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LIII. *On the Physical Cause of the Glacial Epoch. By* E. FRANKLAND, *F.R.S., Professor of Chemistry in the Royal Institution**.

AMONGST the causes that have profoundly influenced the present physical condition of our earth, the action of ancient glaciers upon a scale of almost inconceivable magnitude has gradually but irresistibly forced itself upon the notice of philosophers, since their attention was first called to it by Venetz† in Switzerland, and Professor Esmark‡ in Norway. There are few elevated regions in any quarter of the globe which do not exhibit indubitable evidence of the characteristic grinding and polishing action of ice-masses, although at present perhaps they are scarcely streaked by the winter's snow. The researches of Dr. Buckland and others first revealed the evidence of this ancient glacial action in Great Britain; but it is especially to Professor Ramsay that we are indebted for our present extensive knowledge of the effects produced in this country during the glacial epoch. His explorations have demonstrated that the Highlands of Scotland, and the mountains of Wales and Cumberland, to which I would add the limestone crags of Yorkshire, abound in these *roches moutonnées*, which leave no doubt that the valleys of these mountain-ranges were once filled with glaciers of dimensions unsurpassed, if even equalled, by those which at the present day stream down the sides of their gigantic Swiss rivals. Not only was there this development of perennial ice where no such phenomenon is now observed, but the glaciers of the pre-

* Communicated by the Author.
† Transactions of the Swiss Natural History Society, vol. i. part 2 (1821).
‡ Edinburgh New Phil. Journ. vol. iii. (1827).

sent age existing in Switzerland, Norway, and elsewhere are evidently but the nearly dried-up streamlets of ancient ice-rivers of enormous size. These glaciers have eroded the alpine valleys of which they once held possession, have scooped out the lochs and kyles of Scotland, as well as the grander fjords of Norway, and have contributed in a most essential manner to the present aspect of our mountain scenery. Ramsay* and Tyndall have recently called attention to this action of ancient glaciers, and have contended, the former that the lake-basins, the latter that the valleys of the Alps have been scooped out of a comparatively uniform surface.

In no part of the world perhaps can the problem of the glacial epoch be more advantageously studied than in Norway, on whose ice-scarred coasts and fjords two of the essential portions of the glacial apparatus—the ocean and the mountains—are constantly and contemporaneously under the eye of the traveller. 2000 miles of coast, from Christiania to the North Cape, afford almost uninterrupted evidence of the vast ice-operations which, during the epoch in question, moulded nearly every feature of this remarkable country. In this respect Norway has already invited the researches of Esmark, Von Buch, and especially of Professor James Forbes, whose laborious explorations and acute philosophical reasoning have most materially increased our knowledge of the physical phenomena of Scandinavia. To his work on Norway and its glaciers I am indebted for many of the data employed in the following pages. It was likewise during a vacation trip to Norway last summer that I received the impressions regarding the physical cause of the glacial epoch which form the subject of this paper.

Starting from Christiania coastwise, the traveller cannot fail to remark the peculiar appearance of the gneiss and granite rocks composing the coast and the innumerable islands which, forming a natural breakwater, protect the mainland from the heavy seas rolling in from the Atlantic. These rocks, here rarely rising to the height of 800 or 900 feet, present nothing of that sharp and rugged outline which generally characterizes such formations; on the contrary, they are smooth even to their summits, all their angles worn off, and every trace of boldness and asperity effaced. To the casual and uninstructed observer the action of the sea suggests itself as a sufficient cause for these appearances: but it does not require much scrutiny to be convinced that the ocean waves have had little to do with this smoothing and polishing of the coast. The want of uniformity in structure and chemical composition of masses of gneiss and granite causes them to be unequally acted upon by water. The latter dissolves and disin-

* Quart. Journ. Geol. Soc. August 1862.

tegrates the more soluble and friable parts, producing a cellular or fissured surface according to circumstances, instead of the smoothed and comparatively polished condition which obtains on this coast. Such a weathering of the rocks can in fact be plainly seen in many places superposed upon the polishing due to the more remote agency of moving masses of ice. In short, it may be stated as a general proposition, that the action of the sea and weather upon rock produces a corrugated, irregular, and especially a fissured surface; whilst that of glacier-ice occasions a rounded, comparatively smooth and uniform appearance. If further proof of the exclusively glacial origin of the surface of the Norwegian coast-rocks be needed, it may be found, first, in the frequent occurrence of the scratchings and fine markings which so incontestably characterize rocky surfaces that have formed the bed of a glacier, and, secondly, in the circumstance that the smoothing action has evidently come as a rule from the direction of the land. All the surfaces inclined towards the land are invariably, as far as I have seen, rounded and polished, whilst in some places, where the rock descends precipitously towards the sea, it has been protected from the abrading action and presents merely a weathered surface.

Doubling the Naze and proceeding northward, the coast presents, with slight exceptions, the same general features until the arctic circle is approached, when the character of the scenery rather suddenly changes. The rocky hills acquire the dignity of mountains, and tower up in rugged, sharp, and fantastic peaks, contrasting strongly with the rounded summits of the lower latitudes. But these arctic peaks owe their immunity from the abrading action of ice solely to their height; around their bases, and even high up their sides, the slow surges of the moving sea of ice have made their unmistakeable marks, having ground and even undercut them into most extraordinary forms,—as instances of which I may mention the Seven Sisters, and Torghatten with its singular tunnel, south of the arctic circle, the Hestmand standing upon the circle, and the mountains of the Folden and Vest fjords, the latter having been graphically compared by Mr. Everest to the jaws of an immense shark.

