be ascribed to a more remote or a more recent era, to the great confusion of any attempt to understand either variations of climate or distribution of species during the glacial epoch.

The classification of boulder clays in this paper is given as a suggestion rather than in any way as an established arrangement, with the view of urging upon the members of the Society the necessity for more extended investigations.

XII.—*On* Modern Denudation. By Archibald Geikie, F.R.S., Director of the Geological Survey of Scotland.

(Read 26th March, 1868.)

CONTENTS.

It is at once an obstacle and an aid to the spread of sound geological knowledge that the wider problems of the science are in some of their aspects capable of easy apprehension. The facility with which their nature and bearings may in many cases be understood, added to the attractiveness of the subject itself, undoubtedly tends to increase largely the number of earnest students of geology. But this facility has brought a long list of followers, who, misled by the simplicity of the first aspect of the subject, have imagined that no more serious difficulties lay beyond. Such a misconception would not, indeed, have been so unfortunate, had not those who laboured under it felt themselves impelled to publish their views to the world. For in this way geological literature in this country has been burdened with a weight of crude opinion and hypothesis which seriously retard the advance of the science.

No branch of geological inquiry offers a more signal example of this result than that which deals more especially with the influence of Denudation upon the present outlines of a land-surface. The subject possesses a strong human interest, and, viewed from certain points, presents itself in a simple and intelligible guise. It has accordingly attracted much attention, and the amount of literature devoted to it has now become very large. Of some portions of this literature it is scarcely possible to exaggerate the value; the contributions of Ramsay, Jukes, and others, are among the most important which have been made in this department of the science for many years. Yet of other parts it is not too much to say, that they consist of mere crude speculations based upon no thorough geological knowledge, and that their publication has been on the whole a damage to the cause of true geology. More especially are they remarkable for the misconception which they display regarding the real nature of the processes involved and the results obtained in denudation. This great geological domain is treated as if it presented no difficulties to the inquirer, but stood out from the other provinces of science in demanding no previous scientific knowledge from those who would enter it. In reality, however, to attain to an adequate realization of what denudation actually involves, demands an amount of study and knowledge which is far from general. Before we are in a position to deal with the denudation of a country, we must first master the geological structure. The varied relations of the different rocks to each other, their lithological changes, their unconformable junctions, the faults which traverse them, the proofs of unequal subterranean movement, with all the other complex phenomena included under the geological structure of a district, must first be mastered before we can legitimately advance to a consideration of its denudation. But it will be readily understood that this demands an amount of patient inquiry which comparatively few are willing or have the opportunity to bestow.

With so much in its first aspect that is simple and attractive, denudation is nevertheless, as it seems to me, one of the most complex and difficult subjects with which a geologist can deal. I believe that we are still far from having mastered all that it involves. Its results, indeed, are everywhere apparent, alike among the vestiges of former terrestrial surfaces and upon the outlines of the existing land. But the manner in which these results were brought about, how the work is to be rightly apportioned to the different forces concerned, how far these forces have varied in their mode or rate of action in former geological periods, to what extent they may have been influenced by cosmical changes,—these are questions to which we are not yet able to give fully satisfactory answers. With so much, therefore, that is difficult and still obscure in this question, one cannot but regret that there should have been so much darkening of counsel without knowledge, and that by this means the profitable discussion of the subject should have been so sadly impeded. I do not wish, on the present occasion, to lay myself open to the same censure by bringing forward any further hypotheses. My object is to direct attention to the existing processes of denudation with the view, if possible, of gathering from them some indications that may guide us in investigating the denudation of past geological times. Hutton, the great founder of modern physical geology, is never tired of reiterating that we must "examine the construction of the present earth in order to understand the operations of time past;" "for so far as it is to natural causes that are to be ascribed the operations of former time, there are in the constitution of the world which we now examine certain means to read the annals of a former earth."—"No powers are to be employed that are not natural to the globe, no action to be admitted of except those of which we know the principle."—"Nor are we to proceed in feigning causes when those seem insufficient which occur in our experience."[1] It is possible to push this principle of uniformity of causation too far, as some of Hutton's followers have probably done. But within certain limits it is a safe guide, and the only one by which we can hope to interpret the history of the planet on which we dwell.

I. *Subærial denudation considered as the removal of so much rock from the general surface of a country.*

I propose in the present paper to consider the nature and rate of progress of modern denudation. This will lead us to inquire into the relative functions of the various denuding forces, and how far we may obtain from them some measure for estimating the value of geological time.[2] Disregarding, for the present, the details of the process, it will be of advantage to look first of all at its results, such as we witness in daily progress around us. It is important to gain a clear, generalized view of these results before we proceed to consider how they are one by one attained. From this stand-point we are led to perceive that the true measure of the denudation of a country, that is, the extent to which it is now being worn away by the various complicated agencies of waste, is to be sought in the amount of mineral matter removed from the surface of the land and carried into the sea. This is an appreciable and measurable quantity, and how much soever we may dispute regarding the way in which the waste is to be apportioned to the different forces which have produced it, we must accept the total amount of sea-borne detritus as a fact about which, when properly verified, no further question can possibly arise. In this manner the subject is at once disencumbered of all those vexed questions regarding the relative importance of rains, rivers, frost, glaciers, &c., considered as denuding agents. We have simply to deal with the sum-total of results achieved by all these forces acting severally and conjointly. In considering

[1] Hutton. Theory, I. pp. 20, 160; II. 549.

[2] "In the destruction of the present earth, we have a process that is performed within the limits of our observation; therefore, in knowing the measure of this operation, we shall find the means of calculating what had passed on a former occasion, as well as what will happen in the composition of a future earth. Let us, therefore, now attempt to make this estimate of time and labour." Hutton. Roy. Soc. Edin. I. 297. The profound philosophy and almost prophetic intuitions manifest throughout the writings of this great master offer to the student of the history of science many points of interest. As a contrast, the Geological Essays of Kirwan, more particularly Essay x. p. 433, may be profitably perused.

the subject in this fashion, we find a new light cast on the origin of existing land-surfaces, and obtain some fresh data for approximating to a measure of past geological time.

Of the mineral substances received by the sea from the land, one portion, and by far the larger, is brought down by streams; the other is washed off by the waves of the sea itself. It is the former, or stream-borne part, which is at present to be considered. The quantity of mineral matter carried every year into the ocean by the rivers of a continent represents the amount by which the general surface of that continent is annually lowered. If, therefore, we can measure the quantity of mineral matter, we may easily calculate by what fraction of a foot the general surface of the land is annually reduced. Much has been written of the vastness of the yearly tribute of silt borne to the ocean by such streams as the Ganges and Mississippi; but "the mere consideration of the number of cubic feet of detritus annually removed from any tract of land by its rivers does not produce so striking an impression upon the mind as the statement of how much the mean surface-level of the district in question would be reduced by such a removal."[1] This method of inquiry is so obvious and instructive that it probably received attention from early geologists, though data were still wanting for its proper application. Playfair, for instance, in speaking of the transference of material from the surface of the land to the bottom of the sea, remarks that "the time requisite for taking away by waste and erosion two feet from the surface of all our continents and depositing it at the bottom of the sea, cannot be reckoned less than 200 years."[2] This estimate does not appear to have been based on any actual measurements, and must, as we shall see, greatly exceed the truth; but it serves to indicate how broad was the view which Playfair held of the theory which he undertook to illustrate. The first geologist, so far as I am aware, who attempted to form any estimate on this subject from actually ascertained data, was Mr. Alfred Tylor, who, in the year 1850, published a paper in which he estimated the probable amount of

[1] Tylor. Phil. Mag. 4th Series, V. 268, 1850.

[2] Illustrations, p. 424. Manfredi had previously made a calculation of the amount of rain that falls over the globe, and of the quantity of earthy matter carried into the sea by rivers. He estimated that this earthy matter distributed over the sea bed must raise the level of the latter five inches in 348 years. Von Hoff, Veränderungen der Erdoberfläche, Band I. 232. See the other authorities there cited.

solid matter annually brought into the ocean by rivers and other agents. From the data which he had obtained, he inferred that the quantity of detritus now distributed over the sea bottom every year would, at the end of 10,000 years, cause an elevation of the ocean-level to the extent of at least three inches.[1] Mr. Croll has recently drawn attention afresh to this subject, particularly instancing the Mississippi as a measure of denudation and thereby of geological time.[2]

When the annual discharge of mineral matter carried seaward by a river and the area of country drained by that river are both known, the one sum divided by the other gives the amount by which the drainage area has its mean general level reduced in one year. For it is clear that if a river carries so many millions of cubic feet of sediment every year into the sea, the area drained by it must have lost that quantity of solid material, and if we could restore the sediment so as to spread it over the basin, the layer so laid down would represent the fraction of a foot by which the surface of the basin has been lowered during a year. Mr. Tylor has well shown that the process by which such startling results are obtained is a simple arithmetical one. In order, however, to obtain them with complete satisfaction, we must first be furnished with carefully collected and verified measurements both of the amount of mineral matter carried into the sea by any given river and of the area of drainage from which that mineral matter is derived. It is to be regretted that, as yet, these measurements have not been generally made with the requisite accuracy. The results at present obtainable from them are therefore necessarily only approximative. Nevertheless, they are of value as indicating the character of the conclusions which must eventually be deduced from more perfect data, and the direction in which research ought in the meantime to be carried.

