CHEMICAL DENUDATION

IN RELATION TO

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T. MELLARD READE

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BY

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London:

DAVID BOGUE,

3, St. Martin's Place, Trafalgar Square, W.C.

1879.

DEDICATED

(BY PERMISSION)

TO

ANDREW C. RAMSAY Esq., LL.D., F.R.S., &c.,

(Director General of the Geological Survey of the United Kingdom),

AS A SMALL MARK OF PERSONAL REGARD

AND APPRECIATION OF HIS GREAT SERVICES IN PROMOTING

THE STUDY AND ADVANCING THE SCIENCE OF

PHYSICAL GEOLOGY.

INTRODUCTION.

The special line of investigation characterising the three papers now published together, has developed itself from an attempt to estimate the amount of solid matter conveyed annually in solution in river water to the sea from the surface of England and Wales.

The method was found so fruitful in suggestions, that by the time I had completed what proved an intricate calculation, a vista of the immensity of past time seemed to open out, with a new modulus with which to gauge it ready to hand.

The original idea (though not in a fully developed form) was embodied in my first paper on "Geological Time," delivered as my Presidential Address to the Liverpool Geological Society in 1876.

The information contained in this paper excited considerable interest among Geologists, both in this country and America.

Through the reception it met with, and by natural inclination—in fact, by thought almost spontaneous—I was led to further develope the ideas the investigation had given birth to.

The second paper of the series, on "The Geological Significance of the *Challenger* Discoveries," though principally only suggestive, applies some of the discoveries of the *Challenger* to the elucidation of the same question, and embraces them in a chain of reasoning based on the facts disclosed in my first investigations.

The third and final paper, on "Limestone as an Index of Geological Time," read before the Royal Society this year, is an attempt of a more comprehensive nature than either of the preceding.

By an examination of all that is known and inferred of the original constitution of the Earth, and a reduction of the possibilities of its cosmogony within certain limits, I have attempted to form a basis upon which to reason.

By a logical application of the methods developed in my previous papers, together with a review of what is known of the sedimentary structure of the Earth, I have essayed to arrive at a *minimum* limit to the "Age of the Earth;" with what success I leave men of science to judge.

Though quite conscious of the imperfections of workmanship, almost necessarily dependent upon the opening out of a novel line of investigation, I am induced to think that by presenting the whole of the matter to Geologists, in the form and sequence in which it originated, whatever of value it may possess will be enhanced. At all events, it will enable them to form a judgment of its significance, which a perusal of only scattered papers would scarcely enable them to do. I trust that what might be looked upon as a dreary array of figures, were it not for the consequences involved, may be found to yield some little profit to the science of Geology, as it certainly has afforded much pleasure to the Author.

With these few words I submit the work to those interested in those great problems of Geology which in our own time have led up to one of the most remarkable developments of thought in the history of the human mind.

Tabulated Statement of the Total Solids in Solution remove

Depth of Rain, in Inches.	Area of each depth of Rainfall in English square miles, arranged according to the Strata.	Total of each Depth, in English Square Miles.	NAMES OF COUNTIES.	DESCRIPT OF STRATA
Over 75	333·68	....	.......Wales......	Cambrian, Silurian, Rocks.
	49·29	....	......Devon......	Granite.
	233·19	....	.. Cumberland....	Silurian and Granit
		616·16	....	....
From 50 to 75	2065·90	....	.......Wales......	Silurian, Old Red, C
	253·89	....	......Devon......	Granite, Devonian, rous, Millstone G
	1173·14	....	.. Cumberland....	Silurian, Carbonifer
		3492·93	....	....
From 40 to 50	2813·52	....	.......Wales......	Cambrian, Silurian and Carbonifero
	2352·90	....	......Devon......	Granite, Devonian, Grit, Yoredale F
	2178·43	....	Cumberland and Northumberland.	Silurian, Mountain Carboniferous, M and Permian...
		7344·85	....	....
From 30 to 40	1669·86	....	...... Wales......	Silurian, Old Red, Carboniferous .
	492·43	....	...... Do.	Mountain Limesto boniferous .....
	1290·65	....	....South Coast ..	Old Red, Millstone Red, and Marls .
	132·99	....	...... Do.	Silurian and Devoni
	3940·87	....	...... Do.	Lias, Wealden, and
	418·50	....	....South West ..	Mountain Limesto ferous, New Red
	1129·95	....	...... Do.	Lias and Oolites .
	5156·97	....	North of England.	Mountain Limeston Ditto, Millstone Measures, Permi Red..........
		14232·22	....	....
From 25 to 30	....	14876·17	.. Mid England. .. from Lancaster.	½ New Red, ⅓ Cre Oolites ....
Under 25	....	17737·67	East of England.	New Red, Lias, Oo ceous, and Lond
		58300·00		

Mean Depth run off Ground per annum = 18·3 inches. Mean Rain

Mean of Solids in Solution = 12·23. Total Solids in solution, 8,3

or = ·093 of an inch. That is, it will take 12,978 years to denude the

GEOLOGICAL TIME.

Presidential Address to the Liverpool Geological Society. Session 1876-7.

Since the time when Hutton laid the foundation of our present knowledge of Physical Geology, our acquaintance with the structure of the Earth has advanced with rapid strides. The various formations have been reduced to order and sequence through the combined influence of Palæontology and careful Stratigraphical Surveying. But to make Geology essentially a science, the mathematical method must step in to measure, balance, and accurately estimate.

Though fully recognising that there still remain vast and varied unexplored fields for original research, the direction of advancement will be towards reducing those comprehensive generalisations for which we have to thank the old generation of Geologists—now almost past away—and their rough though wonderful approximations to truth, to careful and accurate measurement.

Instead of giving you, as is usual on these occasions, a *resumé* of geological progress during the year, I purpose devoting the time to what I trust will prove, in my case, more valuable, viz., an investigation of the nature and amount of the solvent action of rain-water upon the crust of the earth, and its influence in that direction as an agent of denudation.

There have, as you know, been various estimates made of the amount of mechanical denudation caused by rain, calculated upon the amount of mud held in suspension and carried annually to the ocean by our great rivers; and all of us whc prize Lyell's Principles will remember the masterly manner in which he treats the question in the case of the Mississippi and the Ganges, with the Brahmapootra. Other geologists have also calculated from the same data and the area of the river basins, the amount of time it takes to reduce the whole of these river basins one foot in depth; the result being in the case of the Mississippi 6,000 years, and the Ganges 2,300 years.

There have also been estimates of the amount of carbonate of lime carried into the sea annually by the Thames and other rivers draining calcareous districts; but, even if it exist, I am not aware of any attempt having been made to estimate as a whole the soluble constituents removed annually from the varied formations which constitute the crust of the earth. Most of you, no doubt, are aware of the valuable information contained in the Sixth Report of the Rivers Pollution Commission. and the wonderful elaboration and accuracy of all the information relating to the potable waters of Great Britain.

When first I turned over its pages it at once occurred to me that here is the very thing which a geologist wants for the solution of several interesting problems! I made up my mind that I would use it on the very first opportunity. The present I consider a suitable occasion. In page 131 of the report is a table of the average composition of unpolluted potable waters, commencing with rain water, but it is chiefly the upland surface waters that I purpose dealing with to-night. In the first column we get the ' total solid impurity," which means the total ingredients held in solution, consisting practically of the *soluble inorganic ingredients*, as the proportion of organic constituents is almost invariably very weak. For an explanation of the other columns I quote from a letter Dr. Frankland kindly sent me, and without which I could have made but a limited use of the stores of information collected, through the analyses having been made in a form suited to the immediate object of the Commission. He says:

. . "'*Ammonia*' is generally present in very small quantity, and may be left out of consideration. It is probably always present as Carbonate of Ammonia, and is therefore an *in*organic constituent.

'*Nitrogen*' as nitrates and nitrites means almost invariably nitrogen as nitrates, since the occurrence of nitrites in any but shallow well water is exceedingly rare. If you multiply the numbers in this column by six, you will obtain with close approximation the weight of nitrates in the water.

'*Chlorine.*'—This exists practically as 'chloride of sodium,' and if you multiply the numbers in the chlorine column by 1·65, you will get approximately the proportion of common salt. 'Temporary hardness' means in most cases (except water from Dolomite or Coal-measures, in which there is a good deal of carbonate of magnesia) carbonate of lime, with a little carbonate of magnesia.

'*Permanent hardness*' means, except as aforesaid, hardness produced by sulphate of lime; and if you multiply the numbers in the column by 1·36 you will get approximately the proportion of *sulphate of lime*, with a little sulphate of magnesia.

Of ingredients of any importance there only remain: Alkaline sulphates—that is, sulphate of soda and sulphate of potash.

Carbonate of Soda.

Silica.

Iron.

Of these, the last two are rarely present in any but very small proportion—about 1 part of silica and 0·1 part of peroxide of iron in 100,000 parts of water."

With this preliminary information I proceed to explain my application of the data for a solution of the problem before us—that is, the estimation of the total solids annually removed by the solvent action of rain from the surface of England and Wales.

To have gauged every river and stream delivering into the sea during a period of say ten years, and to have analysed the water in each case from day to day under the varying circumstances of the dry weather and flood flow, would no doubt have been the most accurate way of determining the question. It is needless to say such a course is fraught with too much labour and expense to be practicable to any individual. There is, however, another method used by engineers, accustomed to design water-works, for estimating, in the absence of gaugings, the flow off the land which gives us what we want with sufficiently close approximation.

By taking the mean rainfall over a given area, and then allowing a certain depth for evaporation and absorption, with judgment, the flow off the land can be arrived at with tolerable accuracy. In the case of several rivers, through elaborate gaugings and observations of the mean rainfall of the basin, it is known with certainty what the proportion is. In the Thames basin, for instance, with a mean rainfall estimated at 27 inches, only 8 inches reaches the sea; whereas in the basin of Loch Katrine, in the area of rainfall exceeding 75 inches of Symons' Hyetographical map, 81·7 inches, according to Bateman, and at Rivington Pike, in the area of between 40 and 50 inches of the same map, according to Stephenson, 39·8 inches runs off the ground. The yield of a gathering-ground is in all cases determined by the total rainfall, the nature of the rocks, and the steepness of the land surface.

In a porous area and small rainfall, like the Thames basin, the maximum of loss takes place, measuring in that case 19 inches per annum; while in the mountainous tracts of siliceous rocks in Wales and Cumberland it is doubtful if more than 10 inches is lost.