It is important to determine the direction of the striæ upon these *roches moutonnées*. So far as my own observations go, they confirm the statement of M. Siljeström, that the abrading action proceeded generally in a N.W. direction; that is, from the land towards the sea. In cases where there was a variation from this general direction, some sufficient cause, such as the embouchure of a fjord, or the interposition of an obstacle seaward, presented itself. I could not, therefore, resist the conclusion that the masses of ice which caused these striæ moved down the mountain-slopes to the sea, and did not visit the coast as floating masses from the polar regions. I must not omit to state, however, that on this point Forbes inclines to a different opinion. He says*, "I cannot pronounce on the direction of the striæ, which I could not land to examine. It rather appeared to me, however, that on the coast at least the direction of friction, marked by the *stos* and *lee Seite*, was *parallel* to the coast and from north to south."

However this may be with regard to the coast, the exploration of several of the fjords convinced me that the ancient glaciers followed tracks leading them from the gathering-basins of the mountains by the nearest available route to the sea. The Hardanger, Romsdal, Trondhjem, Namsen, and Salten fjords exhibit everywhere the most unmistakeable evidence that they were once filled with vast glaciers, to which, in fact, those fjords without doubt mainly owe their existence. The Hardanger, with its modern glaciers which stream down from the *névé* of the Folge Fond, is a magnificent example of the channel of an ancient ice-river. Wherever its rocky shores are bare, they are scored with the characteristic flutings; the position of the latter, and the freedom from abrasion of those surfaces which are precipitously inclined towards the mouth of the fjord, plainly proclaim the direction in which this gigantic glacier moved. In the Romsdal, at the head of the fjord of that name, the evidence of former glacial action is perhaps still more striking, because it concentrates itself more closely around the traveller. As far as the eye can define, up the precipitous walls of this grand ravine, the rocks are grooved and planed down by the action of moving ice; and immense gneiss blocks which now lie at the bottom of the gorge, but whose former position can be traced to near the summit of the precipices, show by the smoothed and streaked character of their formerly exposed sides, either that this gorge was once completely filled with ice, or that it was gradually scooped out by a glacier of more moderate thickness.

It was natural that these accumulating evidences of a former condition of the surface of our planet, so different from that which now obtains, should call forth various hypotheses intended to account for a thermal state which permitted the occupation, by such vast masses of ice, of tracts of land which now frequently yield rich pasturage and luxuriant crops. It was suggested by Fourier that the temperature of space is not uniform; and that our solar system, in performing the proper motion among the stars which is believed to belong to it, sometimes passes through regions much colder than others. According to this hypothesis, the glacial epoch occurred during the passage of our system through a comparatively cold portion of space. Some

* Norway and its Glaciers, p. 46.

have imagined that the heat emitted by the sun is subject to variation, and that this epoch was the result of what may be termed a cold solar period. Mr. W. Hopkins believes that a different distribution of land and water, and especially a different direction of the currents of warm water which set from the tropical towards the polar oceans, would render the climate of certain localities colder than it is at present, and would thus sufficiently account for the phenomena of the glacial epoch. Finally, Professor Kämtz* considers that at the time of the glacial period the mountains were much higher than at present, Mont Blanc reaching an altitude of 20,000 feet for instance, the secondary and tertiary formations having been removed from their summits during the glacial epoch.

The two last assumptions are attended with formidable geological difficulties, especially when it is considered that the phenomena of the epoch in question extended over the entire surface of the globe; they have therefore never acquired more than a very partial acceptance†. The first two hypotheses, again, have been recently shown by Tyndall to be founded upon an entirely erroneous conception of the conditions necessary to the phenomena sought to be explained. The formation of glaciers is a true process of distillation, requiring heat as well as cold for its due performance. The produce of a still would be diminished, not increased, by an absolute reduction of temperature. A greater differentiation of temperature is required to stimulate the operation into greater activity. Professor Tyndall does not suggest any cause for such exalted differentiation during the glacial epoch; but he proves conclusively that both hypotheses, besides being totally unsupported by cosmical facts, are not only incompetent to constitute such a cause, but also assume a condition of things which would cut off the glaciers at their source, by diminishing the evaporation upon which their existence essentially depends. Only by a greater difference of temperature between land and ocean is an increase of glacial action possible; and these hypotheses fail, inasmuch as they ignore altogether the necessity for such an augmentation of thermal difference.

* *Mittheilungen der k.-k. geographischen Gesellschaft zu Dorpat*, vol. ii.

† Speaking of the glacial epoch, Ramsay says (Quart. Journ. Geol. Soc. for 1862, p. 204), "I find it difficult to believe that the change of climate that put an end to this could be brought about by mere changes of physical geography. The change is too large and too universal, having extended alike over the lowlands of the northern and the southern hemispheres. The shrunken or vanished ice of mountain-ranges is indeed equally characteristic of the Himalaya, the Lebanon, the Alps, the Scandinavian chain, the great chains of North and South America, and of other minor ranges and clusters of mountains like those of Britain and Ireland, the Black Forest, and the Vosges."

This will be apparent from a consideration of the functions of the three essential parts of the great natural glacial apparatus, viz. the evaporator, the condenser, and the receiver. The part performed by the ocean as the evaporator is too obvious to need description. The two remaining portions of the apparatus, however, are generally confounded with each other. The mountains are in reality the receivers or *ice-bearers*, and are only in a subordinate sense condensers. The true condenser is the dry air of the upper region of the atmosphere, which permits of the free radiation into space of the heat from aqueous vapour*, the latter, as proved by Tyndall's recent researches, possessing extraordinary powers of radiation and absorption. He has shown that the watery vapour at the upper surface of a stratum of air saturated, or nearly so, with moisture, must rapidly radiate its heat into space and condense to rain or snow, according to the temperature of the surrounding atmosphere, dry air being almost completely powerless to arrest this radiation. Thus it is that the enormous amount of heat developed by the condensation of aqueous vapour is got rid of without any appreciable elevation of the temperature of the medium in which the operation occurs. That this process of condensation must be most active and important in meteorological phenomena can scarcely be doubted, when it is considered that the great accession of heat to the surrounding atmosphere, which occurs when aqueous condensation takes place from any other cause, must soon put a stop to the further deposition of moisture under such circumstances. Thus the condensation of one cubic foot of water at 40° from aqueous vapour at 32° F. would raise the temperature of 352,053 cubic feet of air through 10°. Such an enormous accession of heat, where condensation takes place without radiation, could not fail promptly to arrest the process.

