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ORDINARY MEETING.*

THE PRESIDENT, SIR G. G. STOKES, BART., IN THE CHAIR.

The PRESIDENT.—The author of this paper being resident in the United States, it will be read in his absence. Professor E. Hull, LL.D., F.R.S., has kindly undertaken to do so.

The following paper was then read :—

CAUSES OF THE ICE AGE. By WARREN UPHAM, of the New Hampshire, Minnesota, and United States Geological Surveys.

IT is universally recognized that the century now nearing its end has been one of most rapid intellectual and material progress. Not less grand and beneficent than the inventions of the steamship and locomotive, of photography, the telegraph and the telephone, have been the investigations through the natural sciences revealing the chemical constitution and relationships of matter, the long and varied history of plant and animal life on our globe, and the gradual processes by which God has worked to create, and to bring into their present condition, the stars, the sun, and the earth. Though it was not His purpose in the Bible to reveal and teach science, there is given as the portal of approach to that Book a very brief chronicle of the creation of this place of man's abode, which, if regarded according to Hugh Miller's suggestion, is so completely in accord with the history made known by the rocks to the geologist that Dana, the most eminent of Americans in this science, declares the record of Genesis "profoundly philosophical . . . .

* 14th of 29th Session. The consideration of the subject was concluded and the author's reply received September, 1897.

true and divine . . . . a declaration of authorship, both of Creation and the Bible."*

2 The science of geology has produced a vastly enlarged understanding of the six days, with the work therein done, which in this most ancient record represent the very long eras of the earth's development, succeeded by God's crowning work, man and woman, endowed with the lofty capabilities of the human mind.

3 Ushering in the Human or Psychozoic present era, at the end of the geologic ages of the long past, and upon the threshold of the period known to us by written history, was the marvellous Glacial period or Ice age, with envelopment of large land areas by continental glaciers or ice-sheets. Far the greater part of the earth's surface, however, then as now, had a kindly temperate climate. The succession of the Creator's work in the evolution of plants and animals, and of man, moulded intellectually into a likeness with the Divine Mind, was continued in other regions during this reign of cold, and snow, and ice, in the high latitudes surrounding both the north and south poles.

4 When the ice-sheets occupied their greatest area, at the culmination of the effects of the extraordinary climatic conditions of the Glacial period, the southern border of the ice crossed the northern United States from Nantucket, Martha's Vineyard, Long Island, and northern New Jersey, through Pennsylvania into south-western New York, thence west-south-westerly to southern Illinois and St. Louis, thence westward nearly to the junction of the Republican with the Kansas river, thence northward through eastern Nebraska, and north-north-west through South Dakota, bending from this course about thirty miles west of Bismarck, thence passing westerly through northern Montana, Idaho, and Washington, reaching the Pacific ocean not far south of

* Hugh Miller's suggestion was a series of separate representative visions granted to a *Seer* upon the earth's surface. In obedience to the Creator there came, in the first Mosaic vision, light, and the division of day and night; in the second vision, a world-wide ocean, and the gathering of a dense cloud-bank above a stratum of open air; in the third vision, areas of land, clothed with vegetation; in the fourth, the appearance of sun, moon and stars, when rifts were first made in the previously continuous envelope of clouds; in the fifth, swimming and flying animals; and in the sixth and last vision, lowly and higher land animals.

[In regard to the "suggestion" in the foregoing note, Mr. Upham writes, August 21st, 1897:—"It seems to me desirable thus to state, indirectly, my belief in the harmony of *The Book* with geology."—Ed.]

Vancouver island. It extended beyond the Ohio river only for short distances in the vicinity of Cincinnati; but the Missouri river lies mainly within the glaciated area. On the Mississippi, 300 to 450 miles north of the boundary of the ice-sheet, where it reached farthest south, a large driftless area, including south-western Wisconsin and parts of adjoining states, escaped glaciation. In the Rocky mountains, the Cascade range, and the Sierra Nevada, ice-fields of great extent were accumulated along distances of 700 to 800 miles south from the border of the continental ice-sheet to latitude 37° S.; but no evidences of such local glaciation south of the ice-sheet are found in the Appalachian mountains.

Upon British America the directions of the glacial striæ and transportation of the drift show that there were two areas of glacial outflow, one reaching from Newfoundland and Labrador to the Rocky mountains and the Arctic ocean, having its greatest thickness of ice, probably about two miles, over the Laurentide highlands and James Bay, with outflow thence to the east, south, west, and north; and the other west of the Rocky mountains, covering British Columbia, where the ice-sheet attained a maximum thickness of about one mile, outflowing south into the United States, west into the Pacific ocean, and northward to the upper part of the Yukon basin. The portions of the ice-sheet pouring outward respectively from these two areas have been named by Dr. George M. Dawson the Laurentide and Cordilleran glaciers. Toward the south, west, and north-west, the Cordilleran outflow extended to the boundaries of our glaciated area; but eastward, pouring through passes of the Rocky mountains, and in the Peace river region probably overtopping the highest summits, which there are only about 6,000 feet above the sea, the Cordilleran ice pushed across a narrow belt adjoining the mountains, to a maximum distance of nearly 100 miles, and there (on land about 2,500 feet above the sea) became confluent with the Laurentide ice, the two united currents thence passing in part to the south and in part to the north from the interior tract where the confluent ice was thickest. At the time of maximum extent of the North American ice-sheet, it was continuous from the Atlantic to the Pacific, covering approximately 4,000,000 square miles of this continent.

5 Nearly half as large an area was ice-covered in Europe, with the basins of the Irish, North, Baltic, and White seas, the principal centre of outflow being the plateau and moun-

tains of Scandinavia, whence the ice moved west and north into the Atlantic, southward over northern Germany, and eastward over a large part of Russia. Smaller ice-sheets were formed upon Scotland and Ireland, and these became confluent with each other and with the Scandinavian ice which crossed the present bed of the shallow North Sea to the borders of Great Britain. Glaciers also were far more extensive than now in the Alps, Pyrenees, Caucasus, and Himalayas; but no large portion of Asia is known to have been overspread by ice. A most remarkable feature of the accumulation of the ice-sheets was their absence from Siberia and northern Alaska, while so heavily massed in the same and more southern latitudes of British America, the northern United States, the British Isles, and north-western Europe.

6 In the southern hemisphere, at about the same time with the northern glaciation, but whether alternating or contemporaneous with it we cannot know, a similar but less extensive sheet of land-ice covered Patagonia, and the mountains and highlands of the middle island of New Zealand bore immense glaciers far exceeding their still magnificent remnants of the present day.

7 The Ice age yet lingers upon the Antarctic continent, as also in Greenland, and to less degree in the St. Elias region of Alaska and British America, and in Norway. Land-ice surrounds the south pole to a distance of 12° to 25° from it, covering, according to Sir Wyville Thomson, about 4,500,000 square miles. Its area is thus slightly greater than that of the Pleistocene ice-sheet of North America. Whether the Antarctic ice covered an equal or greater extent in the Pleistocene period, contemporaneous with the glaciation of now temperate regions, we have no means of knowing. Along a portion of its border of perpendicular ice-cliffs, Sir J. C. Ross sailed 450 miles, finding only one point low enough to allow the upper surface of the ice to be viewed from the masthead. There it was a smooth plain of snowy whiteness, extending as far as the eye could see. That this ice-plain has a considerable slope from its central portions toward its boundary is shown by its abundant outflow into the sea, by which its advancing edge is uplifted and broken into multitudes of bergs, many of them tabular, having broad, nearly flat, tops. As described by Moseley in *Notes of a Naturalist on the "Challenger,"* these bergs give strange beauty, sublimity and peril to the Antarctic ocean, upon which they float away northward until they are melted.

Many parts of the borders of the land underlying this ice-sheet are low and almost level, as is known by the flat-topped and horizontally stratified bergs, but some other areas are high and mountainous. Due south of New Zealand the volcanoes Terror and Erebus, between 800 and 900 miles from the pole, rising respectively about 11,000 and 12,000 feet above the sea, suggest that portions or the whole of this circumpolar continent may have been recently raised from the ocean to form a land surface, which, on account of its geographic position has become ice-clad.

8 What were the causes of the accumulation of the ice-sheets of the Glacial period? Upon their areas warm or at least temperate climates had prevailed during long foregoing geologic ages, and again at the present time they have mostly mild and temperate conditions. The Pleistocene continental glaciers of North America, Europe, and Patagonia, have disappeared; and the later and principal part of their melting was very rapid, as is known by various features of the contemporaneous glacial and modified drift deposits and by the beaches and deltas of temporary lakes that were formed by the barrier of the receding ice-sheets. Can the conditions and causes be found which first amassed the thick and vastly extended sheets of land-ice, and whose cessation suddenly permitted the ice to be quickly melted away?

9 Two classes of theories have been presented in answer to these questions. In one class, which we will first consider, are the explanations of the climate of the Ice age through astronomic or cosmic causes, comprising all changes in the earth's astronomic relationship to the heat of space and of the sun. The second class embraces terrestrial or geologic causes, as changes of areas of land and sea, of oceanic currents, and altitudes of continents, while otherwise the earth's relations to external sources of heat are supposed to have been practically as now, or not to have entered as important factors in the problem.