My method of procedure thus has been to take out the areas of rainfall from Symons' Hyetographical map attached to the report, to allow to the best of my judgment for evaporation, and then, grouping the formations together in each rainfall area, to estimate the number of tons of water yielded by each gathering-ground annually. Instead of, however, taking out each group exactly as given in Dr. Frankland's table referred to, I have roughly divided them where it could readily be done; and in other cases, judging their relative proportions, I have added up the figures opposite the "Total solids in solution" given for surface water off each formation, and then averaged the results before multiplying the total yield of water by the fraction of 100,000 in that way obtained. I consider that this method is more likely to be near the truth than a more minute analysis. A reference to the table prepared will, however, explain the operation better than any description by me. I have exercised very considerable care in the calculations, so I trust they may be relied upon as close approximations.

As there is a certain amount of chloride of sodium in most rain water, due to the spray of the sea being carried inland, I have deducted the average amount from the "Total solid impurity," as not being a product of denudation; but I have not deducted the other solids in solution in the rain, for primarily they must emanate from the land itself. This, however, is but a small fraction of the whole.

Looking at the more remarkable features developed by this analysis, perhaps the one I was least prepared for is the curious way in which the smallest percentages of solids in solution, such as is contained in water from granitic and metamorphic rocks, rise in the aggregate, through the greater rainfall on these formations, to the total solids in solution from such specially soluble rocks as constitute the Thames basin.

With few exceptions, in England the greatest rainfall follows the older formations, whether as cause or effect it is difficult to say; but the older formations constituting the higher grounds collect more rain, while the denudation being so much greater has no doubt had a tendency to cut down the rocks formerly overlying them so as to expose the old rocks forming the core beneath. Will not this help us to understand those grand examples of denudation in Wales so forcibly shown by Ramsay to have taken place, and which I called your attention to in my last address.

Is it not strikingly apparent from this what a leveller the rain is? Certainly it was never brought to my mind so vividly before.

A reference to the Geological and to the Rainfall maps of England, and a comparison of them, shows that the mountainous districts, generally composed of rocks from the Cambrian to the Carboniferous, being situated on the west coast intercept the greatest rain, which is from the south and north-west, and that here in Devon, Wales, and the Lake district of Cumberland and Westmoreland, the rainfall ranges from 50 to over 75 inches.

The extremes of rainfall in 1874 were at five stations in the Lake district, from 107·53 at Little Langdale to 148·79 at Seathwaite; while in Wales, at three stations, it was from 116·56 to 149·00 inches. The smallest, as might be expected, was on the east coast, ranging from 12·85 at Chatteris, in the Isle of Ely, to 14·97 at Ipswich; and in Wales from 22·33 at Holywell, to 27·96 at St. Asaph.

The rainfall, expressed in inches, if distributed evenly over England and Wales, would be for 1874, 34·02, or 1·50 below the average from 1860 to 1865, if we take the mean of all the stations. Estimated, however, by areas, as given in Symons' map, the mean rainfall of England and Wales, is 31·988 or say 32 inches.*

Dividing the country in sections, as shown in the table, and estimating each separately, gives a total of 68,450,936,960 tons of water run off the area of England and Wales annually, equal to 18·3 inches in depth, which leaves 13·7 inches for evaporation.† The total solids in

* The difference arises from the fall at some of the mountain stations being much in excess of the average; and the areas of this excessive fall being restricted, the mean of all the principal stations naturally gives the excess we see. Mr. Symons, in a letter to me, says he has never worked out the mean rainfall, but is "under the impression it would come out about 35 inches."

† It must not be lost sight of that it is the *evaporation* only that affects our calculations. Water that *percolates* will find its way eventually into the river system, or directly by springs into the sea itself. This water is, of course, more highly charged with mineral matter than surface water, and may help to balance flood surface water, which often contains less than the mean quantity of soluble mineral matter. On the whole, it will be seen that the figures work out fairly in unison with each other.

solution amount to 8,370,630 tons, or 12·23 parts in every 100,000 of water. This total includes, calculating on the method pointed out by Dr. Frankland, and on the averages of the samples 9·50 parts of the carbonates and the sulphates of lime and magnesia, the sulphates predominating in the averages of the water from all the rocks below the New Red and the carbonates in those above the Permian, reaching its maximum in the Cretaceous. The average amount of chloride of sodium, deducting ·36 as that contained in the rain, is 1·66 for the upland waters. The nitrates amount to ·08.*

There is now left ·99 for the alkaline sulphates and carbonates of soda, silica, and peroxide of iron.

I have intentionally taken the upland surface water as a Geological basis to work upon, for in consequence of drainage works, artificial manures, and other disturbing causes incidental to a thickly populated country, the primitive denudation of the world is not accurately represented by the constituents held in solution in most of our river waters far down their course. The chloride of sodium in the Thames water, for instance, as supplied by five different companies, averaged in 1873 3·1 parts in 100,000, and most of this is no doubt of artificial origin. In the Mersey at its junction with the Irwell the chloride of sodium is 4·12, and in the Irwell at its junction with the Mersey it reaches the enormous amount of 21·28 per 100,000.

Again, the drainage and culture of calcareous soils adds considerably to the amount of the carbonates and sulphates of lime held in solution, and these disturbing

* The averages of all the samples of upland water give 12·66 as the total solids in solution, which is a very close approximation to the 12·23 estimated in the totals as before described, and is calculated to verify the accuracy of the method I have adopted.

causes I have endeavoured to eliminate from my calculations.

If we may estimate the various solids held in solution at 15 feet to the ton, the weight of limestone,* the amount of denudation if distributed equally over the area of England and Wales reckoned at 58,300 square miles would be ·0077 of a foot per century, that is it would take 12,978 years to reduce it one foot.

It is certainly a rather remarkable coincidence of figures that Professor Prestwich, I find, in his address to the Geological Society of London, 1872, calculates that the Thames removes from the Chalk, Upper Greensand, Oolitic strata and Marlstone, carbonate of lime alone to the extent of 1 foot over its basin in 13,200 years. This he arrives at by referring 10 grains to the gallon on the total discharge at Kingston to these strata, estimated at 2,072 square miles. The total denudation due to solids in solution over the whole area is, as will be seen further on, 149 tons per square mile per annum, as against 140 tons of carbonate of lime alone removed from the restricted area calculated by Professor Prestwich.

Taking the Carbonates and Sulphates of Lime and Magnesium at 9·5 and 15 feet to the ton, that would represent the removal of those substances in solution at the rate of 1 foot in 16,707 years.

The Chloride of Sodium estimated at 1·66 would represent the removal of 1 foot in thickness (16 feet to the ton) of Rock Salt in 89,640 years.

The remaining portions consisting of Silica, Alkaline Sulphates, Peroxide of Iron, &c., have not been directly determined by analysis, and are therefore only very

* Some very compact limestones only contain 13 feet to the ton.

rough approximations. The analyses of river waters by Bischof * shew these ingredients to be very variable, even in the same river at different times. If we estimate them at 12 feet to the ton, ·99 parts per 100,000, would give 200,405 years to remove 1 foot in thickness.

After very carefully reviewing my data and calculations, I am of opinion that these figures in the main represent very nearly what would be the denudation of England and Wales in their primitive condition, before the hand of man had interfered much with the surface.

If, however, we desire to know what is now being removed, I think we must increase this estimate by one-fifth, as Dr. Frankland's analyses clearly shew that cultivation of the land, and drainage especially in calcareous districts, increases the soluble substances in the water to a very considerable extent.

It would have been impossible to rely upon the data had not a very great number of samples been analysed, taken, be it observed, at all seasons of the year, for we find these averages tend to correct one another, and to give a very close approximation to the aggregate result.

Stated simply, this then, is the result. If we imagine the area of England and Wales, consisting of 58,300 square miles, to form one river basin, the delivery of water by such river would be 68,450,936,960 tons, or 18·3 inches per annum, containing a total of 8,370,680 tons of solids in solution, representing a general lowering of the surface from that cause alone of ·0077 of a foot per century, or one foot in 12,978 years.

Thus far we have got with our geological modulus of time; but before attempting to apply it to the solution of the larger problems of Geology, let us see if we can

* Chemical and Physical Geology, Vol. 1, p. 76.

institute a comparison between England and the other parts of the world best known and Geologically surveyed.

A reference to the Geological Map of the world, constructed by Jules Marcou, shews that in the continent of Europe the principal difference from the Geology of England is the much greater development of what in his classification are Crystalline Rocks, consisting of gneiss, metamorphic rocks, granite, porphyries and trappean rocks, principally situated in Norway and Sweden, and the Tertiaries in mid-Europe, between the Baltic and the Black Seas. Roughly speaking it is easy to see that in England and Wales a line may be drawn, dividing them into two nearly equal halves, on the western side of which are the rocks from the New Red downwards, and on the eastern the rocks from the Lias upwards, including the Tertiaries. I have, at considerable trouble, calculated the areas of the several formations of Europe from Jules Marcou's Map.

They are approximately as follows:—

	English Square Miles.
Modern Rocks	468,277.
Tertiary do.	613,043.
Cretaceous Rocks	552,282.
Jurassic do.	246,983.
New Red Sandstone	466,292.
Carboniferous Rocks	181,940.
Paleozoic or Grauwacke	463,661.
Crystalline Rocks	714,960.
Volcanoes and Basalt	13,062.
Total	3,720,500.

It will thus be seen that the formations from the base of the Jurassic up to the Modern Rocks constitute almost exactly half of the continent, and those from the New

B

Red downwards, inclusive of the Volcanoes and Basalt, the other half; consequently the dividing line is nearly the same in the Continent as in England and Wales. The Geological structure of England is almost an epitome of that of Europe, excepting that in the Continent the Carboniferous rocks are in less force, and the Tertiary and Metamorphic in greater.

The average solubility of the rocks, I suspect, is not very different on the Continent from that of England, but the rainfall is less, averaging, according to Sir John Herschell,* 23 inches for the *non*mountainous districts, and 42 inches for the mountainous ones.

We may, therefore, assume that the total solids in solution removed annually are proportionally not so great as in England, excepting in the Swiss mountains, where, no doubt, the denudation is more rapid than in any area in England or Wales.

As bearing upon this comparison, I have collected all the available information I could as to the discharge of several of the principal rivers of Europe; and though the data is imperfect in many particulars, the facts bear out the views I have just stated.