Thus the condenser is an apparatus perfectly distinct from the

* I have devised a simple mode of experimentally demonstrating the radiation from aqueous vapour, so that the effect can be seen by a large number of persons at once. A charcoal chauffer, 14 inches high and 6 inches in diameter, is placed about two feet from, and in front of, a thermo-electric pile, the radiation from the chauffer and fuel being carefully cut off from the pile by a double metallic screen. The deflection of the galvanometer due to the radiation from the ascending and heated carbonic acid being now carefully neutralized by a constant source of heat radiating upon the opposite face of the pile, a current of steam is made to ascend through an iron tube passing vertically through the chauffer. Instantly the galvanometer deflects for heat much more powerfully than it did previously to its compensation, when it was exposed to the full radiation from heated air and carbonic acid. When the current of steam is interrupted, the needle immediately returns to zero. If now a current of air be forced up the central tube instead of steam, either no deflection at all, or a slight one for cold occurs. The heat of the chauffer effectually prevents any condensation of the steam.

ice-bearer, which last occupies in fact the position of the receiver in ordinary distillation; and hence so long as the temperature of the ice-bearers, inclusive of the surrounding atmosphere, does not rise above 0° C., their functions remain intact. Other things equal, an ice-bearer at 0° C. is scarcely surpassed in efficiency by one at −15° C. But it must be borne in mind that the actual efficiency of an ice-bearer, on an annual average, is dependent upon the length of time during which its temperature does not rise above the freezing-point. Hence it is that those mountains which penetrate furthest into the increasingly cold heights of the atmosphere are most efficient,—not because their temperature is sometimes far below the freezing-point, but because they maintain a temperature below that point throughout a greater portion of the year.

These considerations lead to the conclusion that, assuming the supply of aqueous vapour to the atmosphere to remain constant, increased condensation could only arise from greater facilities for the radiation from that aqueous vapour into space,—a condition which involves cosmical changes of which we have not the slightest evidence. On the other hand, as the powers of the radiating condenser are at the present moment far from being taxed to the utmost, the more copious supply of aqueous vapour to the atmosphere would at once produce a corresponding increase of condensation. Such an increased supply of aqueous vapour, extending over a considerable period of time, could only arise from the association of a greater amount of heat with the waters of the ocean. But all the hypotheses hitherto propounded to account for the glacial epoch have failed to recognize this feature of the problem, inasmuch as they have all assumed that cold alone was necessary to the development of the phenomena of that epoch. This important omission must serve as my apology for advancing a new hypothesis, which necessarily rests in some respects upon data as yet imperfectly ascertained, and which has gradually elaborated itself out of the impressions I received during my recent visit to Norway. Any such theory must take cognizance of the following points in the history of the glacial epoch. 1st. That its effects were felt over the entire globe. 2nd. That it occurred, or at least terminated at a geologically recent period. 3rd. That it was preceded by a period of indefinite duration, in which glacial action was either altogether wanting, or was at least confined to regions of considerable altitude. 4th. That during its continuance, atmospheric precipitation was much greater, and at one period the height of the snowline considerably less than at present. 5th. That it was followed by a period extending to the present time, when glacial action became again insignificant.

All these conditions would be the natural sequences of a gradual cooling of the ocean from a higher down to its present temperature. *The sole cause of the phenomena of the glacial epoch was a higher temperature of the ocean than that which obtains at present.*

This hypothesis rests chiefly upon the two following propositions:—

1st. That a higher oceanic temperature would give rise to an increased evaporation, and consequently to an augmented atmospheric precipitation.

2nd. That this increased atmospheric precipitation would augment the average depth of permanent snow upon the ice-bearers, and would, within certain limits, depress the snow-line.

Let us now examine these propositions in detail. As a general proposition, the first is an indisputable truth, and it is therefore only necessary to inquire into the extent to which oceanic evaporation would be thus affected. The rate of evaporation of water at different temperatures and under various circumstances was determined by Dalton, whose results are embodied in the following Table. The evaporation took place in each case from a circular surface 6 inches in diameter:—

Temp. F.	Evaporation per minute in calm.	Evaporation per minute in breeze.	Evaporation per minute in high wind.
°	grs.	grs.	grs.
85	4·92	6·49	8·04
75	3·65	4·68	5·72
65	2·62	3·37	4·12
55	1·90	2·43	2·98
45	1·36	1·75	2·13
35	·95	1·22	1·49

We have no sufficient data for calculating the present mean temperature of the ocean; but in lat. 69° 40′, off the coast of Norway, at noon on a remarkably hot summer's day, Forbes found the surface temperature to be 46°·5 F. The assumption of 40° F. as the mean temperature off the coast of Norway will therefore probably be in excess of the truth. Now, taking the mean of Dalton's results obtained at 35° and 45°, the evaporation in each minute from a circular surface 6 inches in diameter would be at 40°:—

In calm.	In breeze.	In high wind.	Mean.
1·15 grain.	1·48 grain.	1·81 grain.	1·48 grain.