[1] Phil. Mag. loc. cit.

[2] Phil. Mag. for February, 1867. My attention was first called to this subject by this paper of Mr. Croll's, and Mr. Tylor's earlier paper was afterwards pointed out to me by Professor Ramsay. Since the present communication was read before the Geological Society of Glasgow, Mr. Croll, following up the line of argument suggested in his former memoir, has gone into further detail upon this question in a memoir published in the *Philosophical Magazine* for May last, which will be of essential service to geology. The conclusions given by him in that memoir agree with those in the present one—a resemblance which arises from our having been engaged simultaneously in working out the same idea. In the one case, however, that idea was, as I have said, derived by me from one of his earlier papers; in the other it was, so far as he was concerned, original, as his deductions from it have been independent. I wish, therefore, fully to acknowledge that the merit of priority lies wholly on the side of my friend.

The material removed from the land by streams is twofold; one part is chemically dissolved, the other mechanically suspended in the water or pushed along the bottom by the onward motion of the stream. The chemically dissolved ingredients are derived partly from springs, partly from the flow of rain and streams over decomposing rocks at the surface. The reality and magnitude of this source of waste are apt to escape notice from the quiet and invisible way in which the process is carried on. The published analyses of river water, however, suffice to show its importance.[1] The nature and amount of these chemically dissolved constituents vary in different rivers, and even in the same river at different seasons. The Thames, for example, carries into the sea every year about 450,000 tons of salts invisibly suspended in its waters. Carbonate of lime in this as in most other rivers is the chief ingredient. Bischoff has calculated that the Rhine, in addition to the other salts which it contains, carries annually into the sea a sufficient amount of carbonate of lime to form the shells of 332,539 millions of oysters of the usual size.[2]

Properly to estimate the amount of loss sustained by the area which any given river drains, we ought to know the mean annual discharge of river water, the proportion of saline matter held in chemical solution in the water, the average ratio of mud held in suspension, and of sand and coarser sediment pushed along the channel of the stream. I am not aware that all these data have yet been collected with care from any river, though some of them have been ascertained with great accuracy, as in the Mississippi Survey of Messrs. Humphreys & Abbot. As a rule, more attention has been shown to the amount of mechanically suspended matter than to that of the other ingredients. For the present, therefore, I must confine myself to this part of the earthy substances removed from the land by running water. It will be borne in mind that the following estimates, in so far as they are based upon only one portion of the waste of the land, are understatements of the truth.

The proportion of mineral substances held in suspension in the water of rivers has been variously estimated, but the older calculations, based on mere conjecture, are hardly worth serious consideration. Manfredi, for example, set down the proportion as

[1] Bischoff has collected a list of these analyses. See his Chem. Geol., i., p. 75.
[2] *Ibid*, p. 80.

$\frac{1}{175}$; Maillet, $\frac{1}{1700}$; Hartsoeker, $\frac{1}{100}$; Sir George Staunton, in the case of the Yellow River, $\frac{1}{200}$, and another writer quoted by Von Hoff, $\frac{1}{51080}$.[1] Some uncertainty arises with regard to the older estimates, whether the figures refer to the proportion of sediment by weight or by bulk. It is most advantageous to determine the amount of mineral matter by weight, and then from its average specific gravity to estimate its bulk as an ingredient in the river water. The proportion by weight is probably, on an average, about half that by bulk.

According to experiments made upon the water of the Rhone at Lyons, in 1844, the proportion of earthy matter held in suspension was by weight $\frac{1}{17000}$. Earlier in the century the results of similar experiments at Arles gave $\frac{1}{7000}$ as the proportion when the river was low, $\frac{1}{230}$ during floods, and $\frac{1}{2000}$ in the mean state of the river. The greatest recorded quantity is $\frac{1}{45}$ by weight, which was found "when the river was two-thirds up with a mean velocity of probably about 8 feet per second."[2] Lombardini gives $\frac{1}{300}$ as the proportion by volume of the sediment in the water of the Po. In the Vistula, according to M. Spittell, the proportion by volume reaches a maximum of $\frac{1}{48}$.[3] The Rhine, according to Hartsoeker, contains $\frac{1}{100}$ by volume as it passes through Holland, while at Bonn the experiments of the late Mr. Leonard Horner gave a proportion of only $\frac{1}{16000}$ by volume.[4] Stiefensand found that, after a sudden flooding, the water of the Rhine at Uerdingen contained $\frac{1}{1282}$ by weight. Bischoff measured the quantity of sediment in the same river at Bonn during a turbid state of the water, and found the proportion $\frac{1}{4878}$ by weight, while at another time, after several weeks of continuous dry weather, and when the water had become clear and blue, he detected only $\frac{1}{57800}$.[5] In the Maes, according to the experiments of Chandellon, the maximum of sediment in suspension in the month of December, 1849, was $\frac{1}{2100}$, the minimum $\frac{1}{71420}$, and the mean $\frac{1}{10000}$.[6] In the Elbe, at Hamburg, the proportion of mineral matter in suspension and solution has been found by experiment to average about $\frac{1}{7400}$.

1 Von Hoff, *op. cit.* I. 232.

2 Humphreys & Abbot. Report upon the Physics and Hydraulics of the Mississippi, 1861, p. 147.

3 *Ibid*, p. 148.

4 Edin. New Phil. Jour., xviii., p. 102.

5 See his Chemical Geology, i., 122.

6 Annales des Travaux Publics de Belgique, T. ix., 204.

The Danube, at Vienna, yielded to Bischoff about $\frac{1}{4200}$ of suspended and dissolved matter.[1] The Durance, in floods, contains $\frac{1}{48}$ of suspended mud, and its annual average proportion is less than $\frac{1}{1000}$.[2] The Garonne is estimated to contain perhaps $\frac{1}{100}$.[3]

The observations of Mr. Everest upon the water of the Ganges show that, during the four months of flood in that river, the proportion of earthy matter is $\frac{1}{428}$ by weight, or $\frac{1}{856}$ by volume; and that the mean average for the year is $\frac{1}{510}$ by weight, or $\frac{1}{1021}$ by volume.[4]

But by far the most extensive and accurate determinations upon this subject yet made, are probably those of Messrs. Humphreys & Abbot, who were employed by the United States government to report upon the physics and hydraulics of the Mississippi river. The voluminous memoir which these observers have produced may be taken as a model of patient and exhaustive research. As the mean of many observations carried on continuously at different parts of the river for months together, they found that the average proportion of sediment contained in the water of the Mississippi is $\frac{1}{1500}$ by weight, or $\frac{1}{2900}$ by volume.[5] But besides the matter held in suspension, they observed that a large amount of course detritus is constantly being pushed along the bottom of the river. They estimated that this moving stratum carries every year into the Gulf of Mexico about 750,000,000 cubic feet of sand, earth, and gravel. Their observations led them to conclude that the annual discharge of water by the Mississippi is 19,50C,000,000,000 cubic feet, and, consequently, that the weight of mud annually carried into the sea by this river must reach the sum of 812,500,000,000 pounds. Taking the total anunal contributions of earthy matter, whether in suspension or moving along the bottom, they found them to equal a prism 268 feet in height with a base of one square mile.

It is much to be desired that careful measurements should be made of the quantity of silt carried down annually by our British rivers. The amount which is deposited in harbours at river

[1] *Op. cit.* 130.

[2] Payen cited by E. Réclus. *La Terre*, tome i., p. 537.

[3] Baumgarten cited by Réclus, *op. cit.*—*Ibid.*

[4] Jour. Asiatic Society of Calcutta, March, 1832.