The Rhine, the Rhone, and the Danube all rise in the Alpine district, and flow to the west, the south, and the east, through formations of which the basin of the Thames and the Severn, would form, perhaps, the nearest English equivalents. The basin of the Rhine is rather more than the area of England and Wales; so we may readily institute a comparison between the country drained by the Rhine and England. Above Lauterbourg, its area is 63,000 square miles, and the annual discharge of the river is 34,216,560,000 tons, equal to a depth of 8·53

* Physical Geography, 4th Edition, p. 241.

inches.* The rainfall is from 16·4 inches at Frankfort-on-the-Main to 26·3 at Bonn; but, of course, it is also fed by the Alpine snows through the Lake of Constance. The mean of the analyses of solids in solution, as given by Bischof, is 17·1, say 17 in 100,000, this gives 5,816,805 tons per annum, or 92·3 tons per square mile.

The Rhone at Avignon has an area of 35,745 square miles, and an annual discharge of 53,144,040,600 tons, equal to 22·86 inches in depth. The mean of four analyses given by Bischof is 15·6, which will give 8,290,464 tons of solids removed per annum in solution, or 232 tons per square mile.

The Danube has an area of 310,000 square miles, and the mean discharge into the Black Sea, from ten years' observation is, according to Sir C. A. Hartley, M.I.C.E.,† 207,000 cubic feet per second, equal to 181,332,000,000 tons per annum.

The discharge appears, however, to be very variable, the maximum being 383,000 cubic feet per second in 1871, and the minimum 125,000 cubic feet per second in the years 1863 and 1866.

The rainfall at Sulina also varies from 10·08 inches to 34·28, the mean for ten years being 18·76 inches; but whether it is as variable over the whole basin I cannot say.

This discharge equals a depth of 9·06‡ inches run off the ground, or one-half of the mean rainfall at Sulina. The amount of solids in solution was 12·42 at Vienna. Bischof, however, only gives the one analysis. If this is an average quantity, the total solids in solution would amount to 22,521,434 tons per annum, or 72·7 tons per square mile, or as nearly as possible one-third of the

* Beardmore's "Manual of Hydrology."

† "Minutes of Proceedings of the Institution of Civil Engineers," vol. xxxvi, p. 224.

‡ Stated in error at 6·8 inches in the First Edition of this Paper.

average amount of matter held in suspension, which is given as 67,760,000 tons, estimated from surface samples.

The total drainage area of these three great rivers is, therefore, 408,745 square English miles, their annual discharge 268,692,600,600 tons, and the total solids in solution 36,628,703 tons.

Comparing this with the calculated denudation of England, it amounts in England to 143·5 tons per square mile and 90 tons per square mile in the three European river basins.

The data for these latter calculations are, indeed, insufficient, more especially as regards the Danube, from the absence of analyses at more points than Vienna. I think it extremely probable that the estimate should be increased, as the direct determination of the solids in solution amounts to 14·14.

The result is, however, in accordance with what we should *a priori* expect; the greater rainfall on the western coast produces its effect upon the land, not only in removing detritus mechanically, but in its solvent action upon the rocks. It works more quickly.

The Garronne removes 142 tons per square mile.

The Seine contains, according to two analyses by Bischof, 21·72 parts per 100,000. The drainage area is at Paris 17,111 square miles, and the discharge equals 6·98 inches per annum; it therefore removes about 97 tons of solids in solution per square mile.

The Thames, estimating the discharge at eight inches per annum and the total solids in solution at 29·26, as given by Prestwich, removes 149 tons per square mile per annum.

It is thus seen that there is much less variation than one would have expected between the soluble constituents removed by one river and another; for if we compare the maximum of our examples, which is the Rhone at 232 tons per square mile per annum, with the minimum, the Danube at 72·7 tons, we find there is only about the same difference between them as there is between the maximum and minimum annual discharge of water of the Danube itself! If, on the other hand, we compare the quantity of solids in solution removed to the solids in suspension, we find that the former is a much more constant quantity. The detritus carried down to the Black Sea by the Danube was, in 1866, 12,500,000 tons, and in 1871 it rose to 154,000,000!

It is also evident that the character of the solids in solution is determined by the nature of the rocks the water flows over. On the western half of England the sulphates of lime in the upland waters predominate over the carbonates in the proportion of 7·15 to 2·9; while in the Thames area the carbonate of lime is in excess of the sulphate in the proportion of about two to one. It is extremely probable, therefore, that over the whole area of England and Wales the carbonates and sulphates of lime are about equal.

On taking the mean of eighteen analyses of water from European rivers, given by Bischof, I find the carbonates in excess of the sulphates of lime in the proportion of 9·32 to 1·79. Bischof, himself, says, "Among the mineral substances in these rivers, carbonate of lime is always in the largest quantity." The basins of these rivers are, however, composed nearly wholly of the strata above the New Red Sandstone, excepting as regards the Crystalline rocks. The Volga is a river flowing through the New Red; of this water I have no analysis, but, as might be expected, the sulphates of lime predominate over the carbonates in the Caspian

Sea, which receives its waters. The mean of two analysis, one by Göbel, the other by H. Rose, gives 89·6 parts per 100,000 of sulphate of lime to 18·9 of bicarbonate of lime.

It is evident, therefore, that, estimated over the whole Continent of Europe, and taking into consideration the proportions of the various rocks, the carbonates of lime will still be in excess of the sulphates.

The extensive development of Carboniferous strata in England, together with the New Red, to a large extent accounts for this diversity between England and the Continent; but the proportional excess of sulphates of lime in the Thames water over the Continental European river waters may perhaps be partly traced to the more artificial state of the Thames basin. If the information we require is limited with respect to Europe, it is still more restricted in relation to the rest of the world. Of the geology of Asia our knowledge is very partial and very indefinite, as a glance at Jules Marcou's map will show. To calculate the proportion of the various formations would be impossible, with the accuracy required for our purpose. Dr. Frankland has, however, kindly supplied me with several unpublished analyses of water in various parts of the world, and among them is one of Tienshan Lake, in China, in which the total solids in solution are 13·10 per 100,000. Of these 5·31 are due to carbonate of lime and 1·91 to sulphate of lime. The River Wangpoo, above the influence of ordinary tides, has 10·46 per 100,000 of solids in solution, of which 4·14 are carbonates and 1·57 sulphates of lime.

Above the bridge at Wangdoo the water holds 21·54 of solids in solution, of which 9·31 are carbonates and 1·65 sulphates of lime; at Tyking 30·52 of total solids in solution, of which 11·30 are carbonates and 3·88 sulphates of lime.* The chloride of sodium in Tienshan Lake amounted to 1·71, and in the Wangpoo to 1·48. The Tisai (Tienshan) Lake, according to another analysis, holds 10·90 solids in solution, of which 5·31 are carbonate and 2·32 sulphate of lime, while the chloride of sodium is 1·73.

There are other analyses by Dr. Frankland, but I cannot make any deductions from them, as the samples were apparently taken within the influence of the tides.

In South America an analysis of the Parana in front of Carabelos gives 10·08 of total solids in solution, of which ·28 was carbonate of lime and 3·03 sulphate, and 2·97 chloride of sodium, the nitrates amounting to ·42.

It is rather a pity this analysis did not determine the separate amount of each constituent, as there is a large balance to be accounted for, viz., 3·38 to be divided between the alkaline sulphates, carbonate of soda, silica, and iron.

I have now pretty nearly exhausted all the information I can bring to bear on the "matter removed in solution in river water," which, for brevity, I shall call "*Soluble Denudation.*"

The rainfall is so variable in different parts of the world, that it is difficult to estimate the average annual amount of the "Soluble Denudation" of the globe; but we find that Nature, on the whole, averages the results; and, though there is as much as 300 inches of annual rainfall in some places in the tropics, and 600 inches, or 50 feet, on the Khāsi Hills at Cherra Poonjee, on the other hand we have great rainless districts in the interior of Africa and Asia. The River Nile, with a basin of 600,000 miles, above Cairo, according to Girard, runs off only 3·78

* Probably affected by the tide.

inches per annum; but this, if the data of my calculations are reliable, must be in excess of the actual depth.*

The Ganges at Sikreegulee, with a basin of 330,000 English square miles, runs off 20·51 inches per annum.

The Mississippi and Missouri have a basin of 1,300,000 English square miles; and according to Messrs. Humphreys and Abbott, as quoted by Lyell, 132·36 cubic miles of water are discharged annually, equal to 8·19 inches in depth over the whole area.†

Keeping the above facts in view, and seeing how constant a quantity the solids in solution are, for when the rainfall is small the river water as a rule holds a larger proportionate quantity of dissolved matter; and taking into consideration what we know of the geology of the world, I think we have sufficient grounds for a provisional assumption that about 100 tons of rocky matter is dissolved by rain per English square mile per annum.

Of this total, if we allot 50 tons to carbonate of lime, 20 tons to sulphate of lime, 7 to silica, 4 to carbonate of magnesia, 4 to sulphate of magnesia, 1 to peroxide of iron, 8 to chloride of sodium, and 6 to the alkaline carbonates and sulphates, we shall probably be as near the truth as present data will allow us to come.

Before leaving the subject, let us now see what light, if any, these figures throw upon Geological Time.

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* The mean annual delivery of the Nile is calculated by M. Talabot at 101,000 cubic feet per second, and its supposed drainage area, according to Herschell, 520,000 square geographical, or 686,400 statute miles. This would give only 2·01 inches run off the ground. (See Herschell's "Physical Geography," p. 210, 4th Edition.)

† This is arrived at by dividing the cubic quantity of sediment by the fraction representing the proportion it bears to the water, that is $\frac{1}{1321}$. Beardmore calculates the depth run off the ground at 8·40 inches.—"Manual of Hydrology."

