been tossed over waterfalls and rapids in its journey. He ascertained also that sand with a mean diameter of grain of $\frac{1}{10}$ mm. will float in feebly agitated water; so that all sand of finer grain must remain angular. The same observer has noticed that sand composed of grains with a mean diameter of $\frac{1}{2}$ mm., and carried along by water moving at a rate of 1 metre per second, gets rounded, and loses about $\frac{1}{10000}$ of its weight in every kilometre travelled.

The effects of abrasion upon the loose materials on a river bed are only a portion of the erosive work performed by the stream. Where the bottom is covered with a layer of debris only the upper portion of which is pushed onward by the current, the solid rock of the river channel is there protected from waste. But this protection is only local, and is apt to be swept away from time to time by violent floods. In those parts of a river channel where the current is strong enough to keep gravel and boulders moving along, these loose materials rub down the rocky bottom over which they are driven. As the shape and declivity of the channel vary constantly from point to point, with at the same time frequent changes in the nature of its rocks, this erosive action is liable to continual modifications. While there is a general abrasion of the whole bottom over which loose detritus is rolled, the erosion goes on most briskly in the numerous hollows and grooves along which chiefly these loose materials travel. Wherever an eddy occurs in which gravel is kept in gyration, erosion is much increased. The stones in their movement excavate a hole in the channel, while, as they themselves are reduced to sand and mud, or are swept out by the force of the current, their places are taken by fresh stones brought down by the stream. Such *pot-holes*, as they are termed, vary in size from mere cup-like depressions to huge cauldrons or pools. As they often coalesce by the giving way of the intervening walls between two or more of them they materially increase the deepening of the river bed.

The shape of a river channel at any given point in its course depends mainly upon the nature and structure of the material out of which it has been eroded. One of the most characteristic features of streams, whether large or small, is the tendency to wind in serpentine curves when the angle of declivity is low and the general surface of the country tolerably level. This peculiarity may be observed in every stream which traverses a flat alluvial plain. Some slight weakness in one of its banks enables the current to cut away a portion of the bank at that point. By degrees a concavity is formed, whence the water is deflected to the opposite side, there to break with increased force against the bank. Gradually a similar concavity is cut out on that side, and so, bending alternately from one side to the other, the stream is led to describe a most sinuous course across the plain. By this process, however, while the course is greatly lengthened, the velocity of the current proportionately diminishes, until it may, before quitting the plain, become a lazy, creeping stream, which in England is bordered perhaps with sedges and willows. Such meandering courses are most frequent in soft alluvial plains, but they may also be found in solid rock if the original form of the surface was tolerably flat. The windings of the gorges of the Moselle and Rhine through the table-land between Treves, Mainz, and the Siebengebirge form a notable illustration.

Abrupt changes in the geological structure or lithological character of the rocks of a river-channel may give rise to waterfalls. In many cases waterfalls have originated in lines of escarpment over which the water at first found its way, or in the same geological arrangement of hard and soft rocks by which the escarpments themselves have been produced. In the case of the falls of Niagara, for example, the stream may have fallen over the Queenstown cliff when the river first sought its way to the sea. But much more probably the escarpment and waterfall began to arise simultaneously and from the same geological structure. As the escarpment grew in height, it receded from its starting point. The river-ravine likewise crept backward, but at a more rapid rate, and the result has been that at present the cliff worn down by atmospheric causes stands at Queenstown, while the ravine extends 7 miles further inland, with a width of from 200 to 400 yards, and a depth of from 200 to 300 feet. In this as in other cases the waterfall has cut its way backward up the course of its stream, and will continue to do so as long as the structure of the gorge continues as it is now—a thick bed or beds of limestone resting horizontally upon soft shales. The softer strata at the base are undermined, and slice after slice is cut off from the cliff over which the cataract pours. It has been estimated that at their present rate of recession the Niagara Falls must have taken about 35,000 years to cut their way backward and excavate the gorge between their present position and Queenstown. In other cases waterfalls have been produced by the existence of a harder and more resisting band or barrier of rock crossing the course of the stream, as, for instance, where the rocks have been cut by an intrusive dyke or mass of basalt. In these and all other cases the removal of the harder mass destroys the waterfall, which, after passing into a series of rapids, is finally lost in the general abrasion of the river-channel. The most marvellous river gorges in the world are those of the Colorado region in North America. The rivers there flow in ravines thousands of feet deep and hundreds of miles long, through vast table-lands of nearly horizontal strata. The Grand Cañon (ravine) of the Colorado river is 300 miles long, and in some places more than 6000 feet in perpendicular depth. The country is hardly to be crossed except by birds, so profoundly has it been trenched by these numerous gorges. Yet the whole of this excavation has been effected by the erosive action of the streams themselves.