10 It has been suggested that, as the sun and his planets are believed to be moving forward together through space, the Glacial period may mark a portion of the pathway of the solar system where less heat was supplied from the stars than along the earlier and later parts of this pathway. To this suggestion it is sufficient to reply that the researches of Prof. S. P. Langley, now Secretary of the Smithsonian Institution, show that at the present time no appreciable measure of heat comes to us in that way, and that probably

not so much as one degree of the average temperature of the earth's climates was ever, within geologic times, so received from all other sources besides the sun and the earth's own internal heat. Concerning the latter, also, it is well ascertained that during at least the Mesozoic, Tertiary, and Quaternary eras, it has affected the climatic average by no more than a small fraction of a degree.

11 Others have suggested that the sun's heat has varied and that the Ice age was a time of diminished solar radiation. To this we must answer that during the centuries of written history, and especially during the past century of critical investigations in terrestrial and solar physics, no variations of this kind have been discovered. Such a cause of the glacial accumulations would have enveloped Alaska and Siberia with ice-sheets and their drift deposits. The anomalous geographic distribution of the drift forbids this hypothesis.

12 Among all the theories of the causes of the Glacial period, the one which has attracted the most attention, not only of geologists, but also of physicists and astronomers, was thought out by Dr. James Croll, and published in magazine articles, during the years 1864 to 1874, and is most fully stated in his work entitled, *Climate and Time* (1875). His answers to criticisms and more full elucidation of some portions of the theory are given in his later volumes, *Discussions on Climate and Cosmology* (1885), and *Stellar Evolution and its Relations to Geological Time* (1889).* Dr. Croll's theory, which also has been very ably advocated by Prof. James Geikie in *The Great Ice Age* (1874 and 1877), and recently by Sir Robert S. Ball in *The Cause of an Ice Age* (1891), attributes the accumulation of ice-sheets to recurrent astronomic cycles which bring the winters of each polar hemisphere of the earth alternately into aphelion and perihelion each 21,000 years during the periods of maximum eccentricity of the earth's orbit. Its last period of this kind was from about 240,000 to 80,000 years ago, allowing room for seven or eight such cycles and alternations of glacial and interglacial conditions. The supposed evidence of interglacial epochs therefore gave to this theory a wide credence; but the uniqueness of the Glacial period in the long geologic record,

* A full list of Dr. Croll's scientific papers and works is appended to an interesting biographical sketch, with portrait, in *Transactions of the Edinburgh Geological Society*, vol. vi, pp. 171–187, for Feb. 19, 1891.

and the recent determinations of the geologic brevity of the time since the ice-sheets disappeared from North America and Europe, make it clear, in the opinions even of some geologists who believe in a duality or plurality of Quaternary glacial epochs, that not astronomic but geographic causes produced the Ice age. From the meteorologist's standpoint this astronomic explanation of a formerly glacial climate in now temperate latitudes has been alternately defended and denied,* just as geologists have been divided in respect to its applicability to the history of the Glacial period.

13 Many eminent glacialists, as James Geikie, Wahnschaffe, Penck, De Geer, Chamberlin, Salisbury, Shaler, McGee, and others, believe that the Ice age was complex, having two, three, or more epochs of glaciation, divided by long interglacial epochs of mild and temperate climate when the ice-sheets were entirely or mainly melted away. Professor Geikie claims five distinct glacial epochs, as indicated by fossiliferous beds lying between deposits of till or unstratified glacial drift, and by other evidences of great climatic changes. Mr. McGee, in the United States, recognizes at least three glacial epochs. On the other hand, the reference of all the glacial drift to a single epoch of glaciation, with moderate oscillations of retreat and readvance of the ice-border, is thought more probable by Dana, Hitchcock, and Wright in America, Prestwich and Lamplugh in England, Falsan in France, Holst in Sweden, and Nikitin in Russia. To myself, though formerly accepting two glacial epochs with a long warm interval between them, the essential continuity of the Ice age seems now the better provisional hypothesis, to be held with candour for weighing evidence on either side. The arguments supporting this opinion are well stated by Prof. G. Frederick Wright in his works on the *Ice Age in North America* (1889), and *Man and the Glacial Period* (1892), and especially in articles in the *American Journal of Science* for November, 1892, and March, 1894.

14 In accordance with Dr. Croll's astronomic theory, glacial periods would be expected to recur with geologic frequency, whenever the earth's orbit attained a stage of maximum eccentricity, during the very long Tertiary and Mesozoic eras,

* One of the most adverse criticisms is by the Russian meteorologist and geographer, Dr. A. Woeikof, in the *Am. Jour. of Science*, third series, vol. xxxi, pp. 161–178, March, 1886.

which together were probably a hundred times as long as the Quaternary era in which the Ice Age occurred.* But we have no evidence of any Tertiary or Mesozoic period of general glaciation in circumpolar and temperate regions, although high mountain groups or ranges are known to have had local glaciers. Not until we go back to the Permian period, closing the Paleozoic era, are numerous and widely distributed proofs of very ancient glaciation encountered. Boulder-bearing deposits, sometimes closely resembling till and including striated stones, while the underlying rock also occasionally bears glacial grooves and striæ, are found in the Carboniferous or more frequently the Permian series in Britain, France and Germany,† Natal,‡ India,§ and south-eastern Australia.‖ In Natal the striated glacier floor is in latitude 30° south, and in India only 20° north of the equator. During all the earth's history previous to the Ice age, which constitutes its latest completed chapter, no other such distinct evidences of general or interrupted and alternating glaciation have been found; and just then, in close relationship with extensive and repeated oscillations of the land, and with widely distant glacial deposits and striation, we find a most remarkable epoch of mountain-building, surpassing any other time between the close of the Archean era and the Quaternary.

15 Alfred Russel Wallace therefore concludes that eccentricity of the earth's orbit, though tending to produce a glacial period, is insufficient without the concurrence of high uplifts of the areas glaciated.¶ He thinks that the time of increased

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* *Climate and Time*, chap. xix, with plate iv, representing the variations in the eccentricity of the earth's orbit for three million years before A.D. 1800, and one million years after it. Compare *Am. Jour. Sci.*, III, vol. xx, pp. 105–111, with plate, Aug., 1880.

† *Climate and Time*, chap. xviii; Wallace's *Island Life*, chap. ix.

‡ *Quarterly Journal of the Geological Society*, vol. xxvi, 1870, pp. 514–517; vol. xxvii, 1871, pp. 57–60.

§ *Manual of the Geology of India*, part 1, pp. xxxv–xxxviii, 102, 109–112, 229.

‖ *Quart. Journ. Geol. Soc.*, vol. xliii, 1887, pp. 190–196. *Die carbone Eiszeit*, by Dr. W. Waagen, in *Jahrbuch d. k. k. geol. Reichsanstalt*, Vienna, 1888, vol. xxxvii, part 2, pp. 143–192 (reviewed in the *Am. Geologist*, vol. ii, pp. 336–340, Nov., 1888). *Carboniferous Glaciation in the Southern and Eastern Hemispheres, with some notes on the Glossopteris Flora*, by C. D. White. *Am. Geologist*, vol. iii, pp. 299–330, May, 1889, very fully discusses the evidences of this exceedingly ancient Ice Age, with citations of its literature for Africa, India, and Australia.

¶ *Island Life*, chaps. viii, ix, and xxiv.

eccentricity 240,000 to 80,000 years ago was coincident with great altitude of north-western Europe, North America, and Patagonia, which consequently became covered by ice-sheets; but that such previous times of eccentricity, not being favoured by geographic conditions, were not attended by glaciation. The recentness of the Ice age, however, seems to demonstrate that eccentricity was not its primary cause, and to bring doubt that it has exerted any determining influence in producing unusual severity of cold either during the Pleistocene or any former period.

16 In various localities we are able to measure the present rate of erosion of gorges below waterfalls, and the length of the postglacial gorge divided by the rate of recession of the falls gives approximately the time since the Ice age. Such measurements of the gorge and Falls of St. Anthony by Prof. N. H. Winchell show the length of the Postglacial or Recent period to have been about 8,000 years; and from the surveys of Niagara Falls, Mr. G. K. Gilbert believes it to have been 7,000 years, more or less. From the rates of wave-cutting along the sides of Lake Michigan and the consequent accumulation of sand around the south end of the lake, Dr. E. Andrews estimates that the land there became uncovered from its ice-sheet not more than 7,500 years ago. Prof. G. Frederick Wright obtains a similar result from the rate of filling of kettle-holes among the gravel knolls and ridges called kames and eskers, and likewise from the erosion of valleys by streams tributary to Lake Erie; and Prof. Ben. K. Emerson, from the rate of deposition of modified drift in the Connecticut valley at Northampton, Mass., thinks that the time since the Glacial period cannot exceed 10,000 years. An equally small estimate is also indicated by the studies of Gilbert and Russell for the time since the last great rise of the Quaternary lakes Bonneville and Lahontan, lying in Utah and Nevada, within the arid Great Basin of interior drainage, which are believed to have been contemporaneous with the great extension of ice-sheets upon the northern part of the North American continent.