And further, the evaporation from a similar surface at 60°, according to the mean of the results obtained by Dalton at 55° and 65°, would be as follows:—

In calm.	In breeze.	In high wind.	Mean.
2·26 grains.	2·90 grains.	3·55 grains.	2·90 grains.

These absolute numbers were obtained with dry air, and therefore they cannot be taken as representing the *actual* evaporation from a surface of water like that of the ocean, which is in contact with air of ever-varying hygrometric qualities. All I contend for is, that Dalton's numbers represent, under similar conditions in the two cases, the *relative*, but not the absolute evaporation from a given oceanic surface; and this being granted, it follows that an elevation of 20° F. above the present temperature of the ocean bathing the shores of Norway would double the evaporation from a given surface. Such an increased evaporation, accompanied as it necessarily must be by a corresponding precipitation, would suffice to fill the fjords and cover the western coast of that country with ice, provided that the ice-bearers were in a sufficiently effective condition. But would not the increased oceanic temperature tend to augment the mean temperature of the atmosphere even at considerable elevations, and thus to raise the snow-line and reduce the area of perpetual snow?

The reply to this question is contained in the second of the above propositions. That the limit of perpetual snow does not entirely depend upon the mean temperature of the atmosphere at that particular elevation is conclusively proved by the very different mean temperature of the snow-line in various localities. Thus, under the equator it is about 35°; in the Alps and Pyrenees 25°; and, according to Von Buch, in lat. 68° in Norway, it is only 21°*. These numbers are very instructive: why does the mean temperature of the snow-line rise as we approach the equator? The answer to this question has been already given by Mr. Hopkins in his admirable memoir on the Influence of the Earth's Secular Heat upon Climate†. He considers that the low snow-line in the tropics is due to a more equable temperature and greater atmospheric humidity. The deluges of rain which fall within the tropics far surpass the precipitation in the temperate and frigid zones; and doubtless the fall of snow upon most intertropical mountains is proportionately great. The important influence which the amount of precipitation alone exercises upon the lower limit of perpetual snow is strikingly exemplified at the fine waterfall of Tysse Strenger near the head of the Hardanger Fjord, and was first noticed by Mr. M. Williams‡. The spray from this fall, being frozen in winter, covers the valley for nearly half a mile with a stratum of snow and ice so thick as to defy the solar

* Humboldt's *Cosmos*, vol. i. p. 9. Forbes's 'Norway,' p. 205.

† Geological Society's Journal, vol. viii. p. 78.

‡ Through Norway with a Knapsack.

rays of summer to melt it. I have also seen in the Sör Fjord, under similar abnormal conditions, a mass of snow lying early in August last, within 10 feet of the level of the sea, although the normal snow-line is there at least 4500 feet above the sea-level. Mr. Hopkins calculates that the snow-line near the equator is 1000 feet lower than the mean line of 32°, whilst in the Alps and at the Arctic Circle it is respectively 2000 and 3500 feet higher than the line of 32°. Hence by the influences above mentioned, the snow-line at the equator is brought down no less than 4500 feet below its thermal position at the Arctic Circle; and therefore, with the equatorial precipitation, and a more equable temperature than at present, the snow-line in Norway would descend to the sea at the Arctic Circle from its present position of between 3000 and 4000 feet above the ocean. This essential dependence of the height of the snow-line upon the amount of precipitation and equable temperature is also confirmed by its comparative height on the coast and in the interior of the Scandinavian peninsula, as given by Forbes in the following Table, compiled partly from his own observations, and partly from those of Von Buch, Naumann, and others*:—

Latitude.	Height of snow-line in feet.		
	Interior.	Coast.	Difference.
60°	5500	4450	1050
62	5200	4150	1050
64	4200	3650	550
66	3700	3250	450
68	3450	3000	450
70	3350	2900	450

Thus the difference between the height of the snow-line near the coast, where, owing to the impact of the Gulf-stream, the winter is mild but the atmospheric precipitation great, and in the interior, where the climate is one of extremes, and the air is comparatively dry, amounts in some cases to as much as 1050 feet, or nearly one-fourth of the total height. Nor must it be forgotten, in connexion with this depression of the snow-line, that copious precipitation is altogether incompatible with great summer heat. The incessantly clouded sky cuts off the solar rays and moderates the summer temperature. It is a trite observation, that a wet summer is always a cold one.

Whilst, therefore, the tendency of augmented oceanic warmth would be to raise the mean temperature of the limit of perpetual snow, there would nevertheless be, within certain limits, a

* Norway and its Glaciers, p. 214.

depression of the snow-line itself from the attendant circumstances just enumerated: viz., 1st, from increased precipitation, which would cause such an accumulation of snow during the winter months, as would defy the heat of the succeeding summer to melt; for it must be borne in mind that the amount melted is proportional, not to the mass, but to the surface exposed to the thawing influence; and 2nd, from the reduction of summer temperature, owing to the interception of the sun's rays by an overcast sky. But it is evident that this lowering of the snow-line by increased oceanic temperature could only occur within certain limits; for although the mean temperature of the snow-line might rise from 21° (its present position in Norway) to 35°, its height under the equator, and perhaps even still higher, without any elevation of the snow-line itself, yet a further rise of mean temperature, which would result from a continued augmentation of oceanic heat, could not fail to elevate the snow-line itself, and eventually to chase the last portions of snow even from the loftiest mountain peaks. A process the inverse of this I believe to have gone on in nature, leading gradually to the so-called glacial epoch, and eventually to the present meteorological condition of our globe. The ocean once possessed a temperature so high that the snow-line floated above the summits, possibly even of the most lofty mountains; but with the reduction of oceanic warmth it gradually descended, enveloping peak after peak in a perennial mantle, until during the most severe portion of the glacial epoch it attained its lowest depression, whence it again rose to its present position, owing to diminished evaporation, the effect of which, in elevating the line of perpetual snow, has already been explained.