In the excavation of a ravine, whether by the recession of a waterfall or of a series of rapids, the action of the river is more rapid than that of the atmospheric agents. The sides of the ravine consequently retain their vertical character. But where, from the nature of the ground, the denuding action of rain, frost, and general weathering is more rapid than that of the river, a wider and opener valley is hollowed out, through which the river flows, and from which it carries away the materials discharged into it from the surrounding slopes by the rain and brooks.

3. Reproductive Power.—Every body of water which when in motion carries along sediment drops it when at rest. The moment a current has its rapidity checked it is deprived of some of its carrying power, and begins to lose hold upon its sediment, which tends more and more to sink and halt on the bottom the slower the motion of the water. In the course of every brook and river there are frequent checks to the current. If these are examined, they will usually be found to be each marked by a more or less conspicuous deposit of sediment. We may notice seven different situations in which stream deposits or *alluvium* may be accumulated.

(*a.*) *At the foot of Mountain Slopes.*—When a runnel or torrent descends a steep declivity it tears down the soil and rocks, cutting a deep gash out of the side of the mountain. On reaching the level ground at the base of the slope the water, abruptly checked in its velocity, at once drops its coarser sediment, which gathers in a fan-shaped pile or cone, with the apex pointing up the water course. Huge accumulations of boulders and shingle may thus be seen at the foot of such torrents,—the water flowing through them often in several channels which re-unite in the plain beyond.

(*b.*) *In River-beds.*—This is characteristically shown in many of the rivers of Britain, by the accumulation of a bed

of sand or shingle at the concave side of each sharp bend of the river course. While the main current is making a great sweep round the opposite bank, the water lingers along the inner side of the curve and drops there its freight of loose detritus, which, when laid bare in dry weather, forms the familiar sand-bank or shingle beach. Again, when a river, well supplied with sediment, leaves rough ground where its course has been rapid, and enters a region of level plain, it begins to drop its burden on its bed, which is thereby heightened, till sometimes, as in parts of the courses of the Po, Adige, and Brenta across the plains of Lombardy, it is higher than the surrounding level region. This could not happen were it not that in floods a river deposits sediment along its banks, which are thus also heightened so as to retain the river in its ordinary state. But in such cases, if man lives along the margin of the river, he needs all his skill and labour to keep the banks secure. And even with his utmost efforts the river will now and then break through, sweeping down the barrier which it has itself made, as well as any additional embankments constructed by him, and carrying its flood far and wide over the plain. Left to itself, the river would incessantly shift its course, until in turn every part of the plain had been again and again traversed. It is indeed in this way that a great alluvial plain is gradually levelled and heightened.[1]

(*c.*) *On River-banks and Flood-plains.*—This deposit is partly implied in the action described in the foregoing paragraph. It is laid down on the level tracts or flood-plain over which a river spreads in flood, and consists usually of fine silt, mud, earth, or sand, though close to the river it may be partly made up of much coarser materials. When a flooded river overflows, the portions of water which spread out on the plains, by losing velocity and consequently power of transport, are compelled to let fall some or all of their mud and sand. If the plains happen to be covered with woods, bushes, scrub, or even tall grass, the vegetation acts the part of a sieve, and filters the muddy water, which may rejoin the main stream comparatively clear. Every flood increases the height of the plain, until, partly from this cause and partly, in the case of a rapid stream, from the erosion of its bed, the river can no longer overspread it. As the channel is more and more deepened, the river continues, as before, to be liable from inequalities in the material of its banks, sometimes of the most trifling kind, to be turned from side to side in wide curves and loops, and cuts into its old alluvium, making eventually a newer plain at a lower level. Continued erosion carries the channel to a still lower level, where the stream can attack the later alluvial deposit, and form a still lower and newer one. The river comes by this means to be fringed with a series of terraces, each of which represents a former flood-level of the stream. In Britain it is common to find three such terraces, but sometimes as many as six or seven or even more may occur. In North America the river terraces exist on so grand a scale that the geologists of that country have named one of the later periods of geological history, during which those deposits were formed, the Terrace Epoch. In the attempt to reconstruct the history of the old river-terraces of a country, we have to consider whether they have been entirely cut out of older alluvium (in which case, of course, the valleys must have been as deep as now before the formation of the terraces); whether they afford any indications of having been formed during a period of greater rainfall, when the rivers were larger than at present; whether they point to any upheaval of the interior of the country which would accelerate the erosive action of the streams, or to any depression of the interior or rise of the seaward tracts, which would diminish that action and increase the deposition of alluvium. Professor Dana has connected those of America with the elevation of the axis of that continent.