17 Prof. James Geikie maintains that the use of paleolithic implements had ceased, and that early man in Europe made neolithic (polished) implements, before the recession of the ice-sheet from Scotland, Denmark, and the Scandinavian peninsula; and Prestwich suggests that the dawn of civilization in Egypt, China, and India, may have been coeval with the glaciation of north-western Europe. In Wales and

Yorkshire the amount of denudation of limestone rocks on which drift boulders lie has been regarded by Mr. D. Mackintosh as proof that a period of not more than 6,000 years has elapsed since the boulders were left in their positions. The vertical extent of this denudation, averaging about six inches, is nearly the same with that observed in the south-west part of the Province of Quebec by Sir William Logan and Dr. Robert Bell, where veins of quartz marked with glacial striæ stand out to various heights not exceeding one foot above the weathered surface of the enclosing limestone.*

18 From this wide range of concurrent but independent testimonies, we may accept it as practically demonstrated that the ice-sheets disappeared only 6,000 to 10,000 years ago. It is therefore manifestly impossible to ascribe their existence to astronomic causes which ceased 80,000 years ago, as is done by Croll's theory. Instead, I now believe, with Prestwich,† that the whole duration of the Ice age, probably 20,000 to 30 000 years, more or less, was not only terminated but begun after the end of the last period of maximum eccentricity of the earth's revolution around the sun.

19 Another astronomic theory, which assigns a date and duration of the Glacial period from about 24,000 to 6,000 years ago, agreeing nearly with the estimate by Prestwich, has been brought forward by Major-General A. W. Drayson, who first published it in the *Quarterly Journal of the Geological Society* for 1871, and later in successive books, of which the earliest is *On the Cause, Date, and Duration of the Last Glacial Epoch of Geology, and the probable Antiquity of Man, with an Investigation and Description of a New Movementof the Earth* (1873), and the latest, *Untrodden Ground in Astronomy and Geology* (1890).‡ This theory asserts that the earth's axis

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* For more ample statements of many of these evidences of the recency of the Glacial period, see the following papers in this *Journal of the Transactions of the Victoria Institute: The Lapse of Time since the Glacial Epoch determined by the date of the Polished Stone Age*, by J. C. Southall, vol. xiii, 1880, pp. 109–132; and *On the Recency of the Close of the Glacial Period in England and Wales, as shown by the limited depth of Post-glacial Stream Channels, the small Extent of Denudation of Limestone Rocks, and the fresh aspect of Moraines*, by D. Mackintosh, vol. xix, 1885, pp. 73–92.

† *Geology*, vol. ii, 1888, p. 534.

‡ In the *Journal of the Transactions of the Victoria Institute*, vol. xxvi, 1893, pp. 259, 260, Major-General Drayson concisely states his theory in a letter commenting on Prof. James Geikie's paper.

during a cycle of about 31,000 years varies 12° in its inclination to the plane of the ecliptic or path of the earth around the sun. In this long cycle the axis and poles of the earth are thought to describe a circle in the heavens with its centre 6° from the pole of the ecliptic. At present the obliquity of the ecliptic or angle between its plane and that of the earth's equator is about 23½°, which therefore is the distance of the arctic and antarctic circles from the poles; and this, according to General Drayson's computations, is nearly their minimum distance. He claims that this obliquity of the ecliptic, which gives the distance of the arctic circles from the poles and of the tropics from the equator, about 5,000 years ago was some 2° more than now; that 7,500 years ago it was increased 6½° more than at present; that its maximum, nearly 12° more than at present, was about 13,500 B.C.; and that the beginning of this latest cycle of variation in the widths of the intertropical and polar zones was about 31,000 years ago. During the middle portion of the cycle, General Drayson affirms that the Arctic circle reached approximately to 54° north latitude, and that the resulting climatic changes caused the Ice age.

20 It is true that the obliquity of the ecliptic varies slightly and is at present decreasing about an eightieth part of a degree in a hundred years. Sir John Herschel computed, however, that its limit of variation during the last 100,000 years has not exceeded 1° 21′ from its mean, although for a longer time in the past, as millions of years, it may range three or four degrees on each side of the mean. The portion of the present cycle of variation which is used as the basis of this theory seems insufficient to establish its conclusion of a wide range of obliquity; but, even if this were true, the same arguments forbid its application to account for the Glacial period as are urged by Gilbert, Chamberlin, and Le Conte, in their dissent from Croll's theory.* These objections consist in the absence of evidence of glaciation during the long history of the earth previous to the Ice age, excepting near the end of Paleozoic time, and the unsymmetric geographic areas of the ice-sheets, northern Asia and Alaska having not been ice-enveloped. According to General Drayson's astronomic conditions capable of producing an ice age have recurred every 31,000 years; but geologists have recognized no other time of glaciation of

* See Wright's *Ice Age in North America*, pp. 439, 440.

large areas besides the Quaternary and Paleozoic ice ages, which were divided probably by ten or fifteen million years.

21 The only remaining theory dependent on the earth's astronomic relationship which we need to examine is the suggestion first made in 1866 by Sir John Evans,* that, while the earth's axis probably remained unchanged in its direction, a comparatively thin crust of the earth may have gradually slipped as a whole upon the much larger nucleal mass so that the locations of the poles upon the crust have been changed, and that the Glacial period may have been due to such a slipping or transfer by which the regions that became ice-covered were brought very near to the poles. The same or a very similar view has been recently advocated by Dr. Fridtjof Nansen, who writes: "The easiest method of explaining a glacial epoch, as well as the occurrence of warmer climates in one latitude or another, is to imagine a slight change in the geographical position of the earth's axis. If, for instance, we could move the North Pole down to some point near the west coast of Greenland between 60° and 65° N.L., we could, no doubt, produce a glacial period both in Europe and America."†

22 Very small changes of latitude which had been detected at astronomical observatories in England, Germany, Russia, and the United States, seemed to give some foundation for this theory, which in 1891 was regarded by a few American glacialists as worthy of attention and of special investigation by astronomers, with temporary establishment of new observatories for this purpose on a longitude about 180° from Greenwich or from Washington. During the year 1892, however, the brilliant discoveries by Dr. S. C. Chandler‡ of the periods and amounts of the observed variations of latitude, showing them to be in two cycles respectively of twelve and fourteen months, with no appreciable secular change, forbid reliance on this condition as a cause, or even as an element among the causes, of the Ice age. This theory is now entirely out of the field. Sir Robert S. Ball, after reviewing Dr. Chandler's investigations, estimates that

* *On a possible Geological Cause of Changes in the Position of the Axis of the Earth's Crust, Proceedings of the Royal Society of London*, vol. xv, pp. 46–54, Feb. 28, 1866.

† *The First Crossing of Greenland* (1890), vol. ii, p. 454.

‡ *Astronomical Journal* (Boston, Mass.), vol. xii, pp. 57–62, 65–72, and 97–101, Aug. 4 and 23, and Nov. 4, 1892.

the place of the pole since the Glacial period, and from even earlier geologic times, has been without greater changes of position than would lie inside the area of a block or square enclosed by the intersecting streets of a city.*

23 We come now to the wholly terrestrial or geologic theory of the causes of the Ice age, which, in terms varying with increasing knowledge, has been successively advocated by Lyell, Dana, Le Conte, Wright, and others, including the present writer. This theory is called by Professor James Geikie the "earth-movement hypothesis," and is adversely criticized by him in a paper which forms, with its accompanying discussion, pages 221–264 in vol. xxvi (1893) of the *Journal of the Transactions of the Victoria Institute.* According to this explanation, the accumulation of the ice-sheets was due to uplifts of the land as extensive high plateaus receiving snowfall throughout the year.

24 Geology is indebted to Gilbert in his U.S. Geological Survey monograph, *Lake Bonneville*, for the terms *epeirogeny* and *epeirogenic* (continent-producing), to designate the broad movements of uplift and subsidence which affect the whole or large portions of continental areas or of the oceanic basins. This view, accounting for glaciation by high altitude, may therefore be very properly named the epeirogenic theory.

25 In the first edition of the *Principles of Geology* (1830), Lyell pointed out the intimate dependence of climate upon the distribution of areas of land and water and upon the altitude of the land. In 1855 Dana, reasoning from the prevalence of fjords in all glaciated regions and showing that these are valleys eroded by streams during a formerly greater elevation of the land previous to glaciation, and from the marine beds of the St. Lawrence valley and basin of Lake Champlain belonging to the time immediately following the glaciation, announced that the formation of the drift in North America was attended by three great continental movements: the first upward, during which the ice-sheet was accumulated on the land; the second downward, when the ice-sheet was melted away; and the third, within recent time, a re-elevation, bringing the land to its present height.† But with the moderate depth of the fjords and submarine valleys then known, the amount of

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* *Fortnightly Review*, new series, vol. liv, pp. 171–183. Aug., 1893.

† *Proc. Am. Assoc. for Adv. of Science*, vol. ix, for 1855, pp. 28, 29; *Am. Jour. of Science*, II, vol. xxii, pp. 328, 329, Nov. 1856.

preglacial elevation which could be thus affirmed was evidently too little to be an adequate cause for the cold and snowy climate producing the ice-sheet. The belief that this uplift was 3 000 feet or more, giving sufficiently cool climate, as Professor T. G. Bonney has shown, to cause the ice accumulation, has been only reached within the past few years through the discovery by soundings of the U.S. Coast Survey, that on both the Atlantic and Pacific coasts of the United States submarine valleys evidently eroded in late Tertiary and Quaternary time reach to profound depths, 2,000 to 3,000 feet below the present sea level.

26 Professor J. W. Spencer has very impressively reviewed the evidences of the formerly higher altitude of the North American continent, immediately before the Ice age.* Though he has not proceeded to interpret these observations as revealing in continental elevation the probable cause of the colder climate and accumulation of ice-sheets during the Glacial period, I believe that this is a legitimate conclusion, and that it strongly reinforces the arguments long ago advanced by Lyell and Dana and recently emphasized anew by Wallace. The submarine border of the continental plateau of North America to depths of more than 3,000 feet is cut by valleys or channels, which if raised above the sea level would be fjords or cañons. These can be no other than river-courses eroded while the land stood much higher than now; and its subsidence evidently took place in a late geologic epoch, else the channels would have become filled with sediments.