Having thus endeavoured to prove that all the phenomena of the glacial epoch would be normally evolved by the gradual cooling of the ocean from a higher degree of heat down to its present temperature, it remains for me to suggest a cause of such a higher oceanic temperature, and to remove certain geological and palæontological objections which may be urged against this hypothesis.

First, as regards the cause of the assumed higher temperature, it may be stated as an exhaustive proposition that the accession of heat must either have been from without, from a cosmical source, or from within, that is, of secular origin. Now only two cosmical causes of the variation of terrestrial temperature have yet been suggested; and to these I have already alluded. The first of them, viz. the hypothesis which assumes that our solar system may have passed through portions of space in which it would receive more heat-radiations from the stars, has been elaborately reviewed by Mr. Hopkins in the memoir already quoted, and he has conclusively shown it to be quite untenable on astronomical grounds. The second requires some consideration, since it is by no means improbable that the sun was once a more active radiator of heat than he is at present, although the assumption that this should have been the case to a marked extent so recently as the close of the glacial epoch is in the highest degree improbable. It might be anticipated that an augmentation of solar energy would increase the temperature of the oceanic surface, and probably not interfere much with the functions of the radiating condenser, the luminous heat-rays of the sun not having yet been proved to be much absorbed by aqueous vapour. But it would doubtless greatly impair the efficiency of the ice-bearers, whose powerfully absorbent surfaces would, under increased solar radiation, be less able to maintain the necessary low temperature. Fortunately, however, it is not necessary to rely upon conjecture in this matter, for the demonstration is constantly before us, in the comparative effects of solar radiation upon glacial phenomena in the different terrestrial zones. The solar radiation within the tropics is augmented as compared with that of the temperate and frigid zones, but this augmentation does not bring on a glacial epoch in the torrid zone; on the contrary, although the snow-line is, as above stated, depressed as regards the line of 32°, yet both are irresistibly driven up the mountains.

Thus no cosmical source of heat is competent to produce the phenomena of the glacial epoch, and there remains therefore only the well-known secular source—the internal heat of the earth. The problem of the influence of the earth's internal heat upon the surface temperature has been most ably discussed by Mr. Hopkins* and Professor W. Thomson†. Taking the result of Poisson's calculation, that the part of the earth's present superficial temperature due to primitive heat amounts to only one-twentieth of a degree Fahrenheit, Professor Hopkins proves that the augmentation of surface temperature from this cause to the extent of 10° F. would involve a descending rate of increase so rapid as to reach 200° F. at a depth of only 60 feet,—a physical condition of our planet which would, as he remarks, scarcely be consistent with the conditions of animal life at the more recent geological epochs. Assuming Poisson's datum to be correct, this result is probably indisputable, as applied to the solid surface of our planet; but it is not necessarily so when extended to the floor of the ocean. Indeed there are some considerations regarding the transmission of heat through a thick stratum of water, which appear to me to render this calculation totally in-

* Journ. of Geol. Soc. vol. viii. p. 56; and Phil. Trans. 1857, p. 805.

† Transactions of the Royal Society of Edinburgh, vol. xxiii. p. 157.

applicable to the determination of the past influence of internal heat upon the surface temperature of the ocean. There are four circumstances which require consideration in attempting to realize the thermal condition of the ocean during the cooling of the earth's crust. These are, first, the conductivity of water; secondly, its convection; thirdly, its power of penetrating into any chasms or dislocations that might be formed from time to time in the floor of the ocean; and fourthly, its specific heat.

With regard to the conductivity of water, the determinations of Despretz* show that, compared with the conductivity of the solid crust of the earth, it may be regarded as a vanishing quantity. But this almost total absence of conducting-power is more than compensated for by fluid convection. If the ocean were free from lateral currents, however, even this convection would not be much superior to the conductivity of granite in transmitting heat to the surface; for if we assume the average depth of the sea to be five miles, then, even if its temperature at the bottom were 100° C., and that at the surface 15° C., we should only have a difference of ·0032° C. for each foot of ascent. There are no determinations of the velocity of convection in sea-water for given differences of temperature, but, for the small foot-difference contemplated, it must be almost inconceivably small. Nevertheless it can scarcely be doubted that the polar and equatorial currents aid this vertical convection to such an extent as to render the total transfer of heat from the floor to the surface of the ocean considerably more rapid than that which would take place through a solid stratum of granite of the same thickness. I have endeavoured roughly to determine the relative powers of water and granite in thus transmitting heat. For this purpose a 6-inch cube was cut out of a block of granite, and a vessel of tin plate was prepared capable of holding a similar cube of water covered with a layer of oil $\frac{1}{10}$th of an inch thick to prevent evaporation. Both cubes were placed upon an iron plate heated below by an atmosphere of steam, their vertical sides being protected from loss of heat by several folds of flannel. Into each of their upper surfaces, which were exposed to the air, the bulb of a thermometer was imbedded, and the time required to elevate the surface temperature 10° C. was noted. The following are the results of these experiments:—

		h	m
Time required to raise temperature of surface of granite cube through 10° C. . . .	=	1	10
Time required to raise temperature of surface of water cube through 10° C. . . .	=		57

* *Ann. de Chim. et de Phys.* vol. lxxi. p. 206.

It is necessary to mention that the surface of the tin-plate cube in contact with the hot plate was coated with a film of lampblack, and that the surfaces of the granite were only roughly ground and not polished; in fact all the experimental conditions were in favour of the transmission through water, and yet the surface temperature of the latter did not rise with much greater rapidity than that of the former. Now taking into account the specific heats and gravities of water and granite, the amount of heat transferred from the base to the summit of each block will be in the following proportion for equal times:—

Granite : Water.
1 : 2·36.