[5] Report, p. 148. The specific gravity of the silt of the Mississippi is given as 1 9.

mouths has indeed been in many cases measured.[1] But this can of course afford but a vague measurement of the total amount which is brought down from the land and carried out to sea. In the case of the river Nith, a series of measurements and deductions made by the resident engineer led him to the conclusion, that the quantity of detritus borne by that stream into the Solway Firth reaches every year the amount of from 112,000 to 120,000 cubic yards.[2]

No one can have witnessed the effects of a violent or long-continued fall of rain upon even the small streams in the hilly parts of this country without being impressed with the amount of waste which the surface of the land is continually suffering from this cause. At Inverness, for example, the burn of Holm, during a "spate," sometimes carries down several thousand tons of stones and gravel into the river Ness.[3] Mr. Thomas Stevenson, the eminent harbour engineer, informs me that at Lybster, on the Caithness coast, where a harbour has been constructed at the mouth of a small stream, between 400 and 500 cubic yards of gravel and sand are every year carried down by the stream. A weir or dam has been constructed to protect the harbour from the inroad of the courser sediment, and this is cleaned out regularly every summer. But by far the greater portion of the fine silt is no doubt swept out into the North Sea. The erection of the artificial barrier, by arresting the seaward course of the gravel, reveals to us what must be the normal state of this stream and of all similar streams descending from maritime hills.[4] Over and above the quantity of fine silt, the presence of which is abundantly manifest in the turbid colour of the water during a rainy season, there are annually carried along the bottom of the channel and thence into the sea enormous quantities of coarser sediment. Even when this under stratum of moving gravel cannot be seen under the discoloured water, the stones of which it is composed

[1] See the evidence on this subject collected in Appendix C. to Tidal Harbours Commission, 1847. In Dundee Harbour the deposit of silt is said to amount to two or three feet in a year. Six inches of deposit annually appears to be a common quantity.

[2] Appendix C. to Tidal Harbours Commission, p. 603.

[3] See Appendix C. to Tidal Harbours Cemmission, 1847, p. 348.

[4] The area drained by this stream is about four square miles; consequently, the amount of loss of surface which is represented by the coarse gravel and sand alone is $\frac{1}{12000}$ of a foot.

may be heard knocking against each other as the current sweeps them onward. I was much struck with observing this on the Rhine and Moselle. Above Bonn, and again a little below the Lurelei Rock, while drifting down the former river, I could, by laying my ear close to the bottom of the open boat, hear the harsh grating of the gravel stones over each other as the current kept pushing them onwards along the bottom. The water was rather low, but the current remained tolerably swift. Again on the Moselle, between Cochem and Coblentz, I observed the same fact. From these observations, it is evident that the quantity of material held in suspension by no means represents all the detritus removed by a river from the area which it drains.

It may seem superfluous to insist that the earthy matter borne into the sea from any given area represents so much actual loss from the surface of that area. Yet this self-evident statement is probably not realized by many geologists to the extent to which it deserves. If a stream removes in one year one million of cubic yards of earth from its drainage basin, that basin must have lost one million of cubic yards from its surface. We are not now to consider whether the loss has been borne equally by the whole surface or falls only on special parts of it: this part of the subject will be reverted to in the sequel. It is sufficient for the present to regard the loss as a reality which we see daily before our eyes, and which we can approximately measure.

From the data and authorities which have now been adduced, I have constructed the subjoined table, in which are given the results of the measurement of the proportion of sediment in a few rivers. The last two columns show the fraction of a foot which each river must remove from the general surface of its drainage basin in one year. In the first of these two columns the sum represents the loss in sediment; and allowing the average specific gravity of river silt to be 1·9, and that of rocks to be 2·5, the second column shows the amount of solid rock which must annually be removed.

Name of River.	Area of basin in square miles.	Annual discharge of sediment in cubic feet.	Proportion of sediment in water.		Fraction of foot by which the area of drainage is lowered in one year.	
			By weight.	By volume.	In sediment.	In rock.
Mississippi,	1,147,000	7,459,267,200	$\frac{1}{1500}$	$\frac{1}{2000}$	$\frac{1}{4566}$	$\frac{1}{6000}$
Ganges,.....	432,480	6,368,077,440	$\frac{1}{510}$	$\frac{1}{1021}$	...	$\frac{1}{2358}$
Hoang Ho,	700,000	17,520,000,000(?)	...	...	...	$\frac{1}{1464}$
Rhone, ...	25,000	600,381,800	...	...	$\frac{1}{1161}$	$\frac{1}{1528}$
Danube,....	234,000	1,253,738,600	...	...	$\frac{1}{5203}$	$\frac{1}{6846}$
Po,...........	30,000	1,510,137,000	...	...	$\frac{1}{554}$	$\frac{1}{729}$
Nith,........	400	1,008,000 to 1,080,000	1 lb. in 32 cubic feet of water.		$\frac{1}{3590}$	$\frac{1}{4723}$

It will be seen that the amount is in some cases nearly ten times greater than in others. In the Po, for example, the rate of waste is more than nine times more rapid than it is in the Danube. The Mississippi rate is only about one-third of that of the Rhone.

At the present rate of erosion, the rivers named in this table remove one foot of rock from the general surface of their basins in the following ratio:—

The	Mississippi	removes	one foot in	6000	years.
,,	Ganges	,,	,,	2358	,,
,,	Hoang Ho	,,	,,	1464	,,
,,	Rhone	,,	,,	1528	,,
,,	Danube	,,	,,	6846	,,
,,	Po	,,	,,	729	,,
,,	Nith	,,	,,	4723	,,

The Mississippi, therefore, is lowering the surface of the great basin which it drains at the rate of one foot in 6000 years. If this rate continues, 10 feet will of course be removed in 60,000 years; 100 feet in 600,000 years; 1000 feet in 6,000,000. The mean height of the North American Continent, according to Humboldt, is 748 feet.[1] Under the Mississippi rate of denudation, therefore, that continent would be worn away in about four-and-a-half million years.

The Ganges works still more rapidly. It removes one foot of

[1] Asie Centrale, tome i., 168.

rock in 2358 years, and if Humboldt's estimate of the average height of the Asiatic Continent be accepted, viz., 1132 English feet,[1] that mass of land, worn down at the rate at which the Ganges destroys it, would disappear in little more than two and a half millions of years.

Still more remarkable is the extent to which the River Po denudes its area of drainage. Even though measurements had not been made of the ratio of sediment contained in its water, we should be prepared to find that proportion a remarkably large one if we look at the enormous changes which, within historic times, have been made by the alluvial accumulations of this river. According to the data already cited, the Po removes one foot of rock from its drainage basin in 729 years. This is equal to the removal of ten feet in 7290 years, 100 feet in 72,900 years. The mean height of Europe is stated to be 671 English feet.[2] If the whole of that continent were denuded at the same rate as in the basin of the Po, it would be levelled in rather less than half a million of years.

It is not pretended that these results are strictly accurate. On the other hand they are not mere guesses. The amount of water flowing into the sea, and the annual discharge of sediment, have been in each case measured with greater or less precision. The areas of drainage may perhaps require to be increased or lessened. But though some change may be made upon the ultimate results just given, it is hardly possible, as it appears to me, to consider them attentively without being forced to ask whether those enormous periods which geologists are in the habit of demanding for the accomplishment of geological phenomena, and more especially for the very phenomena of denudation, are not in reality far too vast. If the Mississippi is carrying on the process of denudation so fast that at the same rate the whole of North America will be levelled in four and a half millions of years, surely it is most unphilosophical to demand unlimited ages for similar but often much less extensive denudations in the geological past. Moreover, that rate of erosion appears on the whole to be rather below the average in point of rapidity. The Po, for instance, works more than eight times as fast. But as the physics of the Mississippi have been more carefully studied than those of perhaps any other river, we shall

[1] Humboldt, *ibid.* [2] Humboldt, *ibid.*

probably not exaggerate the result if we assume the Mississippi ratios as the average. It may not be without advantage to apply this average to the case of a number of British rivers, the drainage-area and water-discharge of which are known. The subjoined table shows the ascertained amount of water discharged by five rivers in this country. Assuming the proportion of sediment to be the same as in the Mississippi, we obtain the result in the last two columns—

Name of River.	Area of Drainage	Annual discharge of Water.	Annual Discharge of Sediment.	Fraction of a foot of rock by which the basin is annually lowered.
	Sq. Miles	Cubic Feet.	Cubic Feet.	
Tay, ...	2,500	144,020,000,000	49,660,000	$\frac{1}{1842}$
Thames, ...	5,162	54,111,200,000	1,865,903	$\frac{1}{10144}$
Forth, ...	450	15,450,000,000	5,328,000	$\frac{1}{3112}$
Clyde, ...	1,580	25,228,000,000	8,699,000	$\frac{1}{6658}$
Boyne, ...	700	94,614,000,000	32,622,000	$\frac{1}{7868}$

Hence it appears that if the proportion of earthy matter in the water of the Tay resembles that in the water of the Mississippi, the area of the Highlands, drained by the former river, must be suffering a loss at the rate of one foot in less than 2000 years. This is possibly not an exaggeration, for we have already seen that, disregarding the finer silt carried off in suspension, the amount of gravel and sand brought down annually by the Nith is equal to a loss of one foot in 4700 years.