27 According to the Coast Survey charts, as noted by Spencer, the bottom of a submerged valley just outside the delta of the Mississippi is found by soundings at the depth of 3,000 feet. This valley is a few miles wide and is bounded by a plain of the sea bed from 900 to 1,200 feet above its floor. It thus appears that the country north of the Gulf of Mexico has been raised for a short time to a height of not less than 3,000 feet.

28 The continuation of the Hudson river valley has been traced by detailed hydrographic surveys to the edge of the

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* *Bulletin of the Geological Society of America*, vol. i, 1890, pp. 65–70, with map of the preglacial Laurentian river; vol. v, 1893–94, pp. 19–22, with map of submarine contour in the West Indies region. The first of these papers was also in the *Geol. Magazine*, III, vol. vii, 1890, pp. 203–212.

steep continental slope at a distance of about 105 miles from Sandy Hook. Its outermost twenty-five miles are a submarine fjord three miles wide and from 900 to 2,250 feet in vertical depth measured from the crests of its banks, which with the adjoining flat area decline from 300 to 600 feet below the present sea level. The deepest sounding in this fjord is 2,844 feet.*

29 An unfinished survey by soundings off the mouth of Delaware Bay finds a similar valley submerged nearly 1,200 feet, but not yet traced to the margin of the continental plateau.

30 Again, the United States Coast Survey and British Admiralty Charts, as Spencer states, record submerged fjord outlets from the Gulf of Maine, the Gulf of St. Lawrence, and Hudson Bay, respectively 2,664 feet, 3,666 feet, and 2,040 feet below sea level. The bed of the old Laurentian river from the outer boundary of the Fishing Banks to the mouth of the Saguenay, a distance of more than 800 miles, is reached by soundings 1,878 to 1,104 feet in depth. Advancing inland, the sublime Saguenay fjord along an extent of about fifty miles ranges from 300 to 840 feet in depth below the sea level, while in some places its bordering cliffs, one to one and a half miles apart, rise abruptly 1,500 feet above the water.†

31 Greenland is divided from the contiguous North American continent and archipelago by a great valley of erosion, which is estimated from soundings and tidal records to have a mean depth of 2,510 feet below sea level for 680 miles through Davis Strait; 2,695 feet for 770 miles next northward through Baffin Bay; and 1,663 feet for the next 55 miles north through Smith Strait.‡

32 On the Pacific coast of the United States Professor Joseph Le Conte has shown that the islands south of Santa Barbara and Los Angeles, now separated from the mainland and from each other by channels twenty to thirty miles wide and 600 to 1,000 feet deep, were still a part of the mainland

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* A. Lindenkohl, *Report of U.S. Coast and Geodetic Survey* for 1884, pp. 435–8; *Am. Jour. Sci.*, iii, vol. xxix, pp. 475–480, June, 1885. James D. Dana, *Am. Jour. Sci.*, iii, vol. xl, pp. 425–437, Dec. 1890, with an excellent map of the Hudson submarine valley and fjord.

† J. W. Dawson, *Notes on the Post-Pliocene Geology of Canada*, 1872, p. 41; *The Canadian Ice Age*, 1893, pp. 71–74.

‡ *Smithsonian Contributions to Knowledge*, vol. xv, pp. 163, 164.

during the late Pliocene and early Quaternary periods.* In northern California, Professor George Davidson, of the United States Coast Survey, reports three submarine valleys about twenty-five, twelve, and six miles south of Cape Mendocino, sinking respectively to 2,400, 3,120, and 2,700 feet below the sea level, where they cross the 100 fathom line of the marginal plateau.† If the land there were to rise 1,000 feet, these valleys would be fjords with sides towering high above the water, but still descending beneath it to great depths.

33 Farther to the north, Puget Sound and the series of sheltered channels and sounds through which the steamboat passage is made to Glacier Bay, Alaska, are submerged valleys of erosion, now filled by the sea but separated from the open ocean by thousands of islands, the continuation of the Coast Range of mountains. From the depths of the channels and fjords Dr. G. M. Dawson concludes that this area had a preglacial elevation at least about 900 feet above the present sea level, during part or the whole of the Pliocene period.‡

34 Le Conte has correlated the great epeirogenic uplifts of North America, known by these deeply submerged valleys on both the eastern and western coasts, with the latest time of orogenic disturbance by faulting and upheaval of the Sierra Nevada and Coast Range in California, during the closing stage of the Tertiary and the early part of the Quaternary era, culminating in the Glacial period.§ In the Mississippi basin, from the evidence of river currents much stronger than now, transporting Archean pebbles from near the sources of the Mississippi to the shore of the Gulf of Mexico, Prof. E. W. Hilgard thinks that the preglacial uplift, inaugurating the Ice age, was 4,000 or 5,000 feet more in the central part of the continent than at this river's mouth.‖

35 Although the adequacy of the preglacial epeirogenic elevation of this continent to produce its Pleistocene ice-sheet was tardily recognized, it was distinctly claimed by Dana in 1870 that the Champlain subsidence of the land beneath its ice-load, supposing it to have been previously at a high

* *Bulletin of the California Academy of Sciences*, vol. ii, 1887, pp. 515-520.

† *Ibid.*, vol. ii, pp. 265-268.

‡ *Canadian Naturalist*, new series, vol. viii, pp. 241-248, April, 1877.

§ *Bulletin Geol. Soc. of America*, vol. ii, 1891, pp. 323-330; *Elements of Geology*, third edition, 1891, pp. 562-569, 589.

‖ *Am. Jour. of Science*, III, vol. xliii, pp. 389-402, May, 1892.

altitude, must have brought climatic conditions under which the ice would very rapidly disappear. The depression would be like coming from Greenland to southern Canada and New England. In Prof. Dana's words: "Such an extended change of climate over the glacier area was equivalent in effect to a transfer from a cold icy region to that of a temperate climate and melting sun. The melting would therefore have gone forward over vast surfaces at once, wide in latitude as well as longitude."*

36 Such explanations as these accounting for the gradual accumulation and comparatively rapid dissolution of the North American ice-sheet are also found to be applicable to the ice-sheets of other regions. The fjords of the northern portions of the British Isles and of Scandinavia show that the drift-bearing north-western part of Europe stood in preglacial time 1,000 to 4,000 feet higher than now, while on the other hand late glacial marine beds and strand lines of sea erosion testify that when the ice disappeared the land on which it had lain was depressed 100 to 600 feet below its present height, or nearly to the same amount as the Champlain depression in North America. Mr. T. F. Jamieson appears to have been the first in Great Britain or Europe to attribute the ice accumulation to altitude of the land, and to hold the view, which I receive from him, that the submergence of glaciated lands when they were loaded with ice has been caused directly by this load pressing down the earth's crust upon its fused interior, and that the subsequent re-elevation was a hydrostatic uplifting of the crust by underflow of the inner mass when the ice was melted away.† Just the same evidences of abundant and deep fjords and of marine beds overlying the glacial drift to heights of several hundred feet above the sea are found in Patagonia, as described by Darwin and Agassiz. On these three continental areas, the widely separated chief drift-bearing regions of the earth are found to have experienced in connection with their glaciation in each case three great epeirogenic movements of similar

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* *Trans. Conn. Acad. of Arts and Sciences*, vol. ii, 1870, p. 67. Compare the *Am. Jour. of Science*, III, vol. x, pp. 168–183, Sept., 1875.

† *Quart. Jour. Geol. Soc.*, vol. xviii, 1862, p. 180; vol. xxi, 1865, p. 178. Later discussions of this subject by Mr. Jamieson are in the *Geological Magazine*, II, vol. ix, pp. 400–407 and 457–466, Sept. and Oct., 1882; III, vol. iv, pp. 344–348, Aug. 1887; and III, vol. viii, pp. 387–392. Sept., 1891.

character and sequence, first, a comparatively long continued uplift, which in its culmination appears to have given a high plateau climate with abundant snowfall forming an ice sheet, whose duration extended until the land sank somewhat lower than now, leading to amelioration of the climate and the departure of the ice, followed by re-elevation to the present level. The coincidence of these great earth movements with glaciation naturally leads to the conviction that they were the direct and sufficient cause of the ice-sheets and of their disappearance; and this conclusion is confirmed by the insufficiency and failure of the other theories which have been advanced to account for the Glacial period.