How can we approach the question? If, as is generally supposed, the sea contains only what is washed into it from the land,* and we can estimate its mineral contents in tons, we at once get a minimum measure of the age of the Earth; whether it will be possible to arrive at a maximum we shall see further on. According to Herschell, the ocean contains 2,494,500 billions of tons of water; and the mean of Dr. Frankland's analyses of sea water gives 48·9 tons of carbonate of lime and magnesia, and 1017 tons of sulphate of lime and magnesia in 100,000 tons. Taking the area of all the land in the world at 51 millions of English square miles, there is in the ocean, in round numbers, 1,222 billions of tons of carbonate of lime and magnesia, or sufficient to cover the whole of it at 15 feet to the ton 12·9 feet thick; and of sulphate of lime and magnesia 25,369 billions of tons, or sufficient to cover it 267·6 feet thick. If, then, we reckon the whole of the sulphates removed from the land at 20 tons per square mile per annum, it would take in round numbers 25 millions of years to accumulate the quantity of sulphate of lime and magnesia contained in sea water, but only 480,000 years to renew the carbonate of lime and magnesia, at the rate of 50 tons per square mile of land surface per annum. We know, however, that the carbonate of lime is constantly being removed by testaceous animals, corals and foraminifera.

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* Herschell says. "Physical Geography," p. 21. As the sea continually receives the drainage of all the land, besides having in the course of countless ages, washed over and over again the disintegrated materials of successive continents, it must of course hold in solution all the saline ingredients capable of being separated and taken up by such lixiviation in cold water; in fact, in greater or less quantity, every soluble substance in nature—such, at least, whose existence in extremely dilute solution are not incompatible.

There is also good reason to suppose that the sulphates of lime are also decomposed by decaying organic matter, and we know from numberless analyses that there is always present in sea water a large quantity of free carbonic acid,* which the result of the "Challenger" expedition proves is sufficient to entirely dissolve the calcareous portions of the dead foraminifera before they in sinking reach the bottom of the greater ocean depths.

The quantity of sulphuric acid in sea water also varies considerably. It is probable, also, that marine organisms can in some way directly utilise the sulphate of lime. Bischof shows very beautifully and clearly that the amount of carbonic acid in sea water is subject to very little variation, and that it is present in sufficient quantity to dissolve five times as much of the earthy carbonates as are actually dissolved, and "that the sea water is so far below its point of saturation as regards carbonate of lime, can only depend upon the constant separation of this carbonate by testaceous animals. By this separation, however, the carbonic acid which had dissolved this carbonate always returns again into the sea water. In the sea, therefore, the solution of carbonates and their separation by organic agency go on constantly, no addition of carbonic acid from without being required." He also shows that the carbonic acid which has been removed in the vapour of water returns to the sea by the rivers.

If we turn to the chlorides consisting principally of chloride of sodium, we find the mean of Dr. Frankland's analyses to be 3,259 parts in every 100,000, which gives 81,295 billions of tons; or, at 16 feet to the ton, sufficient

* Bischof, "Chemical Geology," vol. 1, p. 103.

to cover the whole of the land 914·9 feet deep! * This is certainly a startling result. Reckoning all the chlorides brought into the sea by the rivers annually at 8 tons to the square mile, it would take, in even numbers, 200 millions of years to renew the chlorides of the sea. I have now, I hope, enabled you to form a quantitative idea of the soluble constituents of the globe, so far as we can measure them in water.

The greater portion of the land of the globe is composed of sedimentary rocks, themselves laid down in the seas, lakes, inland seas, or estuaries.

The constituents of the crust of the earth have been again and again dissolved, carried into the sea, separated therefrom by organisms, or by evaporation from portions that have from time to time been cut off from the general ocean, or in that minute chloride dust Dr. Frankland so beautifully shews is constantly being carried into the air from the spray of every wave. What a lengthened vista does not this disclose?

We cannot see the beginning, all that is plain to us is the sequence, the circulation.

The matter of the world is continually changing place—its solvent is the rain, its carrier the river, its receiver and distributor the ocean. How many times the matter of this solid land on which we stand has been in solution, suspension, or moving to and fro on the shore or the sea bottom, it is impossible to say. In the present state of science it defies calculation to reach a maximum beyond which we can say the age of the earth does not extend, for the calculations based upon

* As shewing the necessity to the Geologist of a quantitative knowledge of the constituents of the Earth, even so great a reasoner as Lyell imagines it possible that all the salt in the sea could, during a subsidence of the land, be evaporated in the Runn of Cutch.—See "Principles."

the form of the earth and tidal retardation* are fallacious, through leaving out agencies that we know are at work, and which the calculations I have to-night submitted to you bring out in greater force.

I have said nothing as yet of the comparative potency of mechanical erosion as compared with chemical in reducing the crust of the earth. Strictly speaking, one, however, is the complement of the other. The chemical agency decomposes the matrix, and separates the particles, which the mechanical force of the river in flood carries to the sea. The actual degradation of the rocks by mechanical movement of water containing stones, is a very small matter. The effect of tidal action I have before dwelt upon and explained.

The ocean, I consider, acts merely as a mechanical distributer of matter, which has been introduced from the land; and though tidal action has the power in certain cases of excavating very wide, deep, and long gullies in the shallow seas, its effect is limited by the force and direction of the current, so that it cannot work out its hollows beyond a certain depth below the general floor of the sea. The action of subaërial denudation is on the other hand unlimited, except by the sea-level. It can degrade, excavate, and deepen, so long as anything is left above the water.

The amount of matter brought down mechanically into the sea, in the case of the Danube, we see was $\frac{1}{3000}$ of the water, or about three times the calculated solids in solution. The maximum amount being $\frac{1}{465}$, and the minimum $\frac{1}{73000}$. The solids in solution come down constantly; the mud is pushed along in times of flood. According to Messrs. Humphreys and Abbott the solids in suspension in the Mississippi are $\frac{1}{1321}$ of the

* Sir William Thompson.

water. If we were to take the solids removed mechanically and in solution at six times those in solution, which is a very high estimate, we should have over the whole of the globe 600 tons of denuded matter annually per square mile. † Taking the sedimentary crust of the earth at ten miles thick throughout—a moderate estimate—and allowing for the denudation of the sea and the amount added to sediments by volcanic ejections, matter equal to one-third that which is denuded from the land, we should have annually removed and deposited, matter equal to 800 tons per square mile of land surface, or 40,800 million tons annually. The total surface of the globe is 197 millions of English square miles. A cubic mile of rock at 13½ feet to the ton would weigh 10,903,552,000 tons, so that to cover the whole surface of the globe one mile deep with sediment from the land at the rate of 800 tons per square mile of land surface, would take 52,647,052 years, or 526 million years in round numbers for ten miles deep.*

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* It is not necessary for the accuracy of this calculation that the sedimentary crust of the earth should everywhere now measure 10 miles thick, or even that it should average that thickness, indeed if it were so the estimate of time would have to be enormously increased, because the rocks of one formation are largely derived from the sediments of preceding formations, therefore it is probable that the *maximum* thickness of the whole of the sedimentary deposits is a true guage of the average thickness of rock which has been removed by denudation from the entire surface of the globe. The maximum thickness of the whole of the known sedimentary formations is variously estimated at from 14 to 17 miles.

† Curiously enough since this was written, Amund Elland, in a paper in the *Quarterly Journal of Geological Society*, 1877, Vol. xxxiii, p. 158, estimating the amount of detritus carried down by all the Glaciers descending from the Justedalsbræen, in Norway, covering an area of about 870 square kilometres, considers that 180,000,000 kilograms of mud are carried away annually under the Glaciers. This amounts to about 529 tons per square mile annually.

At $13\frac{1}{2}$ feet to the ton, 800 tons per annum would give one foot of denudation of the land each 2,581 years; so it will be seen that the above is a very moderate estimate of the time which has elapsed since the first of the sedimentary rocks, we are acquainted with, were laid down, on the hypothesis that the denuding agencies had the same average potency as now, and that the area of land surface has been constant.

But it will be said—What proof have we that the denuding agencies were not formerly much greater and more active than now? I reply with Lyell: We have no evidence that such was the case.

It is true that, according to fossil evidence in the earlier periods, the earth appeared to be of a more uniform temperature than now.*

This, it seems to me, would act in the contrary direction, and tend to reduce the rainfall, as it is the mixing of air of different temperatures that produces rain. Again, if we assume the land surface to have been proportionately to the sea greater than it is at present, the evaporating surface would have been lessened; in fact, the forces of nature in this, as in other cases, tend to equalise themselves.

In opposition, therefore, to astronomical calculations, I am prepared to maintain the position of Hutton and Lyell. We may speculate on a beginning, but we can find no trace of it by geological methods, for in no respect do these earlier sediments, so far as they have yet been investigated, lead us up to a particular rock from which the first sediments were derived. The beginning may be a logical necessity, and astronomical and

* See Hooker on Carboniferous plants, Memoirs of the Geological Survey, Vol. II. Also papers by Nordenskiöld and Judd in Geological Magazine and Dana's Manual of Geology.

mathematical reasoning may eventually throw some light upon it, but before then a multitude of circumstances will have to be considered by the mathematician, which he often ignores, through unfamiliarity with geological reasoning.

The calculations I have had the pleasure of laying before you have been laborious, but they have given proportion and definiteness to my ideas of geological cause and effect, and their relations to time. Probably I have dealt too much in figures to make my address as interesting in its delivery as the subject will be found on closer study. It is so vast and complicated that I cannot hope to have given you more than a faint outline of the whole picture as it presents itself to my mind. The value of figures is best seen by those who work them out; but if I have succeeded in demonstrating that the views of geology taken by our greatest masters come out with greater force and truth, the more they are put to the test of calculation—then I have achieved quite as much as I can expect to do, or could hope that you would patiently listen to.

In resigning the Chair of the Society, I wish to express the satisfaction it has given me to meet you all from year to year from the time I first joined the Society, and during the term of my Presidentship, and to thank you for the uniform consideration and courtesy with which all I have said, has been treated. In welcoming my successor to the chair, I can only say that we shall all extend to him the same feeling of good fellowship, begotten of kindred pursuits, which will enable him to perform his duties in the satisfactory manner we know he is capable of, and assist him in upholding the dignity of the science we all love.

ON THE GEOLOGICAL SIGNIFICANCE OF THE CHALLENGER DISCOVERIES.

(Read before the Liverpool Geological Society, November 13th, 1877.)

No knowledge can be more interesting than that which connects us with the past—which attempts to bring the sequence of events in an unbroken history from the earliest geological period to the present time. As a contribution towards the geological history of the world, the discoveries made during the three years' voyage of the *Challenger* have a special significance.

Although the scientific staff are still engaged in formulating the results of the observations, and naturalists in this and other countries are studying the forms of life brought up from the ocean depths, I trust it will not be considered premature and presumptuous of me to call attention to some of the physical problems of geology affected by the remarkable facts which have been now for the first time brought to light.

