of glaciation to the great agencies that affected the constitution of the atmosphere. These agencies were (1) the formation of coal, and (2) chemical reaction between the air and the earth's surface.

1. Relative to the first, it is certain that the glaciation closely followed the great coal-depositing period, and indeed fell in with the latest stages. In Australia there are considerable deposits of coal (the Gretna Coal Measures, embracing twenty to forty feet of coal) deposited "between the erratic-bearing horizon of the lower marine series and the similar horizon of the upper marine series" (David).[2] If, therefore, we look to the deposition of coal as the agency of atmospheric exhaustion, the relationship is nearly ideal.

2. If we look to elevation, and consequent large earth-contact, the relationship does not appear to be what theory would demand. It can scarcely be questioned that at the close of the Paleozoic period there was a very unusual surface movement, affecting great areas of the earth's surface and increasing largely the exposure of the land. The period appears to have been altogether comparable to that at the close of the Tertiary period. If we were seeking the cause of the glaciation assigned to the Triassic, or the occasion of the salt and gypsum deposits

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[1] There is some evidence of another glacial horizon at or about the base of the Triassic (well indicated in White's excellent synopsis, Am. Geol., May 1889, table, p. 315). The present discussion will, however, be confined to the lower horizon, that of the Talchirs and their equivalents.

[2] Quarterly Jour. Geol. Soc., Vol. LII, May 1896, p. 300.

so widely prevalent in the Permian and Triassic formations, this elevatory movement would stand in the proper relations. But, if present evidence is to be trusted, it does not stand in the proper antecedent relations to the Permo-Carboniferous glaciation, at least not as the primary agency. Still, though there is an absence of evidence of large exposure of the land surface to atmospheric degradation for a notable period preceding the Permo-Carboniferous glaciation, there are good grounds for believing that the great era-closing movement of the Paleozoic had made notable advance even at this time.

The Gondwána elevation.—The glacial beds under consideration form the basal members of the remarkable Gondwána series, the chief members of which are land and fresh-water deposits. These in themselves imply a recently rejuvenated topography, for an ancient topography has a perfected drainage system and adjusted gradients. It is the dominant belief of those who have most studied the region circumjacent to the Indian Ocean, that the formation of the Gondwána series and the development and distribution of the remarkable Glossopteris flora, imply extensions and connections of land of a somewhat unusual kind. If this belief were accepted to the full extent urged by its strongest advocates, it would in itself involve a very large exposure. I am not disposed, however, to force the doctrine of a Gondwána continent beyond the most modest limits, however much it might contribute to a favorable reception of the hypothesis under discussion. It appears to me that the distribution of the Glossopteris flora may be in some notable part a climatic rather than a topographic effect; that is to say, the peculiar atmospheric conditions, of which glaciation was the supreme expression, distinguished that quarter of the globe from the rest, and may in themselves have controlled the distribution of the peculiar flora in question. It may therefore only be necessary to postulate such an extension of the land as was required to permit the migration of the flora and its companion fauna.

However this may be, it is very generally agreed that some notable land extension prevailed as early as the origination and distribution of the Glossopteris flora. It will be quite conservative to assume that this involved a land connection between India and Australia, and probably New Zealand, the connection presumably lying along the submerged platform which even to this day stretches southeasterly from Asia to the islands in question with slight interruptions. It is not improbable that between India and South Africa at least a partial bridge was formed by the elevation of the submerged plateau on which Madagascar and the Seychelles rest, together with the tract now accentuated by the Maldive islands.

A connection with South America (where the Glossopteris flora also appeared — southern Brazil and Argentina) involving the least radical departure from modern configuration, may have been made via New Zealand and the Antarctic continent. This, I believe, also best satisfies the general tenor of paleontological evidence.

If the geographic changes were confined to such connections and extensions of land as these, and to such moderate elevations as the nature of the glacial beds and the associated deposits seem to imply, and to such changes in the northern hemisphere as can fairly be assigned to the Permo-Carboniferous period, there does not seem to be adequate ground for attributing a very exceptional depletion of the atmosphere to land-contact alone, or chiefly, though it may have made some notable contribution in that direction.