Although these determinations can only give a rough approximation to the respective velocities with which heat passes through strata of granite and water, yet they show that the convection of heat through the latter is by no means so rapid, when compared with its conduction through granite, as is commonly supposed. There can be no doubt that, in the case of the ocean, the rapidity of transfer would be increased by polar and equatorial currents; nevertheless the assumption that the cooling of the floor of the ocean proceeded as rapidly as if it had been freely exposed to the air is altogether untenable; and I conceive it not only possible but probable that this secular cooling of the earth through the ocean may have continued down to a comparatively very recent geological period, and may, even at the present day, not be altogether interrupted.

The greater facility with which heat is thus conveyed through water would obviously render the rate of downward increase of warmth for a given surface temperature much less rapid than in the case of granite. Thus I consider it probable that the internal heat of the earth affected in a very marked degree the surface temperature of the ocean long after it had ceased to influence appreciably the external warmth of the land. This assumption acquires considerable support from a consideration of the conditions tending to retard the escape of heat from the oceanic surface as compared with that from the land. The facility with which radiant heat escapes from equal surfaces of water and granite at the same temperature through perfectly dry air is nearly equal; but so soon as aqueous vapour is interposed in the path of these rays, the conditions become wonderfully altered; the escape of heat from both is diminished, but its radiation from the water is retarded in by far the greatest degree. This extraordinary intranscalency of aqueous vapour to rays issuing from water has been conclusively proved by Tyndall in a paper just communicated to the Royal Society*.

* Proceedings of the Royal Society, vol. xiii. p. 160.

Whether we take into consideration, therefore, the diffusion of heat through water and granite, the quality possessed by the ocean of abstracting heat, through the agency of dislocations, &c., from depths still more profound than its own floor, or finally the respective facilities with which, under the cosmical conditions contemplated, water and granite throw off their heat into space, we find everywhere a state of things tending not only to the greater conservation of the heat of the water, but also to a less rapid increase of temperature from the surface downwards, than is the case with the solid crust of the globe; and this applies also, *mutatis mutandis,* to the retention of that heat which is received from solar radiation. The luminous heat-rays of the sun pass freely through aqueous vapour, and are absorbed by both granitic and oceanic surfaces; but once absorbed, these rays issue forth again as obscure heat of two different qualities, or rates of vibration. To use Tyndall's explanation of the phenomenon, the vibrations of the liquid water-molecules are of such rapidity as can be best taken up and absorbed by the same molecules in the vaporous condition. But granite is a very complex substance, and fewer of the heat-oscillations of its atoms are in unison with those of aqueous vapour; hence the heat-vibrations of granite disturb the molecules of aqueous vapour in their passage through the atmosphere in a less degree, and consequently the granite rays are less absorbed.

Thus the chief process by which the ocean lost heat was evaporation; for this, as is well known, proceeds at a surface of water until the superambient air is saturated with vapour. The latter, by virtue of diffusion, rises into the presence of the dry-air condenser, there to yield up its latent heat and be converted into rain or snow, according to the temperature of the medium in which the radiating process takes place. Hence the one heat-dissipating process of which the water is most capable, is that by which the ice-bearers are provided with their snowy burthen.

Objections.—To the hypothesis which I have endeavoured to develope in the preceding pages, I am aware that, in addition to those already alluded to, several objections may be urged which appear at first sight very formidable, but which, I think, lose this character, to a great extent at least, when more closely investigated.

1. Perhaps the most palpable of these objections is one which may be taken to my statement that a more copious atmospheric precipitation would cause a greater accumulation of snow upon elevated portions of land, and thus depress the snow-line. It may be urged that although such an increased atmospheric precipitation would have the effect of depositing more snow in

winter, yet the corresponding heavy fall of rain in summer would again liquefy the excess of snow so deposited. In reply to this objection, it might perhaps be sufficient to oppose the facts above given, regarding the comparative height of the snow-line in adjacent moist and dry localities; but I may also add in explanation of these facts, that a comparatively very large quantity of even warm water is required to melt snow or ice. In fact, as is well known, the amount of heat requisite merely to melt them would, if no melting occurred, raise their temperature to 174° F. Let us suppose that upon any given ice-bearer the precipitation throughout the entire year was doubled, that during six months of the year this increased precipitation occurred in the form of snow at 32° F., and that during the remaining six months it fell in the form of rain at 50° F.; still, even with these conditions, so manifestly unfair towards the ice-bearer, very little more than one-eighth of the additional snow would be melted by the warm rain. In fact it requires nearly eight tons of water at 50° F. to melt one ton of snow or ice, even when the latter is already in a thawing condition. Forbes considers that not more than one-fiftieth of the snow upon the snow-fields of Norway is liquefied by the rains of summer; whilst M. Durocher has calculated, from observations made at the convent of St. Bernard in Switzerland, which is slightly *below* the snow-line, that not more than one-ninetieth of the annual snow is dissolved by the rain. Thus the effect of summer rain in melting the snows of winter is comparatively insignificant.