Without going minutely into details, which can be best studied in the Admiralty Reports* and the Reports to the Royal Society†, it appears to be pretty clearly established that there is a definite relation between depth and temperature throughout the ocean, obscured, it may be in some cases, by local circumstances, but, on the whole, remarkably general and uniform.

* "H.M.S. *Challenger's* Reports on Ocean Soundings and Temperature," Nos. 1 to 7.

† "Reports from the *Challenger*."—Proc. of Roy. Soc., vol. xxiv., p. 463 to p. 636.

Excepting in depths of between 100 and 200 fathoms and under the exceptional circumstances produced by the melting of the Antarctic Ice, the water decreases in temperature from the surface to the bottom. In the North Atlantic ranging from above 70° Fah. at the surface to 35° at 2,000 fathoms, continuing at 35° for the greater depths, which reach, in some cases, over 3,000 fathoms. In the South Atlantic the lowest temperature is 31° in what is called the Western tongue of the Atlantic basin; the lowness of the temperature, it is supposed, being due to an indraught of the Antarctic waters. The temperature sections, to my mind, reflect the greatest credit on the Admiralty and their officers; they are the work of careful practical men, who have not allowed theory to run away with them, and evince a commendable common-sense and scientific grasp of the subject. So regular, however, do they find the results of their temperature soundings, that if in any special cases the minimum is reached at a certain depth and below that the water is uniform in temperature, they assume that it is cut off from the general oceanic basin by ridges at a depth approximately the same as that at which the same temperature is found in the general ocean. This is the case with the Celebes, China, and Japan seas, which, if raised above the general ocean, would, in fact, become lake basins or inland seas.

Now, this lowering of the bottom temperature over such immense areas is certainly a remarkable and unexpected fact, and shews that the secular cooling of the earth must be extremely slow, as to all appearances contact with the bottom does not in any case appreciably influence the temperature of the bottom water.

The water is heated at the Equator and cooled at the poles, but the rate of interchange is unknown, and probably very slow. No undercurrents at great depths are recorded. Of course all currents from the Equator to the poles must come back in some form or other, but the greater bulk of water is just as likely to return in undercurrents at small depths as by a general movement of the whole depth of ocean water. The materials for making an exact calculation do not exist, but I am inclined to think the indraught of bottom water from the poles is decidely slow. The heaviest water, always the coldest, excepting it be more saline, necessarily keeps to the bottom, and when we find that contact with the bottom does not influence the temperature of water that has travelled many miles from the poles to the Equator, we must pronounce it to be an interesting and unexpected fact.* Not less remarkable is the fact that, after penetrating the surface waters of the Equator, the colder temperatures are reached nearer the surface than in more northern latitudes.

Thus we see the conditions of increase of temperature in the ocean are the reverse of those on the land. All investigations of underground temperature show a gradual increase of heat as the earth is penetrated, so that if we take it at 1° per 60 feet,† at 3,000 fathoms (the depth of

* Mr. Mallet, in the "Introduction" to his translation of Professor Palmieri's Eruption of Vesuvius in 1872, says, p. 67:—"By application of Fourier's theorem to the observed rate of increment of heat in descending from the Geothermal *couche* of invariable temperature, and the co-efficients of conductivity of the rocks of our earth's crust, as given by the long-continued observations made beneath the Observatories of Paris and Edinburgh, it results that the annual loss of heat into space of our globe at present is equal to that which would liquefy into water, at 32° Far. (0°C), about 777 cubic miles of ice." This would equal a film of ice all over the globe ·25 of an inch thick, or say 1 yard deep of fresh water raised 1° Far.

† I do not consider this by any means established, the increase varies greatly in different localities, and also with the nature of the rock. See my "Age of the World, as viewed by the Geologist and the Mathematician."—*Geo. Mag.*, April, 1878.

part of the Atlantic), the temperature of the earth at that depth, with the surface of land at the sea level would be—allowing 55° as the normal of the surface—355°, or more than half as high again as boiling water at the surface, while at the same zone beneath the Himalayas it would not be less than 600°. The influence of surface heat and cold extends therefore, by convection, to the greatest depths of the ocean, while on land it is limited by conduction to about 80 feet. What influence on climate this great body of ice-cold water can have it would be difficult to say, but it certainly must make itself felt, and in all speculations on changes of climate the effect of former shallow or enclosed seas must not be lost sight of. It is also quite clear that the tendency of the spreading of the cold water of the poles over so large an area of the globe must be to ameliorate the climate of the poles as its place is taken by water of a higher temperature, and it would thus seem that the great depth of the Atlantic and Pacific Ocean is a means of equalizing the temperature of the globe. In addition to the climatic effect of the geographical distribution of land and sea, the actual form and depth of the ocean bottom is a factor that has not been previously considered.

Not the least interesting of the facts brought to light by the *Challenger's* work is the distinctive character of the deposits in relation to the depth. The extended deposits of Red clay which are found to fill up most of the basins below 2,000 fathoms, * and the accompanying nodules of peroxide of Manganese are discoveries of great geological importance. They not only show that chemical changes are taking place, previously unsuspected, but the nature of the deposit is pointed to as

* Mr. J. Murray, on Oceanic Deposits.—"Proc. of Roy. Soc.," vol. xxiv. p. 527.

an indication of the great age of the present oceans. Of course, it is impossible to tell the thickness of this Red clay, but if Mr. Murray's explanation be the correct one, and it is the most reasonable yet advanced, the deposit is the result of the decomposition of volcanic products.

Who, I ask, would have suspected so large an area of the globe to be coated with matter emitted from volcanoes? The rate of accretion must have been extraordinarily slow, as the area covered by the Red clay, compared with volcanic ejections contributed annually direct to the ocean, supplemented, even as Mr. Murray suggests, by the denudation of ancient volcanic deposits on land, is so very great.

The Globigerinæ ooze, first discovered by the "Porcupine" soundings as an extensive oceanic deposit, gradually shades off into the Red clay, and usually finally disappears at about 2,000 fathoms.* Now, there is no reason to suppose that the pumiceous matter is not deposited in moderate as well as great depths, and the inference therefrom is that it is obscured by the quicker accumulation of Carbonate of Lime from the tests of Foraminifera, in depths of less than 2,000 fathoms, at about which point the two deposits usually blend. As reinforcing the argument of its age, the profusion of sharks' teeth and ear bones of cetaceans found in the Red clay has been justly dwelt upon. If we assume that foraminiferal organisms (with calcareous tests) remove annually from sea water the same amount of Carbonate of Lime as is contributed by rivers from the land, we have a rough mode of arriving at the rate of accumulation of Globigerinæ ooze.

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* In an exceptional case it was found at 2925 fathoms in the Mid-Pacific—the depth at which it is found is variable within certain limits. —Mr. J. Murray—"Proc. of Roy. Soc.," p. 525.

In my address on "Geological Time," which I had the honour to read to this Society, I estimated the average amount of carbonate of lime annually removed from each square mile of land surface over the whole globe at 50 tons.*

At 15 feet to the ton the weight of compact limestone, this would give a uniform deposit over the whole ocean of ·0000094 of a foot per annum, but if considering the deposit as one of loose mud holding much water, we assume it to accumulate at three times that rate, it would give ·0000282 of a foot per annum, or, in round numbers, 35,500 years for a deposit of chalky mud 1 foot in thickness. If, however, we say that calcareous deposits are absent where the Red clay is present, and the whole of the Carbonate of Lime from the land is used upon the remaining area, we may reduce the period to 20,000 years. These calculations are made quite independently of any deposit of coarser materials, because they do not, as a rule, exist, except in the form of volcanic products, at the depth affecting my argument. Of course, in shallower water the deposits increase much more rapidly by the admixture of other materials.

We thus find that the maximum average rate of accumulation cannot be more than 1 foot of calcareous

* It is fair to assume that the amount of Carbonate of Lime in the sea remains pretty constant, otherwise it would soon be all used up, as there is only sufficient in the sea to cover it to a depth of 4·5 feet. See Address on "Geological Time." I omit Sulphate of Lime from consideration, because if organisms can decompose it, which is a moot point with naturalists and chemists, it must be in a small degree, otherwise the sulphate would not form, as it does, the bulk of the lime in the ocean, it being contributed by the land only, at the rate of 20 tons per square mile per annum, according to my approximation. Being used up slowly, it accumulates more rapidly.

"Geological Time."—Presidential Address to the Geo. Soc., Session 1876–7; p. 21 in reprint.

ooze in 20,000 years,* but probably it takes much longer for that thickness to be deposited; for we may not unnaturally surmise that coral animals and molluscs remove more lime from sea water, area for area, than the minute Foraminifera. Locally, the deposit may take place more rapidly, but what is deposited in one area is robbed from another area, and I think we may safely assume that not more carbonate of lime is used up annually than what is contributed annually by the land; otherwise, the quantity in the sea would finally, before this, have become reduced to nothing.* These forces of nature, in my opinion, tend to balance each other.

Where the Globigerinæ ooze ends the Red clay begins —the one shades into the other. Pumice and the materials of the Red clay are found in the ooze, and more abundantly as the Red clay is approached; hence the scientific men of the *Challenger* were driven to the conclusion that the Red clay is found in the greater depths because in them the tests become destroyed by carbonic acid before reaching the bottom.

If, then, it takes 20,000 years for an average thickness of one foot of chalky mud to accumulate over the area occupied by it, how long a period will be required for one foot of Red clay?—the mind stands aghast at the

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* Professor Martin Duncan, F.R.S., says of deep sea deposits, in his "Presidential Address to the Geological Soc. of London," vol. xxxiii., p. 74—"I have satisfied myself from late researches that the rate of deposition is extremely slow. Thus an electric cable was laid down in the *Globigerinæ* ooze regions, and five years after a considerable coral growth had taken place on it. Some of these living calices were close above the cable, and, therefore, the deposit had been infinitesmal in that time."

† See Geological Time before quoted.

problem. Probably 10 times as long.* Certainly the volcanic emissions annually directly deposited in the sea, combined with those due to denudation, must be excessively small compared to the amount of carbonate of lime annually contributed by the whole surface of the Land. Not only does Geology tell us this, but the arrangement of the deposits in the sea also tells us the same thing.