Effects of atmospheric depletion by coal deposition.—We therefore turn to coal-formation as the effective alternative. There are no reliable estimates of the total carbon in the coal and carbonaceous deposits of the Carboniferous period, but such approximations as have been made seem to show that it equals several times the present atmospheric content, and that its extraction superadded to the increasing formation of carbonates resulting from the rising land would have been competent to reduce to the point of glaciation an atmosphere three or four times as rich in carbon dioxide as the present; in other words, such an atmosphere as the sub-Carboniferous climate seems to imply.

A question of no small interest is the special kind of effect which an atmosphere reduced by coal formation would induce as distinguished from that induced by depletion through earth-contact. In the latter, as already set forth, bicarbonates were the chief product, and carbon dioxide, temporarily locked up, played a very important part. Through the peculiar agency of the ocean this "loose" carbon dioxide hastened the development of glaciation, prepared the conditions for strong reaction and accelerated the reaction when inaugurated. In the formation of coal and like products no such effective temporary factor is produced. The carbon is, to be sure, temporarily held in the vegetation, but so much as decays goes directly back into the atmosphere, in the main, and the rest becomes permanently fixed. Neither part goes into an intermediate state of reserve, subject to being called forth by change of conditions as in the case of the second equivalent of the bicarbonates of the ocean. The action is somewhat analagous to the original carbonation of the silicates of the crystalline rocks in which the first equivalent of carbon dioxide when once united remains fixed (barring accidents to which coal is also liable), but in this case there is also a second equivalent of carbon dioxide temporarily locked up so long as a state of solution is maintained. Succinctly stated, without the unessential qualifications: (1) Depletion by coal formation is accompanied by no intensifying and reactive factor; (2) Depletion by conversion of silicates into carbonates is accompanied by an intensifying and reactive factor; (3) Depletion by the solution of limestone is wholly temporary in nature and specially capable of promoting intensification and reaction.

If, therefore, the impoverishment of the atmosphere as the prerequisite of glaciation in Permo-Carboniferous times was due, in the main, to the extraction of carbon in the form of coal and like deposits, there was absent, to that extent, the factor to which the hastening of glaciation and of reaction is assigned. Before glaciation could be affected in the measurable absence of this accelerating agent, it was necessary for the permanent depletion to go to greater lengths. Moreover the depletion when once affected was essentially a non-reactive one. Of course the reactive factor was never really absent, for the formation and solution of carbonates was always in progress. In this case it is merely supposed to be the minor rather than the major factor. It is inferred, therefore, that a higher stage of permanent depletion of the atmosphere was reached before glaciation ensued through coal formation than would have been the case had the glaciation been produced by the formation of carbonates. To this, in a measure at least, is attributed the conditions which made it possible for the glaciation to affect lower latitudes in Permo-Carboniferous times than they did in Pleistocene times. As before noted, the Permo-Carboniferous glaciation extended 20° nearer to the equator than the Pleistocene.

The localization of the Permo-Carboniferous glaciation.—It remains to consider the remarkable localization of this ancient glaciation. The general principles involved are assumed to have been the same as those already applied to the Pleistocene problem, but the geographic factors were quite different, and it is here that the lack of complete data is most keenly felt. In Pleistocene times, as also at present, certain great geographical features are thought to have given a pronouncedly oblique circulation to the air currents of the northern hemisphere. In the southern hemisphere at present a much greater approach to symmetrical circulation prevails because great oblique features are absent. It is postulated that the configuration of Permo-Carboniferous lands and oceans was such as to seriously disturb the symmetry of the atmospheric and oceanic circulation of that hemisphere, and to give it peculiar form and special intensity.