37 The epeirogenic movements of the countries which became glaciated were only a portion of wide-spread oscillations of continental areas during the closing part of Tertiary time and the ensuing much shorter Quaternary era. Not only was north-western Europe uplifted thousands of feet, but probably all the western side of Europe and Africa shared in this movement, of which we have the most convincing proof in the submerged channel of the Congo, about four hundred miles south of the equator. From soundings for the selection of a route for a submarine cable to connect commercial stations on the African coast, Mr. J. Y. Buchanan* found this channel to extend eighty miles into the ocean to a depth of more than 6,000 feet. The last twenty miles of the Congo have a depth from 900 to 1,450 feet. At the mouth of the river its width is three miles, and its depth 2,000 feet. Thirty-five miles off shore the width of the submerged channel or cañon is six miles, with a depth of about 3,450 feet, its bottom being nearly 3,000 feet below the sea bed on each side. Fifty miles from the mouth of the river the sounding to the submarine continental slope is nearly 3,000 feet, while the bottom of the old channel lies at 6,000 feet. This very remarkable continuation of the Congo valley far beneath the sea level is like those of the Hudson and St. Lawrence rivers, and like the submerged valleys on the coast of California; but the Congo reaches to a greater depth than those of North America, and even exceeds the Sogne fjord, the longest and deepest in Norway, which has a maximum sounding of 4,080 feet. Another deep submarine valley, called the "Bottomless Pit," having soundings of 2,700 feet, is described by Buchanan on the African coast 350 miles north of the equator, and he states

* *Scottish Geographical Magazine*, vol. iii, 1887, pp. 217–238.

that a similar valley exists in the southern part of the Bay of Biscay. These observations show that within very late geologic time, probably almost the entire Atlantic side of the eastern continent has been greatly uplifted, attaining as high an altitude as that which A. C. Ramsay and James Geikie conjectured as a possible cause of the frost-riven limestone-agglomerates of Gibraltar.*

38 Likewise the tropical portions of the western continent, the West Indies, and the smaller islands of the Caribbean region, appear to have shared the epeirogenic disturbances which were associated with the glaciation of the northern and southern parts of this continent, as is well brought out by the recent studies and discussions of the geology of Barbados island by A. J. Jukes-Browne and J. B. Harrison,† and by the close relationship of the Pacific and West Indian deep sea faunas on the opposite sides of the Isthmus of Panama, made known through dredging by Alexander Agassiz.‡ This testimony, indeed, with that of Darwin, L. and A. Agassiz, and others, of very recent, extensive, and deep subsidence of the western coast of South America, apparently however continuing for no long time, lends much probability to the supposition that the low Panama Isthmus was somewhat deeply submerged for a geologically short period contemporaneous with epeirogenic uplifts of the circumpolar parts of this continent both at the north and south, whereby the effects of great altitude in covering the northern and southern high areas with ice-sheets were augmented by the passage of much of the Gulf Stream into the Pacific Ocean.

39 The end of the Tertiary era and the subsequent Glacial period have been exceptionally characterized by many great oscillations of continental and insular land areas. Where movements of land elevation have taken place in high latitudes, either north or south, which received abundant precipitation of moisture, ice-sheets were formed; and the weight of these ice-sheets seems to have been a chief cause, and often probably the only cause, of the subsidence of these lands and the disappearance of their ice.

40 In an appendix of Wright's *Ice Age in North America*, I have shown that, between epochs of widely extended

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* *Quart. Journ. Geol. Soc.*, vol. xxxiv, 1878, pp. 505–541.

† *Quart. Journ. Geol. Soc.*, vol. xlvii, 1891, pp. 197–250.

‡ Bulletin, *Mus. Comp. Zool.*, at Harvard College, vol. xxi, pp. 185–200, June, 1891.

mountain-building by plication, the diminution of the earth's mass produces epeirogenic distortion of the crust, by the elevation of certain large areas and the depression of others, with resulting inequalities of pressure upon different portions of the interior, and that these effects have been greatest immediately before relief has been given by the formation of folded mountain ranges. There have been two epochs pre-eminently distinguished by extensive mountain-plication, one occurring at the close of the Paleozoic era, and another progressing through the Tertiary and culminating in the Quaternary era, introducing the Ice age. During the last, besides plication of the Coast range, of the Alps, and the Himalayas, a very extraordinary development of tilted mountain ranges, and outpouring of lavas on an almost unprecedented scale, have taken place in the Great Basin and the region crossed by the Snake and Columbia rivers. With the culminations of both of these great epochs of mountain-building, so widely separated by the Mesozoic and Tertiary eras, glaciation has been remarkably associated, and indeed the ice accumulation appears to have been caused by the epeirogenic and orogenic uplifts of continental plateaus and mountain ranges. Since the disturbances, with glaciation, closing Paleozoic time, the same combination of events has not recurred until the Quaternary era, which is not only exceptional in its accumulation of ice-sheets, but also in its numerous and widely extended movements of elevation and subsidence, and its mountain-building and renewed upheavals of formerly base-levelled mountain belts. The earth's surface is probably now made more varied, beautiful, and grand, by the existence of many lofty mountain ranges, than has been its average condition during the past long eras. This explanation appears to me entirely consistent with Dana's teaching that the great continental and oceanic areas have been mainly permanent from very early geologic times. We may also, I think, be encouraged to the hope and belief that a long time will probably pass before the recurrence of epeirogenic conditions producing extensive glaciation. As the rainbow is a promise of recurring fruitful seasons, we see no reason for expecting the return of an Ice age desolating the present most populous and prosperous parts of the world. It may be as far hence to its return, if it shall ever come again, as the ten or fifteen million years since the Coal period and the Permian Ice age.

41 Two formidable objections to this view that the accumu-

lation of the Pleistocene ice-sheets was preceded and caused by great epeirogenic elevation deserve careful attention. The first consists in an approximate identity of level with that of to-day having been held by many drift-bearing areas at a time very shortly preceding their glaciation. This is clearly known to have been true of Great Britain and of New England. Near Boston, Mass., for example, my observations of fragments of marine shells in the till of drumlins in or adjoining the harbour prove for that tract a preglacial height closely the same as now at so late a time that the molluscan fauna, of which we have a considerable representation, comprised only species now living. In respect to this objection, it must be acknowledged that the preglacial high elevation which I think these areas experienced was geologically very short. With the steep gradients of the Hudson, of the streams which formed the now submerged channels on the Californian coast, and of the Congo, these rivers, if allowed a long time for erosion, must have formed even longer and broader valleys than the still very impressive troughs which are now found on these submarine continental slopes. But the duration of the epeirogenic uplift of these areas on the border of the glaciation for the Hudson, beyond it for the Californian rivers, and near the equator in western Africa, can scarcely be compared in its brevity with the prolonged high altitude held during late Tertiary and early Quaternary time by the Scandinavian peninsula and by all the northern coasts of North America from Maine and Puget Sound to the great Arctic Archipelago and Greenland. The abundant long and branching fjords of these northern regions, and the wide and deep channels dividing the many large and small islands north of this continent attest a very long time of preglacial high elevation there. At the time of culmination of the long continued and slowly increasing uplifts at the north, they seem to have extended during a short epoch far to the south, coincident with the formation of ice-sheets in high latitudes. But when these lands became depressed and the ice burden of the glaciated countries was removed, they in some instances, as in Great Britain and New England, returned very nearly to their original levels, beautifully illustrating the natural condition of equilibrium of the earth's crust, which Dutton has named *isostasy*, that when not subjected to special and exceptional stresses it acts as if floating on a heavier plastic and mobile interior.

42 Somewhat analogous with the foregoing is the second of these objections, namely, the fully proved low altitude of the glaciated lands when the ice-sheets attained their maximum extent and during the diversified and fluctuating history of their recession. It must be recognized, however, that we have in the complex series of drift deposits left for our examination only a representation of the later and closing phase of the Ice age, while the land was low or near its present level. In North America the comparatively much longer early phase of high altitude leading to the accumulation and slow extension of the ice-sheets is not clearly represented by the drift and numerous moraines of the glacial retreat or of the extreme limit of glaciation, but by the earlier fluvial Lafayette formation, in which, according to Hilgard, coarse gravel from the Archean areas near the head of the Mississippi was carried down by that stream quite to the shores of the Gulf of Mexico.

43 The wane and departure of both the North American and European ice-sheets have been marked by many stages of halt and oscillation, whereby the flora, including forest trees, and less frequently traces of the fauna, of the temperate areas adjoining the melting and mainly receding ice were covered by its drift at the times of temporary re-advance of the ice-border. No better illustration of conditions favourable for the burial of forest beds in the drift can be imagined than those of the Malaspina glacier or ice-sheet, between Mount St. Elias and the ocean, explored by Russell in 1890 and 1891, and found to be covered on its attenuated border with drift which supports luxuriant growing forests. Let a century of exceptional snowfall cause a thickening and re-advance of that ice-sheet, and sections of its drift exposed after the glacial recession will show a thick forest bed of chiefly or wholly temperate species. Such re-advances of the continental ice-sheets, interrupting their retreat, are known by well marked recessional moraines both in North America and Europe. Near the drift boundary in the Mississippi basin some of these glacial fluctuations have involved long stages of time, measured by years or centuries, with important though minor changes in altitude, as shown by the excellent analytic studies of Chamberlin, Salisbury, and Leverett; but farther north, as in the large region of the glacial Lake Agassiz, the withdrawal of the ice-sheet and formation of successive moraines marking slight halts and re-advances due to secular

changes in temperature, humidity, and snowfall, were demonstrably very rapid, the whole duration of this glacial lake being probably only about 1,000 years.* The vicissitudes of the general glacial retreat seem to me to have been due thus chiefly to variations of snowfall, some long terms of years having much snow and prevailingly cool temperature, therefore allowing considerable glacial re-advance, while for the greater part other series of years favoured rapid melting and retreat.

44 Under this view we may, I think, account for all the observations which have been held in America and Europe as proofs of interglacial epochs, without assuming that there was either any far re-advance of the ice-border or any epeirogenic movements attending the glacial retreat of such magnitude as to induce the fluctuations of which the forest beds and marginal moraines bear witness. The Ice age seems to me to have been essentially continuous and single, with important fluctuations, but not of epochal significance, both during its advance and decline.