There is another point of view from which a geologist may advantageously contemplate the active denudation of a country. He may estimate the annual rain-fall and the proportion of water which returns to the sea. If he can obtain a probable average ratio for the earthy substances contained in the river water which enters the sea, he will be able to estimate the mean amount of loss sustained by the whole country. Thus if he takes the average rain-fall of the British Islands at 36 inches annually, and the superficial area over which this rain is discharged at 120,000 square miles, then it will be found that the total quantity of rain received in one year by the British Isles is equal to about 68 cubic miles of water. Estimates have varied as to the proportion of the rain-fall which is eventually returned to the sea by streams. Some writers have given it as probably about a third, others as a fourth.[1] If we take it at the former estimate, there are 23 cubic miles, if at the latter, there are 17 cubic miles of fresh water sent off the surface of the British Islands into the sea in one year.

When the rain falls it is nearly pure water, but when, after a devious course of sometimes hundreds of miles, it is poured into the sea, it is, as we know, largely charged with mineral matter both in solution and suspension, as well as in motion along the channels of the streams. Let us take some average ratio for these impurities; and we shall probably guard against exaggeration by assuming this ratio to be only $\frac{1}{5000}$ by volume of the water, and the proportion of the rainfall returned to the sea to be $\frac{1}{4}$. At this rate $\frac{1}{8800}$ of a foot of rock must be removed from the general surface of our country every year. One foot will be planed away in 8800 years. The mean height of the British Islands is probably less than 650 feet. Under the existing state of things, therefore, if the ratio now assumed is near the truth, these islands will be levelled in about five and a-half millions of years. We still require much more detailed observation in this country, before any estimate of this kind can be based upon accurate and reliable data. But I have thought it desirable to indicate it as a method of vividly bringing before the mind the reality and extent of the denudation now in progress.

II. *Subærial denudation considered as the unequal lowering of the general surface of a country.*

I have hitherto spoken of the annual discharge of sediment from the surface of a country, as a definite quantity which may be measured, and which, when so measured, gives us the amount of loss which that surface has sustained in one year; in other words, the extent to which the average level of the country has been reduced. It is of importance to look at the subject from this point of view, in order to obtain some adequate idea of the extent of the loss which the land is constantly undergoing from subærial causes even before our eyes. At the same time it is

[1] Mariotte estimated the proportion of the rainfall discharged by the Seine from its catchment basin as $\frac{1}{6}$: Dausse subsequently made a fresh calculation, and set the proportion at $\frac{1}{3}$.—*Vide Becquerel, Eléments de Physique Terrestre*, p. 283.

sufficiently obvious that the earthy matter annually removed from the surface of the land, does not come equally from the whole surface. The determination of the total quantity of earthy materials removed, does not assist us in any way to apportion the loss, or to ascertain how much each part of the surface has contributed to the total amount of sediment. On plains, watersheds, and more or less level ground, the proportion of loss may be small, while on slopes and in valleys it may be great, and it may not be easy to determine the true ratios in these cases. But our estimates and measurements of the sum-total of denudation are not thereby affected. And this must not be over-looked. If we allow too little for the loss from the surface of the table-lands, we increase the proportion of the loss sustained by the sides and bottoms of the valleys, and *vice versa.*

These proportions must vary indefinitely with the form of the surface, rain-fall, &c. But the fact remains, that the balance of loss must always be, on the whole, on the side of the sloping surfaces. In order to show the full import of this part of the subject, I will assume certain ratios which are probably understatements rather than exaggerations.

Let us take the proportion between the extent of the plains and table-lands of a country, and the area of its valleys, to be as nine to one; in other words, that of the whole surface of the country, one-tenth part is occupied by the valleys, while the remaining nine-tenths consist of broad undulating plains, watersheds, or other comparatively level ground. Let it be further assumed, that the erosion of the surface is nine times greater over the latter than over the former area, so that while the more level parts of the country have been lowered one foot, the valleys have lost nine feet. According to the calculations already given, it appears that the mean annual quantity of detritus carried to the sea, may, with some probability, be regarded as equal to the yearly loss of $\frac{1}{6000}$ of a foot of rock from the general surface of the country. Apportioning this loss over the surface in the ratio just given, we find that it amounts to $\frac{5}{9}$ of a foot from the more level grounds in 6000 years, and 5 feet from the valleys in the same space of time. Then if $\frac{5}{9}$ of a foot be removed from the level grounds in 6000 years, 1 foot will be removed in 10,800 years; and if 5 feet be worn out of the valleys in 6000 years, 1 foot will be worn out in 1200 years. This is equal to a loss of only $\frac{1}{12}$ of an inch from the table land in 75 years, while the same amount is excavated from the valleys in $8\frac{1}{2}$ years.

It may seem at first sight, that such a loss as only a single line from the surface of the open country during more than the lapse of a long human life is almost too trifling to be taken into account, as it is certainly too small to be generally appreciable or even to be easily detected by careful measurements. In the same way, if we are told that the constant wear and tear which is going on before our eyes in valleys and water courses, does not effect more than the removal of one line of rock in eight and a half years, we may naturally enough regard such a statement as probably an under-estimate. But if we only permit the multiplying power of time to come into play, the full force of these seemingly insignificant quantities is soon made apparent. For we find by a simple piece of arithmetic, that at the rate of denudation which has been just postulated as probably a fair average, a valley 1000 feet deep may be excavated in 1,200,000, a period which, in the eyes of most geologists, will seem short indeed.

Objection may be taken to the ratios from which this average rate of denudation is computed. My object at present is not to decide what this average rate actually is; we shall be able to do so hereafter, when more accurate and abundant data have been obtained. But it appears to me likely to be useful to point out what, according to the most probable estimates at present possible, is actually in progress around us. Let us assume any other apportioning of the total amount of denudation, we do not thereby lessen the measurement of that amount which can be and has been ascertained in the annual discharge of rivers. We have a certain determined quantity of rock annually worn off the surface of the land. If, as already remarked, we represent too large a proportion as derived from the valleys and water courses, we diminish the loss from the open country, or if we make the contingent derived from the latter too great, we lessen that from the former. Under any ascertained or assumed proportion the facts remain, that the land loses a certain ascertainable fraction of a foot from its general surface per annum, and that the loss from the valleys and water courses is much larger than that fraction, while the loss from the level grounds is much less.

Before proceeding to notice some of the important conclusions which must follow from these statements, I have deemed it desirable to consider certain objections which are often urged against the potency of that subærial denudation, the results of which we have now been discussing. In one sense, indeed, it is unnecessary to reply to objections which are completely refuted by the facts adduced in the previous pages. To deny that the surface of a country is annually suffering a lowering of its general level from denudation, is to shut the eye to the evidence vividly displayed by every brook and river by which the surface of that country is traversed. Some objectors, however, do not deny the annual loss of rock, but maintain that it is not derived from the general surface of the country, but only from comparatively limited portions, and they point to certain features of the surface as affording proofs of permanence. The most ingenious objections of this kind which I have yet met with, are stated by M. Elie de Beaumont.[1] I shall give here a sketch of the argument by which the distinguished French geologist endeavours to shew that the influence of atmospheric causes is quite insignificant.

The solid rocks are usually more or less covered with a layer of vegetable soil which, though at first sight it may seem to present few points of interest, dates in reality from a high antiquity and merits the special study of the geologist. It is intimately associated with human history, and offers in consequence materials for the establishment of positive data in geology. The human monuments which it contains, furnish most important geological evidence, for if the inscriptions graven upon them a thousand or two thousand years ago remain still fresh, it is thereby shown that certain parts of the earth's surface may be preserved unchanged for a long time. But apart from the question of their own conservation, these monuments prove that the surface of the ground and the vegetable soil undergo very little modification. The Roman bridges still span the water-courses over which they were built, for the waters have not risen any nearer to the tops of the arches, nor sunk so as to expose the foundations, but pass to-day just at the height for which the bridges were constructed. Hence, the bed of these rivers has not changed. Along different parts of the lower course of the Rhone, the Roman remains of different kinds are in perfect

[1] Leçons de Géologie Pratique, 1843, tome I. p. 135, *et seq.*

accordance with the existing level of the river, and the present régime of that stream appears thus to have remained as it is from time immemorial. A like inference is to be drawn from the occurrence of the large standing stones so abundant in Europe. These monuments, most of which must be at least 2000 years old, have been simply planted in the soil. If the surface of the soil had been lowered, their base would have been laid bare, had it been raised, their base would have been covered up. But they remain just sunk so far in the soil, as to prevent them from falling. This holds true, not only for these on flat ground, but also for those which stand on sloping declivities, and even when in such circumstances, they are exposed to all the changes of a maritime climate. Further, and still more unexceptionable proof of the insignificance of the degradation undergone by grass-covered soil, is found in those ancient earthen mounds such as tumuli, forts, and camps, which, even with sloping sides, have retained almost perfectly their original forms. The angle of declivity of the ramparts remains what it evidently was at first, and the ditches between the ramparts have not been filled up. Again, in ground which has long been abandoned by the plough, the parallel furrows may still be traced. In Brittany and in Spain, for instance, there are districts where the soil has not been cultivated for a great many centuries, yet where the old ridges made by the plough remain perfectly distinct under the coating of turf. If we watch the influence of sun and rain upon ploughed land, we observe that while the soil is bare, these external agents act with comparative rapidity in reducing its surface to a more stable contour which gets covered with herbage and remains almost without change for an immense period. In this process the action of the atmospheric forces is greater the first year than the second, greater the second year than the third, greater the third year than the fourth, the changes decreasing almost in a geometrical progression. If the effect produced in the second year were half of that in the first, if that produced in the third year were half of that in the second, and so on, the sum-total of change produced at the end of an indefinite time, would only be double that effected at the end of the first year. If the second year's alteration were equal to three-fourths of that of the first year, the result at the end of an indefinite period would only be four times that of the first year. Or lastly, if the second year's alteration were nine-tenths of the first year's, the result after an indefinite time, would be merely ten times that of the first year.