The geographic features of the Permo-Carboniferous period.—The assigned changes introduced by the development of Gondwána land have been mentioned. These are thought to have prolonged the Asiatic continent southeasterly to Australia, and probably to New Zealand, and perhaps to the Antarctic land. This prolongation, taken with its backward projection across Asia and Europe, constituted an oblique feature of great extension. It also interposed a barrier which very notably modified the water connections of the Pacific and Indian oceans. The warm equatorial currents which now flow through the numerous straits of the East Indies and add warmth to the Indian Ocean were turned back, and their heat retained in the Pacific. At the same time the cold currents of the southern Indian and the adjacent Antarctic oceans were shut out measurably or wholly from the Pacific, and turned northward into the equatorial portion of the Indian Ocean. There was thus a concentration of heat in the one and of cold in the other. If the suggested connection of New Zealand with the Antarctic continent was made, these cold southern waters would have been effectively shut out from the Pacific and forced to circulate through the Indian Ocean. If the other conservative changes suggested to meet the demands of the Gondwána phenomena were realities, the Indian Ocean took the form of a great triangle with a very broad base in the antarctic regions, and a narrowed apex reaching across the equator to the vicinity of the Indian glaciation.

In the north Atlantic region there is evidence that the great readjustment which closed the Paleozoic era had made notable advances at the probable time of the Oriental glaciation The New Red Sandstone of western Europe is not unlike the Gondwána series in general characters, and indicates a like rejuvenated land. Within it also are found arkose, conglomerates and breccias, often formed of large, far-transported blocks. "Some of these blocks are three feet in diameter, and show distinct striation. These Permian drift beds, according to Ramsay, cannot be distinguished by any essential character from modern glacial drifts, and he has no doubt that they were ice-borne, and, consequently, that there was a glacial period during the accumulation of the Lower Permian deposits of the center of England."[1] There is good ground to believe that previous to the formation of these deposits the land on the European border of the Atlantic had risen relatively. There are similar evidences on the American side. The close relations between the land faunas and floras on the two continents strongly imply a free

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[1] SIR ARCHIBALD GEIKIE: Text-Book of Geology, p. 753.

land connection. This is most pointedly indicated by the distribution of the amphibians of the Carboniferous and Permian periods. The Branchiosauria, Aistopoda, Microsauria, and Labyrinthodontia vera were all represented on both continents, and unless the doctrine of parallel evolution be pushed to a seeming extreme, the only satisfactory explanation is an ample land connection. The amphibians of today are fatally affected by salt water, and even their eggs lose their vitality after a short submergence in it. It cannot be positively affirmed that this was true of the Carboniferous amphibians, but the presumptions appear to lie in that line. At any rate the occurrence of all the leading branches on both continents renders it quite improbable that a broad ocean intervened. It is therefore assumed that the Atlantic Ocean was restricted at the north by such connection. To be definite, it is assumed that it essentially terminated south of the Greenland-Iceland-Faroe platform, or possibly south of the Telegraphic plateau.

There are few data that give specific indications as to the configuration of the north border of the Pacific at this time, but the considerations that have just been urged with reference to the distribution of the fauna and flora are apparently best satisfied by supposing an emergence of the very slightly submerged continental platform of the arctic region generally. This is in harmony with the history of the preceding Paleozoic periods during which the Eurasian and North American continents were essentially a unit and free migration from one to the other was an oft-repeated, if not predominant, phenomenon. If this be the true inference the Pacific Ocean was limited at the north to about 60° Lat.

In equatorial latitudes it is not improbable that the Atlantic and Pacific oceans were united between the main bodies of the North American and South American continents, so that a commingling of waters took place here not unlike that which now obtains between the Pacific and Indian oceans.

It is not improbable also, judging from the distribution of Permian marine beds, that inland seas extended along the

Mediterranean tract into eastern Europe and perhaps to the Caspian-Ural region of Asia; indeed, it is not altogether improbable that straits or narrow seas may have connected with the apex of the Indian ocean. At least in the later Permian times the marine faunas of India and of Europe were notably similar, and in the early Mesozoic they became so nearly identical as to make a connection along this line extremely probable.