The PRESIDENT (Sir G. G. STOKES, Bart., D.Sc., F.R.S.).—I will ask you to return your thanks both to the author of this paper, and also to Professor Hull for so ably reading it. (Applause.) I now invite remarks on the subject, which presents considerable difficulty.

Professor E. HULL, LL.D., F.R.S., F.G.S.—I think this is one of the most interesting and valuable contributions, to account for the production of the Ice Age of the Quaternary Period, that we have had for a long time.

There is a great freshness about it—a quality which applies to many of the American papers. Fortunately America has produced

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* *Geol. and Nat. Hist. Survey of Canada*, Annual Report, new series, vol. iv, for 1888–89, p. 51 E.

a grand array of geologists who have been quite equal to dealing with the magnificent phenomena with which that great continent abounds, and we in Europe—in the old country—are now deriving the benefit of these new ideas coming across the Atlantic to us, and getting us a little out of the rut into which we were falling.

The two principal points that the author deals with in the paper are, I think, briefly these. The first is as regards the length of time—so many thousands of years—which was necessary to bring into existence the great Ice Age, and to see it to its close; and the second is the question, on what phenomena are we to base our conclusions as regards the origin of that great Ice Age. You will have seen from the paper that there are two extreme views as regards the length of period—the one astronomical, of which Dr. Croll may be considered the author, and the other geological, of which I think I may say Lyell, followed by Dana, Le Conte and equally by the author of the paper, are the exponents. You have seen that the differences in periodic lengths are enormous between these two extremes; and if I might be allowed, as an old geologist myself, to some extent to give my own view, I might say I entirely concur with the author of this paper as regards the length of time.

I have visited, explored, and described glacial phenomena over a very large portion of the British Isles, and it is impossible, I think, to observe the freshness of the glacial striæ and terraces, and the polishing of the rock surfaces, without coming to the conclusion that the geological epoch is, comparatively speaking, exceedingly recent. Just consider for a moment;—the phenomena that have been left by the old glaciers of the British Islands have not yet entirely disappeared, nor have those of the former enormous glaciers of the Alps and other ranges. They consist of boulders and moraines on the one hand, and polishing of the rock surfaces on the other; and it seems to me unquestionable that if the period since the disappearance of glaciers were of the enormous length held by Dr. Croll and his followers Professor James Geikie and others, that the whole of these evidences of the glacial period would have entirely disappeared. The streams, torrents, and atmospheric agents would have swept away these accumulations, and also have completely obliterated the beautiful striations which we find on the rock surfaces. In some districts, in fact, you have only to take the sod off, lift it off carefully, and there you find the surface beautifully glaciated; and if the period had been of such vast

duration since these ice sheets disappeared, it is impossible to suppose that those surfaces would have remained in all their freshness down to the present day.

Then as to the cause of the glaciers, I think it is exceedingly interesting to observe that Lyell's view—which had been partially, at any rate, eclipsed by the more attractive, and probably less understood, views of Croll (because they are entirely astronomical)—is now again rising to the surface, and that fresh evidences have been brought to light by the deep sea dredgings. This is, I think, a most valuable part of Mr. Upham's paper. He has accumulated and brought into this contribution to our Society a large number of instances where the valleys and fjords which dissect the various mountainous ranges of Europe, Asia, and even Africa can be tracked out under the ocean for a great distance; and, as I explained when reading the paper, *no channel of this kind could be cut under the ocean.* As long as the land is under the ocean it is preserved from erosion or denudation of that kind. Channels running out into deep water must have been cut when the area was elevated out of the ocean. This subject has been more recently investigated by Professor Spencer in his papers on "The Reconstruction of the Antillean Continent."

Owing to the depths of these submerged valleys it involves the supposition that the lands bordering the ocean had been elevated 1,000, 2,000 or more feet at the time of these river valleys being eroded. So that there is strong evidence coming to light that Lyell's view, which was based on the supposition of the elevation of the land surface over a large part of the northern hemisphere, as accounting for the glacial period, was in the main the true one. Therefore I think this contribution is of great value as bearing on Lyell's original hypothesis.

Mr. JOSEPH BROWN, C.B.—Although I cannot pretend for a moment to be a scientific geologist, my walk in life having led me in another direction, I certainly have been, I may say, an amateur geologist for the last sixty years, and during many journeys on the Continent I have taken every opportunity I could get of observing geological phenomena, and have frequently been struck by the very significant fact mentioned by Professor Hull, that these striæ and marks of glaciation found on the rocks in many places are a great deal too fresh to admit of the supposition that they were made 20,000, 30,000 or 50,000 years ago. I do not

believe it, certainly. I observed in the valley of Aosta, on the south side of Mont Blanc, where I went to find some of these enormous boulders, the most distinct marks of striæ, as they are called, made on the rocks that flank the valley, and they were so fresh that I said to myself, "It is impossible that these marks could have been made 50,000, 40,000, or 30,000 years ago." They looked to me as if they had not been made more than 100 years; and I made exactly the same observation in regard to the extensive valley that leads from Reichenbach up to the Gemmi Pass. There are portions of that valley, where the guide books point out there are strong marks of glaciation along the rocks and polished surfaces, and I venture to say that nobody could see those marks and believe that they were 50,000 years old, or one-fifth part of that age. I made some observations also in regard to some glacial striæ on what are called the glacial rocks in Cumberland, on the plain that lies not far from the church at Ambleside.

Professor HULL.—Yes, I think I was the first to describe it, about thirty years ago; it is reproduced in Lyell's *Antiquity of Man*—from my original drawing in the *Edinburgh New Philosophical Journal.*

Mr. JOSEPH BROWN, C.B.—It is not possible to suppose that the marks are anything like 20,000, or even 10,000 years old. Rocks wear away too fast for that, although some of them are the hardest things in Nature. For that reason, I cannot bring myself to believe that the Ice Age was so far back as some geologists consider. I have held my mind in suspense all the time I have been investigating the question, some fifty or sixty years, and I cannot bring myself to believe that these marks and indications are anything like so old as they are reputed to be. Although I consider the paper which has been read to-day has thrown more light on this very difficult question, as to the rocks and the cause of the Ice Age, and how many thousands of years back it dates, than any paper I have read for a long time, yet I find myself unable to agree with one suggestion made by the author, whose opinions on the subject are worth a great deal more than mine, (for I do not put forward my observations as more than those of an amateur), and it is this:—I heard the Professor say that these great submerged valleys that have been eroded outside the edge of the great North American Continent, as well as some that appeared to be eroded outside the African Continent, must have

occurred when the sea bottom was elevated and that they had been eroded by some great rivers.

Mr. A. Ent. Gooch, F.G.S.—I should like to refer to paragraph 11 of the paper:—"Others have suggested that the sun's heat has varied, and that the Ice Age was a time of diminished solar radiation." It is well known that many astronomers, and those who are best qualified to speak on the matter, including Sir Robert Ball, admit that we know very little of the present condition or past behaviour of the solar body. Supposing a large portion of the body of the sun to have been gaseous, his temperature would have been lower, and the radiation-rate less. The other point is "Concerning the latter (*i.e.*, the earth's own internal heat);" it is well ascertained that during at least the Mesozoic, Tertiary, and Quaternary eras, it has affected the climatic average by no more than a small fraction of a degree. Many of us would like to know what explanation is given for that, and why such knowledge of the earth's internal heat is assumed.

Rev. John Tuckwell.—Professor Tyndall, in his book on *Heat a Mode of Motion*, draws attention to the singular conditions required of an Ice Age, by saying that it is often overlooked that a large amount of ice accumulating on one part of the earth's surface would necessitate a large amount of evaporation caused by intense solar heat at another part of the earth's surface. The quantity of water on the earth is limited, and if there be a great accumulation of snow at some places, there must be a proportional amount of evaporation at another part of the earth's surface, which would mean very great heat. I should have liked to have had some further information on that point.

The President.—No doubt it implies evaporation; but we do not know what length of time that may have been spread over. Therefore I do not see that we can infer that the temperature must have been very great. It may have been going on slowly.

Rev. John Tuckwell.—Would it not be that if the period of the Ice Age was brief, then the temperature must have been very great, for large accumulations of the frozen vapour to form at the poles of the earth? The shorter the period of the Ice Age, it seems to me, the greater the amount of heat that must have been at other portions of the earth's surface.

The President.—No doubt, but even taking the period that

geologists suppose to represent the glacial period, it would not require a very great temperature if the thing went on gradually.