M. Elie de Beaumont then proceeds to discuss the evidence afforded by vegetation. He contends that, as a tree cannot live unless the soil on which it grows remains beneath it, so trees which have been several centuries in existence, show that the soil during that period has undergone no appreciable change. Even on slopes where the vegetable soil is very thin, there are forests of century-old trees, so that the permanence of the existing surface is thus established for inclined as well as for flat ground. From this point of view, the longevity of certain trees acquires a special interest to the geologist, and the author cites a number of examples in illustration. Nor is it merely the higher forms of vegetation that are appealed to. Certain lichens coating the surfaces of rocks, may be, to use the words of De Candolle, "as old as the last cataclysm." Grass likewise protects the soil on which it grows, and may be very old. Vegetation generally tends to preserve the present form of the surface, and where it has been removed by man, the soil underneath has in many places been carried away by running water and the ground rendered for a long while uncultivable. The natural state of the surface of the globe is to be covered and protected by a coating of vegetation. There are, indeed, many places where that surface is subject to continual and very visible degradation, such as the sea margin and the channels of streams, where the ground is being perpetually, as it were, cut to the quick. But these changes are so perceptible, precisely because, in most places the vegetable soil remains nearly unaltered during the lapse of immense periods. This layer of vegetable soil, therefore, is in fact a kind of fixed point or zero by which to measure the phenomena that take place more rapidly.

In introducing the subject, M. Elie de Beaumont remarks, that it possesses for the general public the recommendation of requiring no previous geological knowledge. Assuredly, a reader who has no pretensions to science, may yet readily detect the fallacy which runs through the whole of the interesting argument of the French savan. The monuments of antiquity on which that argument is founded, form but a small fraction of the number of monuments originally constructed. Every year is thinning them down still more, whether it be by the hand of man or by the inevitable march of decay. Destruction is the rule, preservation is the exception. To select, therefore, the examples which, owing to more favourable circumstances have been preserved, and to take no note of the far greater number which have been destroyed, necessarily leads to a result which is far from being true. Reduced to a syllogism, the argument would be stated thus:— If atmospheric waste could produce during 2000 years any appreciable change upon the surface of a country, human monuments would shew it. Some human monuments cited by M. de Beaumont do not shew it, therefore atmospheric waste is not productive of any sensible alteration of the surface of a country. Somewhat in the same way we might reason, that if old age usually brought grey hairs with it, the heads of octogenarians would shew it, but some worthy friends of ours, who have long passed their threescore years and ten, are as dark as when we first knew them; therefore old age does not as a rule, bring with it grey hairs.

It is not worth while to enter into the details of the reasoning, otherwise it would not be difficult to shew that the preservation of old forts and tumuli is in thousands of cases by no means so perfect as is alleged; that the standing stones which are still erect do not furnish any proof that the soil around them has undergone no change, a statement, indeed, which seems sufficiently negatived by the number of stones lying prostrate: and that for one legible inscription more than two or three centuries old, it would be easy to furnish scores which have been obliterated after a few generations. But even if all these assertions were just, and if it could be conclusively proved, that for a thousand or two thousand years certain human monuments had undergone no appreciable alteration, would the inference necessarily be just that, therefore, rain, frost, streams, and the other meteoric agents of decay exercise no material influence upon the general surface of the earth? Is it not manifest that the time during which observations have been made, is infinitely too brief to warrant any such sweeping deduction? A process which, in two thousand years, has not effected any perceptible alteration on certain parts of the earth's surface, may yet have been rapid enough in the course of the geological ages, to have worked the most stupendous changes upon that surface as a whole. If, following up the foregoing estimates, we put down the amount of rock removed annually from the open country as $\frac{1}{10800}$ of a foot, this would amount to no more than 2·22 inches in 2000 years—the time comprised by the evidence of M. E. de Beaumont. This would be a quantity so small as to be wholly inappreciable. Again, if using still the same estimate, we take the loss of surface from the valleys and water courses as $\frac{1}{1200}$ of a foot in one year, this would give us only twenty inches in 2000 years—an amount which, in default of any trustworthy standard of measurement, would likewise be inappreciable.

To these arguments of M. E. de Beaumont may be added another, based on the same kind of reasoning, and which appears to have great weight in the eyes of some geologists, viz.:—that the ruts, grooves, and scratches, graven upon rocks during the glacial period, remain still fresh, although the surfaces so marked have been opposed to all the vicissitudes of a changeable climate. It is contended that, had atmospheric waste been so powerful as the followers of Hutton maintain it to be, these markings would certainly have been effaced during the lapse of the thousands of years since the ice left them upon the rocks. And the fact of their preservation is pointed to as a proof, that even in a stormy region like that of the western and northern portions of the British Islands, the general surface of the country has remained for thousands of years without appreciable change.

To an eye trained in tracing the effects of ice-action, the general surface of the British Islands wears an unmistakeable ice-smoothed aspect. But the localities where the actual ice-polish and striæ are now exposed, are few, indeed, when compared with the area from which these fine markings have been effaced, yet, which still retain abundant evidence of having once been glaciated. We see the surface in all stages of decay, from rocks where, save perhaps on the large scale, all vestige of ice-action has disappeared to polished and striated surfaces which remain still fresh. In very many cases where these markings retain such freshness, it is easy to see that they have, till comparatively recently, been protected under a covering of soil, turf, gravel, or clay. In cases where the striated faces of rock have been laid bare by human agency, a few years sometimes suffice to remove the sharpness which they had when the protecting clay was removed from them. Those, for example, who remember the appearance of the striated dolerite on the Queen's Drive at Edinburgh when that road was made about a quarter of a century ago will find that even this brief exposure has been enough to remove the original delicacy of the lines. In the old glacier districts of the Highlands, too, I have often noticed well-marked *roches moutonnées* where the rounded form and the parallel grooves and striæ still remained wonderfully distinct. Yet, on examining these bosses of gneiss or schist, I found that the quartz-veins traversing the rock sometimes projected from the general surface a twelfth of an inch or more, and retained the finer striæ, which were all obliterated from the rest of the rock. Yet, looking at these *roches moutonnées* one might have been disposed to say, that they still remained very much as the ice had left them. Nevertheless there was here proof, that while the general ice-worn character of the rock-surface remained still remarkably distinct, one line or more had been gradually eaten away from that surface. A tolerably wide experience of ice-worn rocks in this country, in Norway and in Switzerland, has taught me that glaciated surfaces are no exceptions to the general law of decay, and that as soon as they are directly exposed to the atmosphere, they begin to weather, as all other surfaces do.[1]

In considering an objection of this kind, we must not forget that of all possible forms of surface, that of an ice-smoothed boss or face of rock, is probably the one where the subærial agencies of waste will have least facility for action, and which will therefore longest retain its contour. The polished surface allows rain to run off at once, and the joints which would otherwise permit the disruptive action of frost, are for a long while concealed. The sides of a polished granite obelisk, will resist the weather far longer than the surface of a rough block of the same stone. Those, therefore, who employ ice-worn surfaces as evidence against the potency of atmospheric denudation, argue in precisely the same way as M. E. de Beaumont. It is as if they found in a medieval building the hard well-chiselled corner-stones still retaining the tool-marks, and concluded therefrom that the intervening centuries

[1] I have on a former occasion called attention to the remarkable and increasing freshness of the ice markings as we approach the present sea-margin, more particularly among the western sea-lochs of this country. (Trans. Geol. Soc., Glasgow, I. part 2, p. 170—*note*. See also my "Scenery of Scotland," p. 228). I regard this fact as only explicable, on the admission that the maritime *roches moutonnées* have been for but a comparatively brief period exposed directly to the atmosphere.

had produced no change upon the exterior of the walls. Yet, a little further inspection would show that the tool marks were only visible on the corner-stones, where the hardest freestone had been selected, while the rest of the wall, constructed of less carefully chosen materials, showed, in many places, courses of stone wholly rotted out, crumbling mortar, and general decay.