The nodules of peroxide of Manganese, and the profusion of sharks' teeth both point to the same conclusion, and it is not to be wondered at if some Geologists are almost ready to believe that our great oceans, from the beginning of geological time, have always been as they are now. It has been said that this Red clay deposit has no equivalent in any of the known rocks, and this is used as another argument. †

While believing that the ocean depths are of enormous age, it is impossible to resist other evidences that they

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* Mr. Murray says ("Proc. of Roy. Soc.," vol. xxiv., p. 531): "When there has been no reason to suppose that the trawl has sunk more than one or two inches in the clay, we have had in the Bag over a hundred shark's teeth and between thirty and forty ear-bones of cetaceans; some of them have been imbedded in over an inch of the Manganese arranged in concentric layers, while others have had just a trace of Manganese on them, or none at all. . . . In the *Globigerinæ*, Radiolarian and Diatom oozes we have found during the whole cruise only one or two shark's teeth and perhaps one tympanic bone. In shore deposits they were even more rare. These facts, taken with others that will at once suggest themselves, go to show, as might be expected, that the shore deposits accumulate faster than the organic oozes, and these last faster than the deep sea clay."

† The President of the Royal Soc., Dr. Hooker, stated ("Proc. of Roy. Soc.," vol. xxv., p. 354) that Mr. Sorby informed him that a microscopic examination of the "Red clays" showed them to be, in composison, like the Gault. This is singular, as the Gault is associated with the chalk, but where are the pumice stones and per-oxide of Manganese? On the other hand, Mr. J. Starkie Gardner believes the Gault to be a shallow water deposit.—*Quar. Journ. of Geo. Soc.*, vol. xxxiii., p. 206.

have once been land. The very continuity of animal life on the globe points to it. The molluscous fauna of the Eastern Coast of North America is very similar to that of Europe, and this could not have happened without littoral continuity, and at no very distant period, geologically speaking; yet there are depths of 1,500 fathoms between these continents. Again, the form of the bottom of the North and South Atlantic is so like a continuation of the land; the Dolphin, Challenger, and Connecting Ridges follow so naturally the outlines of the continents they lie between, that it is difficult to believe they have not been formed by sub-aerial denudation—that they are not, in fact, valleys and mountains.*

The probable causes of these subsidences and upheavals I am at present engaged in investigating; so I will not touch upon them now, but will simply confine myself to a consideration of the significance of the alleged absence of rocks corresponding to the Red clay deposit of the ocean.

In the first place, we are not by any means prepared to prove a negative. With so much of the area of the Globe unexamined geologically, he would be a bold man to declare that equivalents in the Earth's crust do not exist. Again, if they do exist, it would probably be in sporadic patches, for any one acquainted with sub-aerial denudation will know what havoc the rain and weather would make with a thin coating (like the deposit in question would probably be), unless protected by denser deposits above. Of all the dangers that beset a geologist,

* Mr. Judd says, speaking of these ridges: "Hence it is not difficult to picture to ourselves the existence in later Tertiary times of a great band of volcanic peaks, comparable in magnitude and parallel in position with the range which now forms the western boundary of the great American continent."—"Contributions to the Study of Volcanos," *Geo. Mag.*, 1876.

that of reasoning from the absence of an expected thing is the worst, as conclusions are so readily based upon it. Again, it is quite within the bounds of possibility it may turn out the true explanation that seas of the depth of over 2,000 fathoms never existed on the sites of our present continents. It is quite consistent with the supposition that the extreme depths of the ocean may at one time or other have been dry land—that only shallow seas or seas of moderate depth may have at the same time flowed over portions of the present continents. The ocean depths may thus prove to be *relatively* permanent indentations. Certainly the character of the rocks, generally composed so largely of sediments, would rather tend to confirm this view. If we consider the Globe in its present form as liable to equal subsidences and upheavals over large areas, it follows that an upheaval bringing the present Atlantic bottom 400 fathoms nearer to the surface, balanced by an equal subsidence in Asia, would lay a great area of land under water without affecting the Atlantic as an ocean to any material extent. As so clearly shown by Darwin 30 years ago in respect to South America,* there are general and tolerably equable upheavals, extending for thousands of miles, occurring independently of the actual fracturing of the Earth's crust, so that it is extremely probable that the deposits over continental areas may be greater, more fluctuating and variable in character than those which take place over the areas now occupied by the oceans.

* "Geological Observations": We have seen that upraised marine remains occur at intervals, and in some parts almost continuously, from lat. 45° 35′ to 12° S along the shores of the Pacific. This is a distance in a North and South line of 2,075 geographical miles." "Judging from the upraised shells alone, the elevation in Chiloe has been 350 ft., at Conception certainly 625 ft., and by estimation 1,000 ft.; at Valparaiso 1,300 ft," &c.—Sec. Edit., p. 276.

The time has not yet come for taking a comprehensive view of the bearings of this recently acquired knowledge of the ocean depths: that must be deferred until all the information is published; and facts are so interlocked and dependant for their thorough comprehension on classification, system and arrangement, that until each specialist has finished his work it were impossible to generalise with complete success. Sufficient is known to enable us to say the work of the *Challenger* will be an important contribution to natural Science, and of the greatest value in assisting to solve some great and enthralling problems of the Earth's history, the interpretation of which has been reserved for the present age.

LIMESTONE AS AN INDEX OF GEOLOGICAL TIME.

Read before the Royal Society, January 23rd, 1879.

The geological history of the globe is written only in its sedimentary strata.

The determination of the age of the various formations, it is true, has enabled the geologist, in some cases, to arrive at the relative age of igneous outbursts, but in the absence of fossil bearing rocks the crust of the earth would be a sealed book.

These sediments are, of course, derivative, the later rocks being largely constructed of pre-existing sedimentary rocks; but unless we assume absolute uniformity through all time, in tracing their history backwards we must arrive at a time when the first sediments resulted from the decomposition or degradation of the original crust of the globe.

Hitherto geology has been content to deal with and investigate known facts, leaving it to the physicist to deal with the earlier conjectural history of our planet, but for the purposes of this paper it will be necessary shortly to consider the possible existence and probable nature of the rocks antecedent to the established geological periods.

Rocks of which the Geological Record Speaks.—The maximum thickness of the sedimentary rocks has been variously estimated at from 14 to 20 miles. Professor

Ramsay in a very original paper, read before the Royal Society,* has grouped the various formations from the Cambrian to the present time into relatively equivalent periods, and Dana has also given his views of the relative value in time of various groups, inferred from their thicknesses, from the Lower Silurian upwards. These views I may have to refer to further on.

Geological investigations have carried us back by stages. It is not long since the Cambrian and Silurian series were classified as unfossiliferous "Grauwacke." Since then we have extended our knowledge below the Cambrian to the Laurentian and Huronian, and who knows but that further research may give us an acquaintance with the pre-existing sediments of which Ramsay and Dana say the Laurentians are composed?

But for my present purposes it will be enough to look upon the Laurentian rocks as primitive sediments.

The Original Crust of the Globe.—There is no rock known to which a geologist could point and say "that is the material from which all sedimentary rocks have been originally derived." But arguing from analogy and various physical considerations, which have a certain force, it is pretty generally assumed that our planet had an igneous origin. Now the only igneous rocks with which we are acquainted are of the nature of granites and traps. Granite, it is well known, when the base of a sedimentary series can be reached, underlies it.† In

* "On the comparative value of certain Geological Ages (or groups of formations) considered as items of Geological Time."—*Proceedings of Royal Soc., 1874.*

† An artesian well in the Lower Silurian at St. Petersburg, 656 feet deep, stops in granite, the lowest portion of the strata being merely a degraded granite.—British Association Report on Underground Temperature, 1871. It must, however, not be lost sight of, that the best authorities, including Ramsay, consider some granites to be metamorphic.

the absence of any more accurate information we can only assume that the original crust of the earth was composed of igneous rocks, somewhat similar in nature to those that have been protruded from the bowels of the earth during all known geological history.

Inferences from the P.eceding Considerations.—Although it does not follow that igneous rocks are not derivative as they may be melted sediments, all the other rocks known to geologists have resulted from the destruction of pre-existant rocks. Therefore this primeval matter must either have been something we know not, that has been totally destroyed or re-worked up, or it must have been, as already stated, of the nature of granites and basalts.

Nature of Limestones.—In the decomposition and destruction of rocks a certain amount of lime is separated, either as a carbonate or a sulphate, by the action of rain water, and is carried into the sea or inland lakes, to be used in the formation of the tests of mollusks, the calcareous portions of corals and sponges, or on a still larger scale, as proved by the *Challenger* soundings in the calcareous shells of foraminifera. Limestone is consequently a derivative rock. But from what has it originally come? At present we know that the bulk of the deposits of carbonate and sulphate of lime are simply the materials of the old sediments used up again, and this has occurred time after time. If we assume as a postulate "inorganic evolution" we are thrown back for the origin of the lime to the igneous crust of the globe.

Evolution of Lime.—An examination of the sedimentary crust of the earth has revealed to geologists the fact that limestone rocks have been in process of formation from the earliest known geological period.

The Laurentians of Canada contain beds of limestone in the region of Ottawa 3,500 feet thick, nearly half consisting of intercalated layers of gneiss.*

The Huronian rocks contain among slates, conglomerates and quartzites, thin layers of a greyish or bluish limestone; but when we come to the Lower Silurians of America the beds are, according to Dana, as preeminently limestones as those before described are sandstones.

In the Appalachian region, according to Rogers, out of 12,000 feet, 5,000 feet are limestones. In North Western Newfoundland the thickness of the Quebec series alone is 6,600 feet, the lower 3,200 feet being mostly limestones, the rest sandstones and shales, with some conglomerate limestone. These limestone deposits cover an immense area, extending even to the Arctic regions. In Great Britain, although the earlier deposits contain limestone beds, they are not of so extensive a character or so great proportionately to the other component rocks as in America. Of the Laurentians in Great Britain termed "Fundamental Gneiss" we know little, but all the beds above to the Devonian contain more or less limestone.