2. Is it not a necessary consequence of this hypothesis that the ocean must have possessed a temperature incompatible with animal life at the comparatively remote protozoic period? This question doubtless raises the most formidable of the objections that can be brought against my view; nevertheless there are several considerations which deprive it of much of its force. Judging from purely geological evidence, the period which has elapsed since marine life first made its appearance, compared with that intervening between the glacial epoch and the present time, would probably not be under-estimated at 1000 : 1; consequently it would appear to be evident that if the ocean has cooled through, say 20° F. during a unit of time, it must have been at a boiling temperature at a far less distant period than 1000 such units. There are three circumstances, however, which forbid such an unqualified deduction. In the first place, the excessive evaporation of water at temperatures not far removed from the boiling-point would rapidly reduce the ocean and its floor to a comparatively moderate temperature. Secondly, the excessive precipitation which must have occurred in the preglacial periods must have accelerated the deposition of most of the sedimentary rocks

to such an extent as to render the proportion above given between the pre- and post-glacial periods considerably too great. Thirdly, the advent of the severer portion of the glacial epoch would necessarily effect a rapid refrigeration of the ocean, and thus magnify the cooling effected during the post-glacial unit of time.

The experiments of Dalton on the rate of evaporation at different temperatures serve to illustrate the truth of the first of these considerations. He found, and his results were afterwards confirmed by Daniell, that the rate of evaporation increases in a geometrical progression with equal increments of sensible heat. From the same cause, the deposition of most of the pre-glacial sedimentary rocks must have also proceeded at a much more rapid rate than that which has obtained since the glacial epoch; in fact the rate of deposition depends so essentially upon the amount of precipitation, as to render it by no means improbable that the rate of decrease from a certain point down to the glacial epoch was also approximately a geometrical one: thus the proportion between the pre- and post-glacial zoic periods would be considerably reduced. Finally, the descent of the snow-line to the level of the sea along an immense length of coast during the glacial epoch must have had the effect of very rapidly reducing the temperature of the ocean, since the precipitation upon the land, instead of reaching the sea after being warmed at the expense of solar heat, would now be thrown into the ocean, partly as ice-cold water, but chiefly as ice itself; and every ton of the latter in melting would cool more than fourteen tons of sea-water through 10° F. It must also be borne in mind that this ice-cold water would not float on the surface, as in a freshwater lake, but would at once sink into the subjacent warm water, because the point of maximum density of sea-water is, according to Despretz*, 6°·6 F. below the freezing-point of pure water. Thus, taking all these circumstances into consideration, and assuming that the ocean has lost as much as 20° F. of heat since the glacial epoch, I conceive it possible that there would still be a sufficient interval, between a temperature incompatible with marine animal life and that epoch, for the development of the various organisms inhabiting the pre-glacial seas. In the case of land animals and plants no such difficulty arises, since, as already explained, the surface temperature was, during the whole of the period contemplated, very little affected by the internal heat of the earth.

3. Recent research has led some geologists to the conclusion that glacial action existed in the Miocene and even so far back as the Permian period; and although the evidence upon which this conclusion rests is by no means generally accepted by geo-

* *Ann. de Chim. et de Phys.* vol. lxx. p. 45.

logists, still I may as well here remark that such comparatively remote glacial action is perfectly compatible with the views I am here advocating. It is in fact a necessary consequence of these views, that the so-called glacial epoch should not be a sharply limited period, although its termination, for the reasons just given, would probably be much more definite than its commencement. I have already argued that perpetual snow would first tip the mountain peaks, and then slowly and gradually descend to the sea-level. But it must be borne in mind that during the whole of the pre-glacial period the atmospheric precipitation was even greater than during that period, and consequently wherever the land rose well above the snow-line, glaciers, on a scale far surpassing any of the present time, would be the inevitable consequence. It is, I believe, exceedingly difficult for a geologist to reconstruct even an approximation to the contour lines of land during the Permian period. Nevertheless in suggesting a glacial episode during this period, Ramsay* believes that he has considerable evidence of the existence of a range of hills whence these glaciers descended.

Such considerations respecting the pre-glacial period present to us a vivid picture of the then terrestrial climate. The shores of the warm seas would possess a genial and remarkably equable temperature, the air always warm and moist, the earth screened from the summer's sun by a clouded sky, and protected from the cold of winter by a canopy of transparent aqueous vapour, impervious to terrestrial radiation. Receding from the coast on level ground, these peculiarities would become gradually fainter; but on a somewhat steep shore the approximation of warm and cold climates must have been much closer than at present. The rivers and lakes fed by mountain-snows would also present a marked contrast to the surrounding lowlands—thus exhibiting within a narrow region a wide range of temperature, adapted to the thermal habits of widely different organisms.

As the glacial epoch approached, this genial zone would be gradually narrowed by the progressive descent of the snow-line; for although the actual amount of heat in activity at the surface of the earth was greater during the glacial period than subsequently, yet the cold of winter became stored up in masses of falling snow, which in melting absorbed the heat of the succeeding summer, and thus reduced both the mean and summer temperature of such tracts of land as were not situated greatly below the snow-line. Nor was this downward march of a frigid climate arrested even by the ocean itself, but the vast flow of glacial ice into the sea formed a belt of cold water along the shores, where many marine organisms that have left their traces

* Proceedings of the Geological Society, August 1855.

in the glacial drift found a congenial temperature. The common notion, therefore, that the glacial epoch was a cold period is correct, although heat, and not cold, was the *cause* of that epoch. This apparent paradox, that heat should be the cause of cold, finds its parallel in the ice-making machines which were in operation at the last Great Exhibition. In those machines, which produced from 2 to 12 tons of ice per ton of coal, the glacial produce was directly proportional to the amount of heat developed by the combustion of coal.

Such are the principal objections to my hypothesis which have occurred to myself or been suggested by others; and although I have thus endeavoured to remove them, yet it would be idle to deny that some of them retain considerable force, or that others, perhaps even more formidable, may occur to the minds of those who possess a far more extensive knowledge of the phenomena of the glacial epoch than I can pretend to. No hypothesis can be considered as of any value until it has been thoroughly sifted, and by the result of this necessary process the one I have now ventured to suggest must either stand or fall. Meanwhile it commends itself by requiring the assumption of no natural convulsion or catastrophe, no vast or sudden upheavals or depressions, and no change in the thermal relations of our earth to the sun or to space. On the contrary, it insists that the glacial epoch was normally and gradually evolved from a thermal condition of the interior of our globe which can scarcely be said to be any longer the subject of controversy.