III. *General Results of Subærial Denudation.*

If the present action of air, rain, streams, and ice, is their normal condition, and we have no evidence that it is not, then the general result of that action in past time must have been to chisel out a system of valleys on the surface of the land. Whether or not the existing valleys of any particular country are due to this cause entirely is another question. If we reflect upon the mass of debris which every river is annually carrying from the surface of the land, we are led to understand the truth of Hutton's doctrine, that "the great system upon the surface of this earth is that of valleys and rivers; and that however this system shall be interrupted, and occasionally destroyed, it would necessarily be again formed in time while the earth continued above the level of the sea."[1] Subterranean movements, in any particular instance, may have aided the operation of the meteoric forces. But this aid is not absolutely necessary. Were a mass of land without a single valley, but with a smooth surface sloping gently seawards from its central portion, to be elevated above the ocean, and exposed to the atmospheric agents of denudation, a system of water-courses and valleys would certainly be excavated. Nor, as we have already seen, would a long series of geological periods be necessary for such a result. At the present rate of waste, valleys 800 feet deep might be carved out in a million years. If, on the other hand, a portion of the earth's crust, crumpled and fractured in the extremest degree, were raised above the sea, it would at once begin to yield to denudation; its surface would crumble away, and the original features, due to subterranean movements, would gradually disappear. These features would, doubtless, for a time, modify the course of many of the streams, but their influence would certainly wane as the features themselves faded; and as Hutton showed,

[1] Theory of the Earth, II. 538.

the normal system of valleys of erosion would necessarily be restored.

It is not my purpose to enter into a discussion of the origin of valleys, but rather to point out the bearing which the evidence furnished by every river has upon this question. That evidence, as it seems to me, leads inevitably to the conclusion that those geologists who point to deep valleys, glens, lakes, and ravines, as parts of the primeval architecture of a country, referable to the upheavals of early geological history, ignore the influence of one whole department of natural forces. For it is evident that if denudation in past time has gone on with anything like the rapidity with which it marches now, the original irregularities of surface produced by such ancient subterranean movements must long ago have been utterly effaced. Every year effects a measurable change upon the drainage area of a river, and after the lapse of a comparatively brief geological period the present features of that area must inevitably disappear. None of the existing external outlines can therefore be, in their present form, of ancient date. No one, indeed, who has ever studied rocks in the field, is likely to overlook the existence of faults, and other traces of underground movement. But he meets everywhere with proofs of the removal of vast masses of rock from the valley-systems —a phenomenon which no amount of subterranean influence will explain. At their present rate of excavation the atmospheric forces will carve out deep and wide valleys in periods which, by most geologists, will be counted short indeed. And when an agency now in operation can do this, it is surely as unnecessary as it is unphilosophical to resort to conjectural cataclysms and primeval earthquakes for which there is no evidence, save the very phenomena which they are called up to explain.

In reference to the origin of the present configuration of the earth's surface, attention has recently been more specially drawn to the Highlands of Scotland as retaining, in great measure, the "aboriginal outline" impressed upon them by ancient upheavals and fractures. To this subject it may be proper to return on another occasion. In the meantime it may be remarked that the crumpling of the Highland rocks must have happened previous to the formation of the Old Red Sandstone. This is a relative date which is demonstrable by the simplest kind of geological reasoning. If then the present features of the surface are due, as is alleged, to the crumpling and fracture of the rocks, they date from a time anterior to the Old Red Sandstone. It follows, therefore, either that the time during which the Old Red Sandstone was accumulated cannot be removed by any long period from our own day, for otherwise the original outlines of the surface would have been obliterated by atmospheric waste, acting even no faster than it is doing now; or that the rate of denudation (and consequently of deposition) must have been in past time indefinitely slower than at present. The former half of the alternative will be at once rejected; the latter goes in the face of all received geological belief.

What is thus true of the Scottish Highlands is equally so of other districts where ancient metamorphic rocks rise into rugged outlines at the surface. If such outlines had been produced so long ago as the time of the Old Red Sandstone or Silurian formations, it is clear that, in the interval which has since elapsed, the common forces of denudation must have been wholly, or almost wholly, inoperative. Had these forces acted even in the feeblest manner conceivable, it is incredible that any vestige of a land-surface should have retained its contour during the lapse of all the ages which have passed away since the middle of the palæozoic period. But we have only to look at the vast thickness of stratified rocks deposited during these ages, to see that the forces of denudation were far from idle; that on the contrary they were probably at least as active, on the whole, as they are now. Hence we are shut up to the conclusion that if the crumpling and fracturing of the crust of the earth during palæozoic times gave rise to broken and rugged land-surfaces, such surfaces could not withstand the ordinary wear and tear of the common denuding agents, but must long ago have been effaced.

The consideration of this subject leads naturally to an inquiry whether some support to the views now combated is not derived from the existence of those numerous rock-basins in which lakes are contained. For it is evident that though running water may hollow out a valley, or a system of valleys, it cannot be supposed capable of excavating a series of deep and wide cavities in solid rock. It would be apart from the purport of the present paper to enter into the vexed question of the origin of lakes. But I wish to point out a line of argument which springs out of the subject we have been considering, and which seems to me to possess considerable weight.

We may conveniently divide the opinions propounded regarding the origin of rock-basins into two classes, of which the one calls in the action of subterranean forces, while the other relies upon the influence of denudation. Under the former division must be grouped many various hypotheses which rest, some on areas of special subsidence, some on synclinal foldings of the strata, some on gaping fissures, some on wider and unequal movements of depression and elevation, but all of which agree in demanding some movement of the crust underneath, as the direct cause of the hollows at the surface in which the lakes are contained. In such rugged and mountainous districts as the Scottish Highlands and Norway, the lakes are appealed to as part of the evidence of the ancient fractures and upheavals, the results of which, it is alleged, are still visible in the contour of the existing surface. Let us see how far this belief is consonant with the present system of nature.

If we survey the phenomena of denudation everywhere in progress over the surface of the globe, we shall be led, I believe, to the conclusion that lakes, as a whole, must be of comparatively modern origin. We see that the streams which enter them push yearly increasing deltas into the water. Every lake in our own country shows this. Many alluvial meadows have evidently at one time been lakes; many lakes have been silted up within the memory of man, many are almost diminishing visibly from year to year. The rate at which mud, sand, and silt are poured into these hollows shows that the hollows cannot be, in a geological sense, very old. The delta of the Rhone, for example, has crept a mile and a half into the lake of Geneva in about 800 years. Eight centuries, therefore, must represent no insignificant fraction of the interval which has elapsed since the lake first began to receive the detritus of the river. Had the basin been of geologically ancient origin, it must necessarily have been long ago filled up with sediment, and once in that condition, no power of running water could re-excavate it so as to turn it into a lake again.

It is a singular and significant fact, first pointed out by my friend and colleague, Professor Ramsay, that lakes are scattered in immense numbers over the more northern portions of the globe, while in more temperate and tropical regions they are in comparison rare. Had these millions of northern lake-basins been due to underground commotion, it might have been expected that they would have been found associated with volcanic eruptions or other phenomena indicative of subterranean activity. But as is well known no such association exists. On the contrary the lakes are for the most part to be found among the oldest stratified formations in which no trace of recent volcanic action is to be seen. We have seen that the lake-basins cannot be assigned to early fractures and convolutions of these ancient rocks, for the aboriginal contour of the surface must long ago have been worn away, and even if the rock-basins could have remained, they must have been filled up with sediment, and thus have ceased to hold lakes. Those, therefore, who appeal to the influence of underground movements as the direct cause of rock-basins must seek them in a late geological period; so late indeed, that it may be considered as almost part of the present epoch. In order to account for the innumerable rock-basins of northern latitudes, they are driven to suppose that in these regions, within geologically recent times, the surface of the ground has been fractured, depressed or upheaved, to an extent which must be admitted to be wholly unknown even in those tracts which are at present most devastated by earthquakes. Nor can any other corroborating evidence of such extensive and violent disturbance be obtained. None of the more recent tertiary and post-tertiary formations give any indication of such a general derangement of their strata.

And when we come to examine the structure of the rock-basins themselves, apart from theory, as to their origin, we find them to be in reality hollows worn out of a denuded surface of rock. They afford no hint as to subterranean movements, but show along every part the strongest proofs of extensive denudation. Any explanation of their origin therefore must take into account the following facts in their natural history:—

1. Lakes are abundantly scattered over the more northern parts of the globe.
2. They have no ascertainable connection with earthquakes or subterranean movements of any kind.
3. They lie in hollows of extensively denuded rocks.
4. They must be of comparatively recent origin.