It is when we arrive at the Carboniferous period that the great development of limestones takes place; the Mountain Limestone being in places in England no less than from 1,500 to 3,000 feet thick, while in Ireland the larger area of the island is covered with it. From the base of the Carboniferous to the present time the rocks of Europe are, generally speaking, of a decidedly calcareous nature. In England, as shewn by the analyses of Dr. Frankland for

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* Dana.

the Rivers Pollution Commission, the water flowing from the rocks above the Old Red Sandstone contains much more soluble matter than that flowing over the formation below. The average amount of carbonate of lime in 18 samples from upland surface waters from igneous rocks in England and Scotland was only 0·1, and sulphate of lime 2·72 parts per 100,000. From the Metamorphic, Cambrian, Silurian, and Devonian rocks the average of 81 samples was 0·3 of carbonate and 3·4 of sulphate of lime. From the calcareous portions of the Silurian and Devonian rocks the carbonate of lime in 3 samples was 1·2 and the sulphate 10·0 per 100,000. From the non-calcareous portion of the Coal-measures and the Yoredale and Millstone grits the carbonate of lime was 0·4 and the sulphate 5·8. From the Lower London Tertiaries and Bagshot beds, the carbonate of lime was 0·3 and the sulphate 4·76. From the Mountain Limestone, through the calcareous portion of the Coal-measures to the Lias, New Red Sandstone, Magnesian Limestone, and Oolites, the proportion varied from 4·0 to 7·6 of carbonate, and 7·88 to 11·28 of sulphate of lime. A reference to my table of the "Denudation of England and Wales, chemically considered," * will shew that the actual amount of "solids in solution" expressed in tons is, from the Mountain Limestone upwards, enormously in excess of the solids in solution from the earlier formations, in consequence not merely of the actually greater amount of calcareous matter in the later rocks, but because of their much greater superficial extension. When we are only acquainted with a comparatively small portion of the crust of our globe it does not do to theoretically dogmatise. It would seem, however, from

* Presidential Address on "Geological Time."—"Proc. of Liverpool Geological Soc.—Session 1876-77."

what we actually know, that the earlier rocks, *on the whole*, are not so calcareous as the later ones. This, however, may be explained on the supposition that we are only acquainted with the non-calcareous portions of the earlier sediments, and that equivalent calcareous rocks lie buried under newer strata. Thus it would be erroneous to generalise on the comparative absence of calcareous matter in our Lower Silurian when we find limestone in such great force in equivalent rocks on the other side of the Atlantic.

Giving due force to all these considerations there does seem, so far as we know now, a balance of evidence in favor of an average progressive increase of calcareous matter in the rocks as we approach our own time.

The wider distribution in space of the products of chemical denudation than those due to mechanical aqueous erosion has been proved by the *Challenger* dredgings and soundings. According to Mr. Murray * the shore deposits throughout the portions of the globe visited by the *Challenger* are limited to a distance of 500 miles from the land, this distance being, no doubt, determined by the depth of the sea bordering the continents.

Detritus dropped by floating ice is, of course, exceptional. On the other hand the floor of the ocean, excepting in excessive depths, is covered with a deposit of chalky ooze, the remains of the calcareous portions of foraminifera. The abyssal depths alone are distinguished by a deposit of Red clay, the result, according to Mr. Murray, of the decomposition of pumice and other volcanic products, which must be accumulating at a slower rate than any other known deposit.

* "Pro. of Roy. Soc. of Edinbro," 1876-7, p. 253.

The extended area which it is thus shewn is affected by the materials brought down to the sea in solution in river water, must, it will be seen on consideration, profoundly influence their distribution in *time*.

If, as is supposed, the basins of the great oceans are enormously old, the deposits of calcareous mud may be of great thickness.

But, in the revolution of time, these old sea bottoms may become dry land, and the present continents be submerged. Then what would result? The calcareous matter now hardened into rock would be subject to rapid denudation, and the products would be partly deposited on the site of the old continents, while the portions of the sea not elevated would continue to gain new accessions of carbonate of lime. By tracing out in detail (which it would be tedious to me to do in this paper) this movement and redistribution of matter, it will become evident that through the greater mobility of matter in solution, combined with the more rapid destructibility of the rocks which yield it, there will be a natural tendency of the later rocks to become built up to a larger extent of the more soluble ingredients which are liable to deposition through organic or other agencies. But there is yet another inference to be drawn from the facts brought to light by the *Challenger*. It can be mathematically demonstrated that the whole, or nearly the whole, of the sea bottom has been at one time or other dry land. If it were not so, and the oscillations of level of the land with respect to the sea were confined within limits near to the present continents, the result would have been a gradual diminution instead of development of the calcareous rocks. To state the case in common language, the calcareous portions of the rocks would have been washed out during the mutations, the destruction and re-deposit of the continental rocks, and eventually deposited in the depths of the immutable sea, far from land. Immense beds of limestone would now exist at the bottom of the ocean, while the land would be composed of sandstones and argillaceous shales. The evidence of chemistry thus confirms the inductions drawn from the distribution of animal life on the globe.

The absolute quantity of Carbonate and Sulphate of Lime in the Sedimentary Crust of the Earth.—In a former paper * I calculated that the absolute amount of denudation since the beginning of the Laurentian epoch would probably be represented by a crust of rock enveloping the globe not less than ten miles thick; this is an excessively moderate estimate, and one I am now convinced is much under the mark. We must not lose sight of the fact that the materials are used up again and again in rock building, therefore, on the assumption that one-tenth of the area of the land of the globe constantly presents absolutely new matter ejected from the bowels of the earth, one mile in actual thickness of the sedimentary crust would equal ten miles of absolute denudation. Who can say how many times in the history of the globe the sediments have been turned over? We find blocks of Laurentian rock in the Huronian formation, and up to the present day every formation is made up principally of the remains of those that have preceded it.

But what is the actual thickness of the crust of the earth? All these calculations being necessarily very rude approximations, we must be careful not to overstate it. The only precise method of ascertaining the facts would be by an extensive series of borings.

Borings we have record of in various parts of the world. In our own country the Sub-Wealden boring finished in

* "Geo. Time."

the Oxford Clay at 1,905 feet; Messrs. Meux's well, in London, reached 1,144 feet, and finished in the Devonian. At Scarle, in Lincolnshire, a boring for coal commenced in Lias reached 2,030 feet, and penetrated the Carboniferous strata 130 feet. Many wells in Lancashire have been sunk from 500 to 800 feet, and one 1,300 feet in the New Red Sandstone. Below the New Red are the Permian Rocks, and then the Coal-measures, in which there are in Lancashire pits 2,400 feet deep. In the Paris basin there are wells up to 2,165 feet deep, finishing in the Greensand. A boring at Sperenberg, near Berlin, reached 4,172 feet, nearly the whole of which was in rock salt!

The Cañons of Colorado disclose the thickness of the strata in that part of North America better than borings would do. By them we learn that the rocks, consisting of limestone of Carboniferous age, and the older Paleozoic, together with the granites on which they rest, are from 3,000 to 6,000 feet thick, the granite occupying from 500 to 1,000 feet of that depth.

"Suliven," a mountain in Sutherland, 2,396 feet high, is given by Ramsay as a remarkable instance of denudation. It is composed of horizontal layers of Cambrian rocks, and, together with "Canisp," another mountain formed of the same Cambrian strata, rises out of a plain of Laurentian gneiss, the whole of the strata between having been removed by denudation. This illustration, though not exactly to our present purpose, yet enables us to realize the great thickness of these ancient sediments.

But if we estimate the thickness by the evidence of faults, we find them with throws reaching as much as

5,000, 10,000, 15,000, and even 20,000 feet, * shewing that the strata on one side of the fault are at least of that thickness now. The Coal Commission estimate the thickness of the Permian and New Red Strata above the Coal in 2,144 square miles at from 800 to 4,000 feet.

If, again, we take the evidence of mountain masses where the strata is supposed to be abnormally thickened, we form a still higher conception of the thickness of the sedimentary crust. According to Judd, the Alps show strata of a combined maximum thickness of nearly eight miles, and the Appalachians, according to Dana, are equally massive.

From the foregoing evidence, I think we may with safety provisionally assume that the actual average thickness of the sedimentary crust of the globe is not less than one mile.†

Now, what proportion of this crust consists of Lime as a Carbonate and Sulphate? The answer to this inquiry will be found in the proportion of soluble to mechanical matter brought down by rivers flowing over various formations. According to calculations made for my paper on Geological Time, already alluded to, I find the Danube carries to the sea three times as much mechanical matter as it does solids in solution. The Nile, according to data procured from Mr. John Fowler, the engineer to the Khedive, also removes three times as much sediment as it does matter in solution.

* The fault at Chambersburg Pa. is 20,000 feet throw and 20 miles long. A man can stride across the crevice with one foot on the Trenton Limestone and the other on the Hamilton Slates (quoted by Dana. "Manual of Geology," p. 339.)

† After writing this, I find that Dana, ("Manual," p. 657) for the purpose of a calculation, assumes the average thickness of the sedimentary rocks under the continental areas at 5 miles. This alone would give 1·3 miles thick if distributed over the whole globe, allowing for none under the oceans.

The data for calculating the amount of solids in solution are, however, more plentiful, and more to be relied on than those for mechanical sediments. The solids in solution are a more constant quantity, winter and summer. To be on the safe side, I have assumed in "Geological Time," taking the whole of the rocks, that the mechanical sedimentary matter, on an average, is five times that which has been contributed by solids in solution. Half of the solids in solution I have estimated to be composed of Carbonate of Lime, and one-fifth Sulphate of Lime. This would give between one-eighth and one-ninth of all the solid matter removed from the land as lime, either in the form of a carbonate or sulphate. To simplify the calculation we will, however, assume that one-tenth of the whole mass of rock is lime, in one form or another.*

This gives us the equivalent of a zone of limestone rock, 528 feet thick, enveloping the globe, as a very rude approximation to the absolute quantity of Carbonate and Sulphate of Lime in the sedimentary crust of the earth.

Were Chemical forces more active in former ages?— Many physicists have stated that chemical forces were more active in early geologic ages than now, partly from the presumed excess of Carbonic Acid then in the atmosphere. But what are the facts? If there were then such an excess in the atmosphere, there would have been also an excess in the river water and in the sea.

This, within certain limits, and without lime to satisfy it, would be fatal to testaceous animals, as their shells would be eaten away and redissolved as fast as formed. If, on the other hand, a proportionate amount of lime

* A reference to Bischof's analyses of Igneous Rocks in his "Chemical Geology" will show that this proportion is not inconsistent with the derivation of Sedimentary Rocks from them.

existed at the time, we should, under these conditions, have a greater amount of limestone in the earlier than the later rocks, but we have already seen that the reverse is the case.

It appears to me that the Limestone beds of the earlier formations, if they tell us anything, say that the sea conditions were then nearly similar to what they are now.