Effect of the supposed geographic changes on atmospheric circulation.—While none of these postulated changes involve great terrestrial movements, or depart widely from the rather definite indications of the phenomena concerned, it will be seen upon a study of the resulting distribution of land and water that they probably profoundly affected the circulation of the atmosphere. The limitation of the Atlantic at the north by the European-American connection rendered it essentially an equatorial and warm temperate ocean. Its present high-latitude connection, involving the transportation of vast quantities of ice and cold water into it from polar regions and the reciprocal loss of heat borne into the high latitudes by the Gulf Stream, was eliminated. The atmospheric function of the Atlantic was, therefore, radically changed. That great oblique factor to which was assigned so large a function in the localization of Pleistocene glaciation, was largely absent from the Permo-Carboniferous circulation. To the similar restriction attributed to the north Pacific a minor limitation of a like kind may be assigned. Instead, therefore, of a polar sea exchanging its thermal properties with an equatorial sea, as at present, there would be substituted a prevailing polar land, relieved probably only by the deep basin of the Arctic sea, whose limited extent and land-locked situation would render it little more significant in general climatology than the present Mediterranean.

On the other hand, very notable oblique features appear in the equatorial and southern regions. The postulated changes of the Pacific Ocean, by shutting off its connections with the Indian Ocean, probably brought into effective influence its long northwesterly and southeasterly trend, now neutralized by its westward connections. In other words, the somewhat balanced distribution of the present Pacific was replaced by an effective obliquity which could scarcely have failed to powerfully influence the general circulation of the Paleozoic atmosphere. The northwest-southeasterly extension of the great Eurasian-Australian land paralleled this and intensified its effects. In other words, the Pacific Ocean and the parallel Eurasian-Australian continent constituted, in Paleozoic times, a couplet of oblique features that were chiefly effective in the equatorial zone and the southern hemisphere. They replaced the similar pair now formed by the north Atlantic and the eastern continent. It is inferred, therefore, that an obliquity of circulation of a pronounced order prevailed in Permo-Carboniferous times, by virtue of which the southern hemisphere was brought under the influence of meteorological agencies analogous to those that in Pleistocene times affected the northern hemisphere.

Some differences, however, are to be noted. The equatorial zone was then profoundly affected by the oblique features which lay directly athwart it. In addition to this there was the peculiar configuration of the Indian Ocean already set forth, namely, a broad, open mouth extended to the Antarctic polar regions, with a convergence to a narrow equatorial apex 20° or more north of the equator. The general course of the circulation in this may be assumed to have been much as it is today; that is, a movement in the polar latitudes, at first northerly and easterly, then curving about to the northward and northwestward as it approached the equatorial zone, and at length returning to the southwest along the African coast, thus forming a free circulation between the high latitudes and the low latitudes, with high latitude influences greatly preponderant. This circulation in Paleozoic times may be reasonably assumed to have been much more intense than at the present time, first, because there were then, by hypothesis, greater intensities of temperature, and second, because a larger percentage of the Antarctic waters were forced to flow into the apex of the Indian Ocean by the configuration of the land. This last statement would hold true even if New Zealand were not connected with the Antarctic continent and South America, for the avenue of escape toward the Pacific would be circumscribed by the minimum elevations which the Gondwána phenomena seem to require. If the Antarctic-South-American connection were made, it would form a barrier to circumpolar circulation, and all the polar ice-drift from South America to New Zealand would doubtless be forced northeasterly into the Indian Ocean. This would certainly lend great intensity to the circulation of the polar currents through the Indian Ocean. The temperature of the latter would therefore be radically affected by the immense quantities of ice and cold water carried through it by this intensified circulation under the atmospheric conditions postulated. A like profound influence upon the overlying atmosphere must necessarily have followed. The narrow apex of the ocean under the tropics would probably have afforded little relief from the dominance of these currents.

If this cold area be contrasted with the heated state which should naturally prevail in the Pacific Ocean, because of its vast breadth under the equator, its limitations at the north and its somewhat narrow communication at the south (particularly if it be shut off from the Antarctic flow past New Zealand) should give rise to antithetical conditions of temperature and pressure sufficient to radically influence the general circulation of the southern hemisphere. It is conceived that this extraordinary couplet might even introduce a systematic exchange of atmospheres between the northern and the southern hemispheres, consisting essentially of a cold north-seeking current flowing across the Indian Ocean into the northern hemisphere, correlated with a warm return current flowing from the northern to the southern hemisphere across the tropical regions of the Pacific, but this conception is not regarded as a vital part of the hypothesis.