Professor J. LOGAN LOBLEY, F.G.S.—Mr. Gooch expresses his anxiety to know on what grounds the author of the paper stated that there was no evidence in the Mesozoic, Tertiary and Quaternary eras, of the sun's heat having been much less than at present. I would go further and say that it appears to me there is no evidence of the sun's heat having been much less than now, even during the Palæozoic times; for I find the same organisms in the Cambrian rocks as live at the present time. The same genera are found in many formations living on without more than specific change to the present time. That, I think, is sufficient proof, apart from vegetable remains (which afford strong evidence of the fact) that the sun's heat has been, practically, unchanged from the earliest geological times to the present. Mr. Tuckwell stated that the production of an enormous quantity of snow round the North Pole must have required an enormous amount of evaporation. That is true; but is there not, under present conditions, an enormous amount of evaporation? It is actually so in tropical portions of the globe. Supposing land to be elevated 2,000 or 3,000 feet above its present level there would be the conditions required to produce a greater condensation of vapour in the atmosphere in the form of snow and less in the form of rain. The normal snow line is a little more than 5,000 feet above the level of the sea in the north part of the British Isles. If the North Sea were turned into dry land with other geographic changes, which would lessen the warmth of the Atlantic waters, there would be a greater amount of cold in this country to produce greater precipitation of snow, and the retention of that amount of snow which produces the glacial conditions. But it might be asked, "What is meant by the Ice Age?" One means one thing and another something different—one may mean the land surface, at its present level north of the 50′ parallel covered with an ice cap, and another may mean the elevated regions only of the northern hemisphere covered with great glaciers that glaciated the lower portions of these regions, and not that the great plain, extending far to the south, was covered with one great ice cap. On the plains of Siberia and Alaska there is no evidence of glaciation; and we can only surmise that, by the rapid melting of accumulated snow and ice, great floods may have been pro-

duced, which would wash away the *débris* caused by glaciation, and this would spread over the plains considerably beyond the fringe of the northern ice. Thus we may, I think, get a very rational conception of what is commonly called the Ice Age, without drawing upon our imagination for that extraordinary state of things which is pictured by so many, and we can do this without requiring an increase of the cold or heat of the globe taken as a whole, which I do not believe to have practically altered from the time of the Cambrian period. An elevation of a portion of the earth's surface to the extent of 3,000 feet may seem enormous; but what is it compared with the diameter of the globe? It is just $\frac{1}{1400}$th, which is really a very slight swelling of the surface, and might be produced in certain cases by the expansion of the substance of the globe by altered local thermal conditions. As to the pressure of ice producing depression, I do not consider that the pressure of any possible accumulation of ice would produce depression on the surface of the globe; cold however causes contraction, and heat expansion. And it is to these agencies I look as having caused changes of level in the past; similar changes are occurring at the present period.

The meeting was then adjourned.

REMARKS ON THE FOREGOING PAPER.

Sir Joseph Prestwich, D.C.L., F.R.S.,* wrote:—

Two questions of great interest are raised by Mr. Upham's paper—the cause of the great Ice Age and the date measured from our own time at which it came to an end. In this country, owing to the prevailing belief in Croll's hypothesis, the date of the last event was placed at 80,000 years ago. My own opinion has long been that 10,000 to 12,000 years was a more probable estimate. The American geologists, upon entirely different and independent data, have arrived at a similar conclusion. Among the reasons assigned by the author, one is the rate of erosion of some of the great water-falls on that continent. Exception

* The last communication received from this author ere his decease.—Ed.

might be taken at this as the rate is known to vary considerably. This estimate would show that the Ice Age came to an end not more than 7,000 to 8,000 years ago. This may give a minimum measure, but it serves at the same time to render more secure the other estimates which are somewhat in excess of this, and which would extend the time to 10,000 years. I cannot but consider these estimates which are founded, as is also my own, upon available geological data as more probably true than that assumed on the astronomical hypothesis. That hypothesis is also entirely discordant with geological facts. It involves the recurrence of a succession of cold periods at geological times of which we have no evidence.

I do not, however, agree with the author in his opinion as to the cause of the great Ice Age, which he considers due to great continental elevations which would make the glaciated areas of North America to have been 3,000 to 4,000 feet higher than they now are. That there has been a submergence apparently to that extent on the coast of that continent, whereby old glaciated valleys and fiords now form great submarine depressions, are very striking facts. But if it is difficult now to account for the glaciation of mountains 5,000 to 6,000 feet high, what will it be if we have to add to this 3,000 to 4,000 feet more, and to imagine an ice-sheet 9,000 to 10,000 feet thick. The author also somewhat damages his case by extending his argument to the tropical regions of Africa and elsewhere. The European area affords no sufficient corroboration. The Rhine, the Thames, and the Severn show no deep submarine valleys. The old Yare is submerged to the depth of 500 feet at Yarmouth, but the Thames and Severn valleys at their entrance show no greater difference of level than 60 to 70 feet, and the smaller rivers on the Cornish coast of 40 to 50 feet. Still the cause of the great Ice Age cannot be different in Europe from what it is in America. That cause has yet, in my opinion, to be discovered.

Prof. J. Geikie, LL.D., F.R.S., writes:—

It is a pity that Mr. Upham should have devoted so little space in his paper towards the explanation of what I have termed the

"earth movement *hypothesis*," but which he prefers to designate by the title of "the epeirogenic *theory*." Well, there is not much in a name, but, to be quite accurate, the view in question has not advanced to the stage of being a theory. To my mind it is only a conjectural explanation, which, as I endeavoured to show in a paper lately read before this Society, has no geological evidence to support it. To the arguments I have advanced, Mr. Upham has not replied, save in the most cursory manner; and, as I shall presently show, his reply practically implies the condemnation of the hypothesis. As to the drowned river-channels which geologists have known about for many years,—their existence is admitted. They and the fiords of N.W. Europe and N. America have long been recognised as yielding evidence of a former wider and more elevated condition of those regions. It has also been long known to geologists that the excavation of those now submerged or partially submerged valleys took place and was practically completed in ages long anterior to the advent of the Glacial Period. I must express my astonishment, therefore, that Mr. Upham should cite the existence of fiords, etc., in support of his "epeirogenic" hypothesis. So far from lending that hypothesis any support, the fiords and drowned river-channels supply most convincing evidence against it. What they show us is that a wide and elevated land-surface existed for a protracted period of time in temperate latitudes without inducing extensive glaciation. The fiords occupy valleys cut by rivers in elevated plateaux of erosion. During that period of elevation, rain and rivers, not snow and ice, were the chief denuding agents. It was not until long after the fiord valleys had come into existence that the great *mers de glace* of the Glacial Period made their appearance. To appeal to the existence of fiords as testimony in favour of a great continental elevation in glacial times is, to my mind, an instance of putting the cart before the horse.*

In my paper already referred to I have drawn attention to the fact that the only direct evidence we have of the geographical conditions that obtained immediately prior to

* Professor E. Hull, LL.D., F.R.S., remarks on this, October, 1897 :— "Yes, but all the while the gradual elevation of the lands may have been preparing the way for the commencement of the glacial conditions."—Ed.

the appearance of massive ice-sheets in Europe and North America shows that the relative level of land and sea in those regions was much the same as it is now. Mr. Upham cannot but admit this, but would fain minimise the admission, which is, in fact, fatal to his hypothesis. He says, "it must be acknowledged that the pre-glacial high elevation which I think these areas experienced was geologically very short." I do not see on what definite geological evidence Mr. Upham bases this statement, and would regard it as a conjecture resting on a predilection for a particular hypothesis, which would vanish if a prolonged period of pre-glacial elevation were to be admitted. And a little further on I note that he admits that the fjord regions of North America and North-West Europe must have experienced a very long time of pre-glacial elevation.

In reply to my argument that the frequent occurrence of marine deposits intercalated amongst and associated with the glacial deposits proves that, during the Ice Age, the land could not have been greatly elevated, he says that "in the complex series of drift-deposits" we have only the records of "the closing phase of the Ice Age, while the land was low or near its present level." This statement will not stand examination. I do not believe it is true of the glacial deposits of North America, and it is certainly not true of their European equivalents. The very earliest of the glacial accumulations of North West Europe are marine clays, etc., with Arctic shells.

Mr. Upham is aware that the existence of inter-glacial deposits is another stumbling-block over which his hypothesis must come to grief. He, therefore, explains them away by referring to the phenomena seen in the neighbourhood of the Malaspina glacier. Can Mr. Upham really think that the phenomena he refers to have been overlooked by those who have specially studied inter-glacial deposits? That glaciers advance and retreat periodically, and that now and again organic remains and alluvial deposits may become intercalated amongst moraine *débris*—are facts which I venture to say have never been overlooked by glacialists of any school whatever. But such considerations entirely fail to explain the occurrence of what are known as inter-glacial beds. Take, for example, the inter-glacial peat and lignite-beds of Schleswig Holstein and North Germany. These contain a flora indicative of more genial conditions than now exist

in the regions where those inter-glacial beds occur. They rest upon the ground-moraine of an ice-sheet which flowed south to the hills of Middle Germany: and they are overlaid by the ground-moraine of another ice-sheet which flowed south to the region lying between the valleys of the Elbe and the Aller. The interpretation of the evidence is obvious. The inter-glacial flora could not possibly have flourished in the vicinity of a *mer de glace*—at the time of its growth snow and ice could not have been developed in Europe on a larger scale than at present.

I need not prolong these remarks. My argument against the author's "epeirogenic" hypothesis has been set forth in the paper I recently gave to the Society, and remains unanswered by Mr. Upham in his present communication.

Major-General DRAYSON, F.R.A.S., writes:—

Mr. Warren Upham has done me the honour of referring to some of my books, in which I have given geometrical proofs of a movement of the Earth, which movement had never before been defined in detail.

It was the certainty of the accuracy of geometry, that caused me to state, 22 years ago, that the Ice Age lasted only about 18,000 years, terminated not longer than 7,000 years ago, and that the glaciation of the two hemispheres was contemporaneous.

Mr. Upham states:—

Sir John Herschel computed, however, that its limits (*i.e.*, the obliquity) of variation during the last 100,000 years has not exceeded 1° 21′.