In conclusion, this hypothesis suggests the probability that the other bodies belonging to our solar system have either already passed through a similar epoch or are destined still to encounter it. With the exception of the polar ice of Mars and the bright clouds of Jupiter, we have hitherto obtained no certain glimpse into the thermal or meteorological condition of the planets: neither is the physical state of their surfaces accessible to our best telescopes. It is otherwise, however, with the moon, whose distance is not too great to prevent the visibility of comparatively minute details. A careful observation of the lunar surface for more than a year with a silvered-glass reflector of 7 inches' aperture and of good defining power, has created in my mind an impression that our satellite has, like its primary, also passed through a glacial epoch, and that several at least of the *valleys*, *rills*, and *streaks* of the lunar surface are not improbably due to former glacial action. Notwithstanding the excellent definition of modern telescopes, it cannot be expected that other than the most gigantic of the characteristic details of an ancient glacier-bed should be rendered visible. Under favourable circumstances the terminal moraine of a glacier attains to enormous dimensions;

and consequently, of all the marks of a glacial valley, this would be the one most likely to be first perceived. Two such terminal moraines, one of them a double one, appear to me to be traceable upon the moon's surface. The first is situated near the termination of that remarkable streak which commences near the base of Tycho, and passing under the south-eastern wall of Bullialdus, into the ring of which it appears to cut, is gradually lost after passing crater 216 (Lubinietzky). Exactly opposite the last crater, and extending nearly across the streak in question, are two ridges curved towards the north, and reminding the observer of the concentric moraines of the Rhone Glacier. Beyond the second and outermost ridge a talus slopes gradually down northwards to the general level of the lunar surface. These ridges are visible for the whole period during which that portion of the moon's surface is illuminated; but it is only about the third day after the first quarter and at the corresponding phase of the waning moon, when the sun's rays, falling nearly horizontally, throw the details of this part of the surface into strong relief, that these appearances suggest the explanation now offered.

The other ridge answering to a terminal moraine occurs at the northern extremity of that magnificent valley which runs past the eastern edge of Rheita. This ridge is nearly semicircular, and is considerably elevated, both above the northern termination of the valley, and the general surface of the moon. It may be seen about four days after new and full moon; but the position of the observer with regard to the lights and shadows renders its appearance in the rays of the rising sun by far the most striking.

With regard to the probability of former glacial or even aqueous agency on the surface of the moon, difficulties of an apparently very formidable character present themselves. There is not only now no evidence whatever of the presence of water, in any one of its three forms, at the lunar surface, but, on the contrary, all seleniographic observations tend to prove its absence. Nevertheless the idea of former aqueous agency in the moon is by no means new; it was entertained by Gruithuisen and others. But if water at one time existed on the surface of the moon, whither has it disappeared? If we assume, in accordance with the nebular hypothesis, that the portions of matter composing respectively the earth and the moon once possessed an equally elevated temperature, it almost necessarily follows that the moon, owing to the comparative smallness of its mass, would cool much more rapidly than the earth; for whilst the volume of the moon is only about $\frac{1}{49}$th, its surface is nearly $\frac{1}{13}$th that of the earth.

This cooling of the mass of the moon must, according to all analogy, have been attended with contraction, which can scarcely be conceived as occurring at considerable depths without the development of a cavernous structure in the interior. Much of this cavernous structure would doubtless communicate by means of fissures with the surface, and thus there would be provided an internal receptacle for the ocean, from the depths of which even the burning sun of the long lunar day would be totally unable to dislodge more than traces of aqueous vapour. Assuming the solid mass of the moon to contract on cooling at the same rate as granite, its refrigeration through only 180° F. would create cellular space equal to nearly $14\frac{1}{2}$ millions of cubic miles, which would be more than sufficient to engulf the whole of the lunar ocean, supposing it to bear the same proportion to the mass of the moon as our own ocean bears to that of the earth.

If such be the present condition of the moon, we can scarcely avoid the conclusion that a liquid ocean can only exist upon the surface of a planet, so long as the latter retains a high internal temperature. The moon then becomes to us a prophetic picture of the ultimate fate which awaits our earth, when, deprived of an external ocean and its axial rotation reduced to a rate between monthly and annual*, it shall revolve round the sun an arid and lifeless wilderness, each hemisphere alternately exposed to the protracted glare of a cloudless sun and plunged into the gloom of an arctic night.

LIV. *On a New Method for the Direct Determination of the Specific Heat of Gases under Constant Volume. By* C. K. Akin, *Esq.*†

SINCE the revival of the theory which considers heat as Energy or *vis viva* due to molecular motions, the exact knowledge, from direct experimental data, of the specific heats of gases under constant volume, which alone of all similar magnitudes represent what have been called *real* specific heats, has become more than ever important. The methods hitherto chiefly followed for the determination of the specific heats of gases under constant volume are exceedingly indirect; and whilst some of them, such as that of Dulong, involve hypotheses which

* Mayer has proved that the action of the tides tends to arrest the motion of the earth upon its axis. And although the length of the terrestrial day has not increased by the $\frac{1}{100}$th part of a second since the time of Hipparchus, yet this fact obviously leaves untouched the conclusion to which Mayer's reasoning leads.

Since the above was written, Mr. James Croll has communicated to the Philosophical Magazine (vol. xxvii. p. 285) an elaborate paper on this influence of the tides.

† Communicated by the Author.