There still remains for consideration the question of rainfall and temperature; these are not so easily disposed of. When we have the evidence of a glacial climate over so large an area of the globe in such geologically recent times, succeeded by a more temperate climate, and preceded by a Miocene sub-tropical Flora in the Arctic Circle, it would be rash to say the average temperature of the globe was not higher, or the rainfall greater than now. Still, we must not lose sight of the fact that Geology tells us the climate of the globe was more equable in early geologic ages than now, and the tendency of this equability, it appears to me, would be towards balancing the conditions and decreasing the precipitation of moisture.

Area of Land in early Geologic Time.—If, in our calculation, we allow for more active chemical forces in the form of temperature and rainfall, we should also, as a set off, estimate our denudation from a decreased area of land surface, as it appears to be generally considered that there existed less land in early times than now. If the oceans were shallower, as we would infer from the preponderance of shore deposits in Laurentian times, the land would necessarily be less. If the oceans were deeper than now, of which it seems there is no geologic evidence, the land would be more extensive than the present continents.

Exposure of Igneous Rocks in Laurentian Times.—The enormous extent and thickness of these early sediments shews that the earth had then attained a very stable state. It is very difficult to estimate the proportion of igneous to aqueous rocks which then existed. On the other hand, it would be difficult to prove that they were greater then than now. The older rocks have been subject to all the mutations of the earth since they were laid down; consequently, if they are penetrated by a greater amount of igneous matter it is not to be wondered at. It is not all contemporaneous.

Physicists have been misled in inferring the greater volcanic activity of early ages by the crumpling and folding of the old rocks through not giving due weight to all the vicissitudes they have undergone.

Rainfall.—The mean rainfall of England and Wales is 32 inches annually, and the estimated depth run off the ground is calculated by me at 18·3 inches. This is much in excess of what takes place on some of the large continents.* According to Beardmore, the Mississippi only discharges 8·4 inches, and the Nile 3·78 annually. The Ganges, according to Girard, 20·51; the Rhone, at Avignon, 22·86; and the Danube, calculating from the observations of Sir C. A. Hartley, 9·06 inches. According to information supplied me by Mr. James Bateman, C.E., F.R.S., the Parana, in the month of December, 1870, then in its lowest state—a continuous draught of six or seven months having diminished the ordinary sources of supply, and the periodical rise from the Andes not having commenced—delivered, according to most careful measurement, 520,000 cubic feet of water per second. The Uruguay, from a consideration of other measurements, Mr. Bateman approximately estimated to be

* "Geological Time."

delivering 150,000 cubic feet at the same time. Thus, these two rivers, having an estimated drainage area of 1,250,000 square miles, were delivering into the River Plate 670,000 cubic feet per second, "a quantity equal to the mean volume of 33 years passing down the Mississippi." Unfortunately, Mr. Bateman has had no opportunity of measuring the mean annual flow, but it must be very considerable when the minimum discharge represents 7·27 inches run off the ground annually, or nearly as much as the mean depth of rain from the basin of the Mississippi, as given by Beardmore. It would be interesting to know what flows off the land in Equatorial Africa, but I fear that the calculations of the discharge of the Congo and its drainage area are not very reliable—such as they are I give. In an article in "Nature," February 14th, 1878, the drainage basin is stated at 1,000,000 square miles, and the discharge at 1,800,000 cubic feet per second; this would give 24·60 inches as annually flowing off the ground. According to Burton, Dr. Behm greatly underestimates the Congo when he assigns it only 1,800,000 cubic feet per second, and states it at 2,500,000 cubic feet, with a drainage area of only 800,000 square miles. This would give 42·77 inches run off the ground annually, which, I should think, is much in excess of the facts.* If, for the purposes of our calculation, we assume the mean quantity

* Since writing this, I find the following confirmation of the views expressed:—

"Perhaps the most remarkable feature of the inter-tropical rains of of Africa is that of their moderate amount. We have seen that, even in the Equatorial belt of rain at all seasons, the whole yearly quantity that falls does not exceed, as far as observations go, *the amount which falls on the Western coasts of our own islands*."—Notes on the Distribution of Rain in Africa, by Keith Johnson—Appendix to Stanford's Compendium of Geography and Travel—"Africa."

of rain run off the land from the regions of Igneous Rocks from the Laurentian to the present period at 28 inches annually, or in excess of what takes place, according to Dr. Behm's observations, in Equatorial Africa now, I think it will be admitted we shall not err on the side of depreciation.*

Areas of Igneous in proportion to Sedimentary Rocks.—The areas of Igneous Rocks in Europe, its Islands, and the portion of Asia between the Caspian Sea and the Bosphorus, shewn in Murchison's Geological Map of Europe, is as follows:—

Europe and part of Asia—			SQUARE MILES.
Granite			147,523
Trap	Including Iceland— Trap	21,147	112,312
Volcanic	Volcanic	27,320	80,748
			340,583

The total area of the countries in which these Igneous Rocks are situated is—

	SQUARE MILES.
Continent of Europe, and Islands	3,933,070
Portion of Asia	360,000
	4,293,070

According to these figures the Igneous Rocks occupy two twenty-fifths of the total area of this portion of the earth's surface. But all these Igneous Rocks are not

* In this estimate of rainfall, I have taken into consideration the fact that the granitic regions are at a greater average elevation than the average elevation of the whole land, and consequently receive more rain proportionately.

I must ask readers of original copies of my "Geological Time" to score out all relating to the Ganges and Brahmapootra combined, as the data is unreliable, and an error has crept into the calculation. The correction is made in the present republication.

constituted entirely of fresh matter emitted from the bowels of the earth.* In fact, it would be difficult to say what proportion, if any, of these rocks have not been at one time or other in the form of sediments. It is quite certain they are largely constituted of melted sediments.

If, therefore, we assume that from the commencement of the Laurentian to the present time the proportion of original matter brought up from below the sedimentary crust to be acted upon by the atmosphere averaged one-tenth of the whole of the land, the estimate will be a liberal one. It must not be lost sight of that for the purposes of our calculation we must assume a beginning, and this first origination of sediment we have already placed at the commencement of the Laurentian period. Following out this train of thought, the first exposures of rock would all be Igneous, but gradually getting covered by sediment when upheavals took place, the Igneous Rocks could not be attacked by the atmosphere until the sediments were denuded therefrom. This comparatively greater extension of Igneous Rocks, we assume, existed in earlier ages, I consider fully balanced by the reduction that must be made in our estimate of the original matter existing in the present exposures of Igneous Rocks, in consequence of their being, as before stated, largely made up of melted sediments.

Estimate of the Time required for the Evolution of the Carbonate and Sulphate of Lime contained in the Sedimentary Crust of the Earth.—Estimating the average quantity of rainfall run off the Igneous ground during all geological time at 28 inches per annum, and the amount of Carbonate and Sulphate of Lime it

* I have already given Ramsay's view of the metamorphic nature of certain Granites. Many of the Granites of Colorado are, according to American surveyors, metamorphic.—See "Geo. Survey of Colorado," 1873, p. 137-144.

takes up from the Igneous Rocks at 4·00 per 100 000, the annual yield of the land, of Lime in these forms would be 71·68 tons per square mile per annum. Calling it 70 tons for simplicity, one-tenth of the area of the land, or 5,100,000 square miles, would yield 357,000,000 tons of these minerals per annum. The area of the globe is 196,900,278 square miles, so that the land would yield to the whole globe 1·813 tons per square mile per annum; at 13½ feet to the ton it would thus take 1,139,032 years for a deposit one foot thick to accumulate; therefore 528 feet thick, the assumed thickness of limestone in the sedimentary crust of the earth would be eliminated from the original material of the earth, in 601,408,896 years, or in round numbers say 600,000,000 years.

Professor Ramsay, from considerations of a mixed physical and palæontological character, has arrived at the conclusion that the great continental era, beginning with the Old Red Sandstone and closing with the New Red Marl, is comparable in point of geological time with all the time that has elapsed from the beginning of the Lias down to the present day. He also considers the Cambrian and Silurian to be comparable, in point of geological time, to that of the continental era of the Old Red Sandstone alone.

If, therefore, the Laurentian time should have been equal to that of the Carboniferous, Permian, and New Red periods we shall have a division of 200,000,000 of years for each of the following great groups:—

	Millions of Years.
Laurentian, Cambrian, Silurian	200
Old Red, Carboniferous, Permian, New Red......	200
Jurassic, Wealden, Cretaceous, Eocene, Miocene, Pliocene, and Post Pliocene	200
	600

Objections that may probably be made to the foregoing calculations, their answer, and conclusion.—An objection may be urged against the foregoing calculations, that they start from a hypothetical base which does not exist, or rather that cannot be proved, viz., that the Laurentian was not the beginning of Geological Time. Such is perfectly true, for, as I have already stated, both Dana and Ramsay are of opinion that the Laurentian rocks are built up from the ruins of earlier sediments. To this I answer, my object has been only to attempt to fix a *minimum* age to the earth. Nor does the particular age in which Geological Time began really matter for my purposes, if the assumed thickness of the limestone in the crust of the earth, including the calcareous matter disseminated through the other sedimentary rocks, is accurate or within the mark.

For it is evident that calcareous matter was not separated in early ages from the original crust of the earth in larger proportions that what takes place now from granite, for the proportions of limestone found in the earlier formations forbid the assumption. Therefore the actual bulk of limestone in the sedimentary crust of the earth is the true index of its age; for if the elimination began at all, it must have begun in the way the preceding calculation provides for.

In all the elements of the calculation, it has also been my object to fairly allow for the possibilities, within the limits of the geological record, of more rapid action in earlier ages. The average area of Igneous Rocks through all Geological Time is probably computed in *excess* of what actually existed, for the first continents were probably smaller than now, and the proporton of melted sedimentary crust in the later Volcanic and Plutonic rocks may be very great indeed.

The average rainfall is the more difficult problem to solve, but the possibilities of greater rainfall, as well as the generally higher levels at which Igneous Rocks are found, are all duly considered.

The proportion of calcareous matter allowed for, dissolved in the rain water from Igneous Rocks through all time, is in excess of that contained in surface water from granitic rocks, as estimated by Dr. Frankland.

I must not be held as endorsing all the physical views which have modified the elements of my calculation; but giving due weight to all that objectors urge against such calculations of Geological Time, my object has been to show that, even if such objections be valid, Geological Time is enormously in excess of the limits assigned by some physicists, and quite sufficient to account for all the organic and inorganic changes we are acquainted with.