All Herschel did was to copy the opinions of M. La Place, that the *Plane of the Ecliptic* could not vary more than 1° 21′ according to accepted theories. But the variation in the obliquity is dependent mainly on the course traced by the Earth's axis; and this course M. La Place failed even to examine.

In my book, *Untrodden Ground*, I devoted chapter 8 to showing this oversight of La Place, and how error had been repeated and promulgated by the repetition of the incorrect statement, that because the plane of the ecliptic was supposed to vary only 1° 21′, therefore the obliquity could vary only 1° 21′.

Again, Mr. Upham says:

The portion of the present cycle of variation, which is used as the basis of this theory, seems insufficient to establish its conclusion of a wide range of obliquity.

As a geometrician, I am at once at issue with Mr. Upham. I have stated that the radius of the circle now traced by the Pole is 29° 25′ 47″. If I were even half a degree in error, I could not calculate accurately the position of a star for even ten years in advance. The error would be manifest. But I, and others, can now calculate for 150 years in advance to within a fraction of a second. I should like to know whether Mr. Upham has formed his conclusions on opinion or on calculation. If the latter, I shall be happy to compare our two calculations to see who is in error, and I would submit that some star, say Alpha Draconis, should have its right ascension and declination taken from Bradley's Catalogue of 1755, and from this one observation calculate its right ascension and declination for 1850 and 1890. I can predict that if Mr. Upham makes this calculation, he will soon find that the slightest error in his radius will produce a considerable error in his results. But we have Ptolemy's Catalogue of 140 A.D. for reference, so that 1750 years gives us a check on our work.

Again Mr. Upham says:—

The same arguments forbid its application to account for the Glacial epoch. . . . . as against Croll's theory. According to General Drayson, astronomical conditions capable of producing an Ice Age have occurred every 31,000 years.

This may be Mr. Upham's theory, but it is not mine; see chapter 17 of my book. I fear, however, I cannot quite agree with his logic. The daily rotation of the Earth fully explains the rising and setting of the various celestial bodies, but it fails to explain the changes in the Sun's midday altitude from summer to winter. Hence we ought to reject the daily rotation as an explanation of the rising and setting of celestial bodies, because it fails to explain summer and winter. I will give a few quotations from chapter 17 of my book. I have there pointed out that the present position of the Pole of second rotation is probably due to the position which the centre of gravity occupies relative to the Earth's centre. I then refer to the elevation or depression of land, or even of continents, causing the waters of the ocean to be distributed differently from what they are at present, and hence causing the centre of gravity of the Earth to slightly alter its

position, and hence causing the Pole of second rotation to alter its position. At page 258 I state:—

Now, a comparatively slight change in the position of the Poles of second rotation may produce a very great change in the climatic conditions during a second rotation.

At page 259 I state:—

To conclude, however, that because the Poles of the second axis of rotation are now 29° 25′ 47″ from the Poles of daily rotation, they must always have been so, no matter how much or how little the position of the centre of gravity of the Earth has varied, is unsound and is impossible.

At page 260 I state (with the aid of a diagram), that a small change in the position of the Pole of second rotation would cause an uniform climate on the Earth during many thousand years; and at page 261 I point out that the formation of coal beds, with sandstone and shale intervening, would be the results of a change in the position of the Pole of second rotation, yet Mr. Upham says, "According to General Drayson astronomical conditions capable of producing an Ice Age have recurred every 31,000 years."

It must be borne in mind that when the summer midday altitude of the Sun was 12° greater than at present, the heat in summer in *Polar regions* would have been much greater than at present. If more ice were formed in winter than could be melted in summer, there would be an annual increase of ice. If, however, the whole of the ice formed in winter were melted in summer, there would be no ice annually accumulated in high northern regions, especially where the ground was flat. Siberia and Alaska seem to meet these conditions, and it is probable that during the height of the Ice Age the regions *close to the Poles* were more free from ice than they are at present.

I refrain from venturing any remarks on the geological statements put forward by Mr. Upham. If I did so, I might soon show that I was writing on a subject with which I was only superficially acquainted. It does, however, seem to me that confirmation is required to prove that the Earth's surface was forced up 4,000 feet to cause the Ice Age, and that the weight of this ice pressed down the Earth's crust upon its "fused interior."

Professor James Geikie, at the end of his paper, vol. 26, page 248, *Journal of the Victoria Institute*, states:—

There are many other objections to the Earth's movement hypothesis which the limits of this paper forbid me entering upon. But those

already indicated may suffice to show that the hypothesis is not only baseless, but wholly fails to explain the facts, most of which in fact tell strongly against it. It accounts neither for the wide-spread phenomena of the Ice Age, nor for the remarkable climatic conditions of interglacial times.

Somewhat similar objections are apparent to me.

An important question for geologists to decide is whether one, two, or more second rotations occurred under such conditions as now prevail, viz., with a radius at, or near to, 29° 25′ 47″, or whether only one such second rotation took place, with no interglacial conditions. For my own part, I place more dependence on a geometrical proof, corroborated by recorded observations, and which states the dates when certain phenomena *must have occurred* long before these dates were suspected to be even approximate, than I do on any hypothesis framed to explain effects, when it has been found that these effects occurred at certain dates.

THE AUTHOR'S REPLY.

Respecting the greater part of the criticisms and questions brought forward in these discussions, no detailed reply seems to be needed. In part the different comments and communications sufficiently answer one another; and in other instances a careful reading of the paper will make my views more clear and perhaps more acceptable.

To Mr. Gooch it may be answered, in addition to the remarks of Professor Lobley, that the transmission of the earth's internal heat through the cooled crust appears to me certainly to have been so slow and of such small amount as to be quite unimportant in its influence on the mean temperature of the atmosphere during the late eras of geologic time mentioned, which far antedate the Ice age.

Professor Geikie's objections to my explanation of the causes of accumulation of continental ice-sheets were elaborately presented in his valuable paper in the twenty-sixth volume of this journal: and in the ensuing pages 254–256 of that volume, my answers to his arguments are stated, but less fully than here. It is my belief that the long continued pre-glacial uplift of the far

northern lands was attended, in its culmination, by a less prolonged high uplift of the more southern drift-bearing regions of North America and Europe, and of portions of the continents reaching much farther south, and that then the great ice-sheets of the Glacial period were amassed. But the elevation was followed by subsidence. Under the weight of the snow and ice, these lands were finally depressed somewhat below their present altitude, whereby, as I think, a warm temperate climate was restored, and the ice was gradually, and in a geological sense rapidly, melted away. Moderate fluctuations of the ice-front during its general recession, like those of alpine glaciers or of the Malaspina ice-sheet in Alaska, seem to me an adequate explanation of the inter-glacial beds. No more surprise need be occasioned by the occurrence of remains of warm temperate floras and faunas in these beds than we must feel in seeing tropical and temperate plants and animals at the foot of the Himalayas and the Alps. These extensive mountain ranges, frigid and largely snow-covered, doubtless exert as much influence on the climate of the contiguous valleys and lowlands as could be due to the waning ice-sheets of North America and Europe. Each of these ice-sheets, in its time of retreat, being wasted by a warm climate at its edge, probably rose to an altitude of 5,000 feet above the land within 100 or 200 miles back from the ice-border, which, therefore, might considerably re-advance during any series of exceptionally cool years, with plentiful snowfall.

Since my paper was written, Dr. George F. Becker, of the United States Geological Survey, has published the results of his recent mathematical investigation of the effects of the unequal amounts of solar heat received by different portions of the earth's surface, under varying astronomic conditions.* He cannot accept the theory of the late Dr. Croll, but agrees with General Drayson that increased obliquity of the ecliptic must favour snowfall and ice accumulation. The greatest possible obliquity, however, Dr. Becker believes to be 24° 36′, or only 1° 9′ more than now. His conclusions are stated as follows :—

> "I began this enquiry without the remotest idea as to what conclusion would be reached. At the end of it I feel com-

* *American Journal of Science*, III, vol. xlviii, pp. 95–113, August, 1894.

pelled to assert that the combination of low eccentricity and high obliquity will promote the accumulation of glacial ice in high latitudes more than any other set of circumstances pertaining to the earth's orbit. It seems to me that the Glacial age may be due to these conditions in combination with a favourable disposition of land and water. This theory implies, or rather does not exclude, simultaneous glaciation in both hemispheres. It does not imply that the Ice age should last only ten or twelve thousand years. . . . The date at which a minimum of eccentricity last coincided with a maximum of obliquity can almost certainly be determined. According to Stockwell, the obliquity has been diminishing for the past 8,000 years, and was within 21 minutes of its maximum value at the beginning of that time. According to Leverrier, the eccentricity passed through a minimum 40,000 years ago, the value being then about two-thirds of the present one. So far as I know, the obliquity has not been computed beyond 8,000. This can, of course, be done for Stockwell's value of the masses of the planets, or for newer and better ones. All the indications seem to be that within thirty or forty thousand years conditions have occurred, and have persisted for a considerable number of thousand years, which would favour glaciation on the theory of this paper."

After a careful consideration of Dr. Becker's investigation, and bearing in mind the difficulty of reconciling any astronomic theory with the uniqueness of the Glacial period, it seems to me that the ice accumulation was due chiefly to the pre-glacial high altitudes of continental areas, of which we have undeniable evidence in the fjords and submerged continuations of river valleys. To a less degree, as I think, the areas of glaciation were probably increased, or the boundaries of the ice-sheets may at times have retreated and re-advanced, because of varying astronomic conditions.