The configuration of the Atlantic is supposed to have caused it to play a subordinate part, the northern portion becoming an auxiliary of the Pacific and the southern portion more or less largely an auxiliary of the Indian Ocean. If we assume that the Gondwána extension connected New Zealand with the Antarctic lands and South America, the ocean currents may be pictured as sweeping eastward from South America along the icy borders of the Antarctic continent into the great bay south of Australia, out of which they recurved and flowed northward across the equator to the Indian peninsula, which they freely bathed, and, returning along the supposed Gondwána connection, wrapped about South Africa and then flowed northward toward the equatorial regions, a portion then curving backwards and descending the coast of South America to complete the circuit. Such a circulation would throw perhaps two thirds of the antarctic influence into the Indian Ocean. On the other hand, seven eighths or more of the equatorial influence would probably be brought to bear upon the Atlantic and Pacific oceans. As a result these oceans, notwithstanding the impoverished condition of the atmosphere, received and retained a large percentage of the sun's heat.

Referring to the principles stated earlier in this discussion, it may be remembered that it was noted that a diathermous atmosphere permits a larger part of the sun's heat to reach the surface of the earth than a thermally opaque atmosphere, and that the portion which falls upon the ocean for the most part penetrates it until it is absorbed. A certain part, to be sure, is reflected, but in the zone of nearly vertical rays this is reduced to the minimum. As the result of the ocean's ability to absorb and retain heat, the diathermacy of the atmosphere is of less consequence in equatorial oceanic regions than in land tracts and hence the great equatorial oceans may have remained measurably warm throughout the glacial period.

It is conceived, therefore, that under these conditions, glaciation may have been produced in exceptionally low latitudes, and that its distribution was closely associated with the Indian Ocean. At the same time it is conceived that the lands immediately adjacent to the Atlantic and Pacific oceans, especially in low latitudes, were so far affected by the favorable thermal condition of those great bodies as to enjoy relatively mild temperatures, at least temperatures sufficiently genial to save them and the adjacent lands from the exterminating effects that might naturally be associated with a glaciation in the tropics.

Relative to the more specific location of the Permo-Carboniferous glaciation, it may be noted that a tendency to form "lows' in India, Australia, and South Africa, not far from the ancient glaciated areas, is observable even under the present conditions. It is presumed that much more pronounced eddies were, in Permo-Carboniferous times, located on the borders of the cold belt formed by the intensified antarctic circulation and that these determined the areas of specific glaciation.

Conditions in the northern hemisphere.—In the arctic regions, a very low temperature may be confidently postulated under the supposed conditions, because of the extent of the land and the absence of oceanic circulation between the high north and the equatorial regions. A Siberian climate of an intensified order is therefore assumed to have prevailed over the high latitudes of the northern hemisphere. This may doubtless have given rise to limited accumulations of snow in favored localities, developing into glaciers, but on account of the general low precipitation and the dryness of the atmosphere, giving rise to large evaporation, this may not have become a pronounced fact. In so far as glacial deposits originated in the interior of the land they would be liable to destruction by surface denudation before submergence. The Permo-Triassic land period was long. Here and there, as already noted, there are phenomena which find their easiest explanation in glaciation and ice transportation. It is to be anticipated that, if this view be correct, further indications of severe temperature in northern latitudes will be developed in the course of future studies. It may be remarked that there is now nearly as much evidence of Permian glaciation in the northern hemisphere in regions away from mountains as there is of Pleistocene glaciation in the southern hemisphere in like situations.

As remarked at the outset of this part of the paper, a really satisfactory discussion of the Permo-Carboniferous glaciation is impossible in the present state of knowledge. I am by no means blind to the uncertain factors that inhere, at once, in the time relations, in the geographic features, and in the meteorological inferences drawn from them. The most that could be hoped from an attempt to explain so extraordinary phenomena in so imperfect a condition of the data is to suggest the general direction in which, perchance, the truth may ultimately be found to lie.

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