The only explanation which will account for these facts is, I believe, that propounded by Professor Ramsay, that the rock basins were scooped out by the ice of the Glacial period. I regard this explanation as one of the most important contributions made in recent years to theoretical geology. It removes in the most simple way a difficulty which has long perplexed all who have tried to trace the history of the present outlines of land-surfaces, and who have felt that the existence of rock-basins presented an anomaly which they could not satisfactorily explain. The glacial-erosion theory removes this difficulty, harmonizes many seemingly discordant facts, and furnishes a new and important method of elucidating the history of the earth's surface.

I have hitherto spoken of the general results of subærial denudation considered as a whole, and without any particular regard to the varying nature of the rocks upon which the denuding forces have to act. It is sufficiently obvious, however, that though there may be a general and tolerably uniform result obtained over the whole of the surface of the land, there must be at the same time constant modifications according to the varying nature of the rocks underneath. Thus, hard, jointed rocks will tend to produce rugged outlines, while softer strata will crumble into smooth slopes or plains, though in each case the exposure to denudation may be the same. It would take me far beyond the limits necessarily assigned to this paper to enter into the details of this part of the subject. I would only remark that most of the well-marked varieties of rock have, when in sufficient mass, distinctive forms of weathering, which impart a character to the local scenery [1] The peculiarities of landscape shown by districts of granite, limestone, chalk, or basalt, are sufficiently familiar illustrations. In these cases we can watch the influence of subærial denudation and assure ourselves of the reality and extent of its influence. But over and above the mere texture and structure of the rocks, much of the present contour of a country may be traced to the guiding influence of the geological arrangement of the rock-masses. Lines of anticlinal axis, for example, frequently coincide with lines of valley, while synclinal troughs form lines of hill—a relation which is precisely the reverse of what might have been expected.[2] Faults sometimes have determined the course of valleys, though this has happened much less frequently than many geologists are in the habit of asserting. The boundary line of two geological formations, or of two groups of strata, the upper part of which is harder than the lower, has frequently given

[1] See my *Scenery of Scotland*, Chaps. viii. and xi. and references.
[2] *Op. cit.* 147 and note.

rise to the formation of an escarpment, or range of inland cliffs.[1] These and other influences of the rocks underneath upon the form of the surface belong to the history of denudation in past times, but they require to be taken into account if we would truly follow the results of the denudation actually in progress.

IV. *Marine Denudation.*

In what has now been considered we have had regard only to that portion of the annual loss of land which is evinced by the transport of mineral substances by rivers into the sea. But besides this portion, there is likewise removed, every year, a considerable amount of material by the waves that beat along the margin of the land. We see this annual waste visibly advancing, and sometimes too, with a melancholy rapidity. We find that even the most iron-bound shores yield to the ceaseless grinding of the breakers. The denudation is often more marked along the coast-line than it is inland, and thus we are apt to take for granted that the sea is much the most powerful agent of destruction, and that marine denudation is the most important of all the various modes in which the bulk of the solid land is from year to year reduced. Such an inference is but natural in a country like our own. Here, islanders as we are, and familiar from infancy with the fury of the breakers which beat along our coast-line, and strew it with wrecks, we are prone to attribute to the ocean the chief share of the work of wearing down the land. Yet, if we attentively consider the abrasion, due directly to marine action, we are led to perceive that its extent is comparatively small. In what is called marine denudation, the part played by the sea is mainly that of removing what has already been loosened and decomposed by atmospheric agents. When these decayed portions are carried away, a fresh surface is again laid open to subaerial influences, to be in turn reduced to fragments, and borne away seawards. Were it not, therefore, for the aid given by rains, springs, frosts, &c., the progress of the waves would be comparatively slow. Yet, let us grant to the action of waves and tides all that is usually included under the term *Marine Denudation*, we shall still find that the sum total of waste along

[1] See Foster and Topley, Quart. Jour. Geol. Soc. xxi., p. 443. Topley, Geol. Mag., iii., 435; iv., 184. Whitaker, Id. iv., 450. Mr. Whitaker has given an admirable summary of the evidence in favour of the subærial origin of escarpments.

the margin of the land must be trifling compared with that which is produced by the meteoric agents upon the interior.

At the outset, it is evident that the extent of surface exposed to the power of the waves is very small indeed when contrasted with that which is under the influence of atmospheric waste. Even in an island like Britain, the discrepancy is great, and, of course, in the case of the continents, it is infinitely greater. In the general degradation of the land this is an advantage in favour of the subærial agents, which would not be counterbalanced unless the rate of waste by the sea were many thousands or millions of times greater than that of rains, frosts, and streams. But in reality, no such compensation exists. In order to see this, it is only necessary to place side by side, measurements of the amount of work actually performed by the two classes of agents. Let us suppose, for instance, that the sea eats away a continent at the rate of ten feet in a century—an estimate which probably attributes to the waves a much higher rate of erosion than can, as the average, be claimed for them.[1] Then a slice of about a mile in breadth will require about 52,800 years for its demolition, ten miles will be eaten away in 528,000 years, one hundred miles in 5,280,000 years. Now we have already seen that, on a moderate computation, the land loses about a foot from its general surface in 6000 years, and that at this rate of subærial denudation, the continent of Europe would be worn away in about 4,000,000 years. Hence, before the sea, advancing at the rate of ten feet in a century, could pare off more than a mere marginal strip of land, between 70 and 80 miles in breadth, the whole land would be washed into the ocean by atmospheric denudation.

Such results as these would necessarily be produced if no disturbance took place in the relative levels of sea and land. But in estimating the amount of influence to be attributed to each of the denuding agents in past times, we require to take into account the complicated effects which would arise from the upheaval or depression of the earth's crust. If frequent risings of the land or elevations of the sea-floor into land had not taken place in the geological past, there could have been no great thickness of stratified rocks formed, for the first continents must soon have been washed away.

[1] It may be objected that this rate is far below that of parts of the east coast of England, where the land sometimes loses 3 or 4 yards in one year. But on the other hand, along the rocky western coast, the loss is probably not so much as one foot in a century.

But the great depth of the stratified part of the earth's crust and the abundant breaks and unconformities among these sedimentary masses, show how constantly the waste of the land was compensated by the result of elevatory movements.

When a mass of land is raised to a higher level above the sea, a larger surface is exposed to denudation. As a rule a greater rainfall is the result, and consequently also a more active waste of the surface by subærial agents. It is true that a greater extent of coast line is exposed to the action of the waves, but a little reflection will show that this increase will not, on the whole, bring with it a proportionate increase in the amount of marine denudation. For as the land rises the cliffs are removed from the reach of the breakers, and a more sloping beach is produced on which the sea cannot act with the same potency as when it beats against a cliff-line. Moreover, as the sea-floor approaches nearer to the surface of the water it is the former detritus washed off the land and deposited under the sea, which comes within the reach of the currents and waves. This serves, in some measure, as a protection to the solid rock below, and must be cut away by the ocean before that rock can be exposed anew. While, therefore, elevatory movements tend on the whole to accelerate the action of subærial denudation, they serve to check the natural and ordinary influence of the sea in wasting the land. Again, the influence of movements of depression will probably be found to tend in an opposite direction. The lowering of the general level of the land will, as a rule, help to lessen the rainfall, and consequently the rate of subærial denudation. At the same time it will aid the action of the waves by removing under their level the detritus produced by them and heaped up on the beach, and by thus bringing constantly within reach of the sea fresh portions of the land-surface. But even with these advantages in favour of marine denudation, the balance of power will probably, on the whole, remain always on the side of the subærial agents.

The ultimate tendency of the erosive action of the waves is to reduce the land to a level under the sea. While this process is in progress many inequalities must necessarily be produced, owing to variations in the power of resistance of the rocks, the set of tides, currents, &c. Hence arise bays, and promontories, peninsulas, and islands, with all those varieties of contour with which we are so familiar along the seaboard of our country.[1] But these irregularities, if long enough exposed to denudation, are in the end planed down to a tolerably uniform surface under the sea level.

It is a familiar fact that the angle at which a mass of land descends to the sea-level serves roughly to indicate the depth of water near shore. Thus, when a coast-line is precipitous, there is commonly deep water near the land, while if the coast be low, the sea for some way outward is shallow. The line of slope above water is found to be, in a general way, prolonged below it—the belt of beach forming a kind of terrace or notch along the slope. Sometimes, of course, this terrace runs out a good way beyond low-water mark; at other times, where the coast-line is precipitous, it is nearly or wholly wanting. I do not remember to have seen these relations of surface discussed by any geologist, though they are well known in navigation. Certainly they do not seem to have been so much studied as they ought to be by those who maintain the immensely superior power of the sea over that of the other denuding agents. If the sea plays so transcendent a part in the denudation of the land, why should there be this continuity of the seaward and landward slope?

It must be granted that the erosive action of the sea is almost wholly confined to the littoral waters. Whatever lies below the influence of winds and waves can suffer but little change. The tides and breakers beating on the land cut away a notch or platform along its margin, and the surface of this platform comes in the end to correspond with the downward limit of breaker-action. Now, if the ocean, as a denuding agent, really deserves the prominent place usually assigned to it, why should there be this common seaward prolongation of the land-slope? Why has the ocean not been able to make a much more noteworthy break in the continuity of the slope, or, in other words, to cut a broad terrace along it? Why should not a line of steep cliff, for instance, be often or even usually fronted with a broad belt of comparatively shallow water lying upon the terrace formed by the gradual backward erosion of the cliff-line?

To these questions it is not easy to find a wholly satisfactory answer, though they serve to indicate that the potency of the

[1] Mr. Whitaker, in the excellent paper on subærial denudation, already cited, has pointed out the different results which are obtained by the subærial forces from those of sea-action in the production of lines of cliff. See Geol. Mag. iv. 447, *et seq.*

ocean has been overstated by many advocates of marine denudation. Possibly the influence of upheaval or depression of the crust of the earth requires to be here taken into account—the rate of marine erosion being so slow, that in many cases it cannot keep pace with the upward or downward movement of the land.

If, then, the various destructive elements have acted upon the surface of the land in past time with any approach to the proportions in which they are acting now, it seems to be clear, from the various considerations which have now been adduced, that the sea can have played but a secondary part in modelling the outlines of a continent. It may, perhaps, be objected to this conclusion that the traces of wide level tracts, known as plains of marine denudation, so commonly to be met with over the earth's surface, can only be attributed to sea-action, and must prove the sea to have had no small share in the general task of planing down the land. These plains are, indeed, in all probability referable to the action of the sea; but if we reflect upon the tendency of atmospheric waste, we must perceive that such plains are the natural and necessary result of that waste. In short, a "plain of marine denudation" is that sea-level to which a mass of land has been reduced mainly by the subærial forces; the line below which further degradation became impossible, because the land was thereafter protected by being covered by the sea. Undoubtedly the last touches in the long process of sculpturing were given by the waves and currents, and the surface of the plain corresponds with the lower limit of the action of these forces. Yet I cannot but believe that in the past history of our planet the influence of the ocean has been far more conservative than destructive. Beneath the reach of the waves the surface of the abraded land has escaped the demolition which sooner or later overtakes all that rises above them; and there, too, in those submarine depths, the sedimentary materials have accumulated out of which the existing continents have been framed.

V. *Conclusion. Bearing of Modern Denudation upon the value of Geological Time.*

In the foregoing pages, denudation has been treated as a process now advancing before us, and producing certain measurable results. In casting our eye backward along the past history of our planet, we see that similar results have been effected in former geological ages, and as we know of no other agents by which they could have been produced save those very agents which are still at work, we infer that the operations of nature have been carried on upon the same plan, and that the present system of change upon the surface of the earth represents the system that has always obtained. It is not necessary, however, to assume, as is too often done by modern geologists, that the present rate of change has always been uniform, and must be taken as the measure for all past and all future time. Though we have good reason to believe that denudation in the past has been the result of the same agencies by which it is still produced, we are not warranted to conclude that these agencies have always acted in precisely the same proportion and at exactly the same rate. The present system may indeed represent a fair average, as it is certainly the only one on which we can safely base any speculations regarding the past changes of the earth's surface. But we must not dogmatically assume that no other rate of change could have been possible, or that uniformity of causation as measured by human experience, is an established truth. The circle of that experience is still too narrow to justify such assumptions. Only within the last few years Mr. Croll has taught us how materially the changes in progress upon the surface of the earth may be modified by cosmical causes, which recur at certain definite intervals. And there may remain other influences to be discovered which have told upon the mutations of our planet's surface, and which, therefore, will need to be taken into account by the philosophical geologist.

But while caution is thus on every account necessary, we are still at liberty to maintain that of the two modern schools of geology—the *Huttonian* or *Uniformitarian* and the *Catastrophic*—the former has an overwhelming balance of probability in its favour. It bases its deductions, not upon inference, but upon the order of nature as ascertained by experience—the only basis on which any sound exposition of physical phenomena can be laid. So long as its views are not pushed to an extreme, and its assumed premisses treated as actually demonstrated truths, it provides us with the only satisfactory method which has yet been discovered for elucidating the bygone history of our globe. Pure *catastrophism* (if one may venture to make use of such a word) will certainly lead us into error; mere *uniformitarianism*, as usually understood, will not bring us into the whole truth.

I have thought it necessary to make these remarks as indicative of the value and real place of the suggestions which remain to be added as a conclusion to this essay. It seems to me that though we are not at liberty to assert that the present rate of change upon the earth's surface has been on the whole uniform from the earliest geological times, nevertheless as it is the only rate of which we have any actual experience, and as it accords with all evidence of changes in the geological past, we are warranted in the meantime to assume it as an average. If the rate has varied, and most probably it has done so, there is some reason to suppose that the variations have on the whole tended rather to the increase of denudation, or, in other words, that the present rate, if not an average, is rather below the mean than above it. In assuming the existing rate therefore as an average from which to speculate upon past changes, I do not think that we shall be likely to exaggerate the results.

When we calmly look at what the various denuding forces are now doing, and when we try to gain a vivid idea of the loss of land by measuring the amount of material which is annually removed from land-surfaces, we cannot but be struck, I think, by the unexpected rapidity of the process. Denudation is commonly appealed to as one of the geological phenomena, which, as measured by results, best attest the enormous duration of geological periods. And this conclusion is based upon the idea that the present rate of denudation is inconceivably slow. Yet, as we have seen in the previous pages, the rate of waste actually in progress would in a few millions of years suffice for the washing away of all the solid land on the face of the globe. The proportions already given for the rate of waste among the different agents of denudation and in different areas of the globe, may be modified, but the general result will doubtless remain, that modern denudation is in reality a far more gigantic and rapid process than we have been apt to believe, and that our demands for enormous periods, in so far as based upon the evidence of past denudation, are unnecessary.

Denudation and deposition are phenomena inseparably connected; the one is the counterpart of the other. If, therefore, all evidence from living nature goes to show that geologists have been in error in requiring too vast a time for the removal of large masses of solid rock, the same evidence suffices to indicate, that they must be equally wrong in demanding enormous periods for the accumulation into stratified rocks of the material so removed. The whole of that chain of reasoning which, assuming the extremely slow rate of waste of a land surface, and the inconceivable tardiness of the growth of a thick mass of stratified deposits, deduces therefrom the incalculable duration of even a single geological period, seems to break down when it is tested by the facts of modern denudation.

Recent researches in physics go to shew that the unlimited ages demanded by geologists cannot be granted.[1] We have been drawing recklessly upon a bank in which it appears there are no further funds at our disposal. It is well, therefore, to find that our demands are really unnecessary; that even the facts of our own science do not require those exorbitant drafts upon the past.

There is, however, a line of objection to this argument in favour of briefer intervals in geological history, the importance of which I am far from under-estimating. It may be granted that the physical evidence certainly favours a curtailment of geological time, but it may be strongly objected that the palæontological evidence goes exactly in the opposite direction. Under any view of the origin of species, a long time must needs be demanded for the appearance and disappearance of successive tribes of plants and animals. And the palæontologist may naturally demur to any explanation of geological phenomena which would deprive him of an appeal to unlimited time for the past development of life upon the earth. I cannot but think, however, that such reluctance would mainly arise from the difficulty of adequately conceiving the length of even comparatively brief periods. When a sum rises above a few hundreds of thousands the mind ceases thoroughly to realize it, and each successive cypher which may be added produces no corresponding impression upon us.[2] Probably the palæontologist would find that the periods, as defined by purely physical evidence, would still remain quite vast enough for the accomplishment of the long history of life. Nor must he forget that changes in the organic world must be to a large extent regulated by those of the inorganic world. If, therefore, we could shew conclusively that physical changes in past time advanced more rapidly than had been supposed, it would be necessary to consider whether the periods

[1] See *Sir W. Thomson* Trans. Roy. Soc. Edin. vol. xxiii., p. 157. Macmillan's Magazine for March, 1862. Trans. Geol. Soc. Glasgow, vol. iii., part 1. *James Croll*, Phil. Mag. 4th ser. xxxv., p. 363, and xxxvi., p. 141. About 100 millions of years is the time assigned within which all geological history must be comprised.

[2] See Mr. Croll's paper in *Phil. Mag.* for May, 1868.

demanded for the growth and extinction of species and genera might not have been likewise exaggerated. From the data furnished by the denudation now in progress, it seems tolerably certain that geologists have required, for the accomplishment of past denudations, periods of time much greater than our experience of the present economy of nature warrants. It might be well, therefore, if the palæontological argument were re-examined with the view of ascertaining whether the intervals of time, which it postulates, might not all be easily comprised within the limits required by physical data.

The above paper was published in *Transactions of the Geological Society of Glasgow,* Vol. 3 (1868), pages 153-190.