(*d.*) *In Lakes.*—When a river enters a lake its current is at once checked, and its sediment begins to gather over the lake bottom. If the lake be long enough in proportion to the volume of the river, the whole of the detritus may be deposited, so that, at its outflow, the river becomes as clear as when its infant waters began their course from the springs, snows, and mists of the far mountains. Thus the Rhone enters the Lake of Geneva turbid and impetuous, but it escapes at Geneva as blue translucent water. Its sediment is laid down on the floor of the lake, and chiefly at the upper end. Hence, lakes act as filters or sieves to intercept the sediment which is travelling in the rivers from the high grounds to the sea. If we look down from a height even upon a small lake among mountains, we observe that at the mouth of each torrent or brook which enters it there lies a little tongue of flat land (a true *delta*), through which the streamlet winds in one or more branches before mingling its waters with those of the lake. Each of these tongues consists of alluvium, laid down in obedience to the same law which governs the formation of river alluvium elsewhere, and continually creeping further out from the land as the deposit of sediment advances. Two streams entering a lake from opposite sides may join their alluvia so as to divide the lake into two, like the once united lakes of Thun and Brienz at Interlaken. Or the lake may be finally filled up altogether, as has happened in innumerable cases in all mountainous countries; the hilly tracts of Britain, for example, furnish abundant illustrations of every stage in this process. Where a large river with abundant sediment enters an important lake (as the Rhone at the head of the Lake of Geneva), the accumulation of its alluvium or delta may quite rival that of a great river in the sea, as described in paragraph (*f.*) below.

(*e.*) *Bars and Lagoon-Barriers.*—If we take a broad view of the degradation of the land, we must admit that the deposit of any sediment on the land is only temporary; the inevitable destination of all this material is the ocean. Most rivers which enter the sea have their mouths crossed by a bar of gravel, sand, or mud. The formation of this barrier results from the conflict between the river and the ocean. Although the muddy fresh water floats on the heavier salt water, its current is lessened, and it can no longer push along the mass of detritus on its bed. It has been ascertained, moreover, that, though fresh water can retain for a long while fine mud in suspension, this sediment is rapidly thrown down when the fresh is mixed with saline water. Hence, apart from the necessary loss of transporting power by the checking of the river current at the mouth, the mere mingling of a river with the sea must of itself be a cause of the deposit of sediment. But a large body of fresh water may float for a long distance before it is thoroughly mingled with the heavier water of the ocean. Ultimately, however, the fine detritus dropped by a river, together with the coarser materials on the bottom, are arrested by the sea. Moreover, in many cases the sea itself piles up great part of the sand and gravel of the bar. Heavy river-floods push the bar farther to sea, or even temporarily destroy it; storms from the sea, on the other hand, drive the bar farther up the stream. Another remarkable illustration of the contest between the alluvium-carrying streams and the land-eroding ocean is shown by the vast lines of bar or bank which, both in the Old World and the New, stretch along the coast. The streams do not flow straight into the sea, but run sometimes for many miles parallel to the coast, accumulating behind the barriers into broad

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[1] It is in the north of Italy that the struggle between man and nature in this department has been most persistently waged. See on this subject Lombardini in *Ann. des Ponts et Chaussées*, 1847.

and long lagoons, but eventually breaking through the barriers of alluvium and entering the sea. The lagoons of the Italian coast and of the Baltic near Dantzic are familiar examples. A conspicuous series of these alluvial bars fronts the American mainland for many hundred miles round the Gulf of Mexico and the shores of Florida, Georgia, and North Carolina. A space of several hundred miles on the east coast of India is similarly bordered. M. E. de Beaumont, indeed, has estimated that about a third of the whole of the coast-lines of the continents is fringed with such alluvial bars.

(*f.*) *Deltas in the Sea.*—The tendency of sediment to accumulate in a tongue of flat land when a river loses itself in a lake is exhibited on a far vaster scale where the great rivers of the continents enter the sea. It was to one of these maritime accumulations, that of the Nile, that the Greeks gave the name Delta, from its resemblance to their letter Δ, with the apex pointing up the river, and the base fronting the sea. This shape being the common one in all such alluvial deposits at river mouths, the term delta has come to be always applied to them. A delta therefore consists of successive layers of detritus, brought down from the land and spread out in the sea at the mouth of a river until they reach the surface, and then, partly by growth of vegetation and partly by flooding of the river, form a plain, of which the inner and higher portion comes eventually to be above the reach of the floods. Large quantities of drift-wood are often carried down, and bodies of animals are swept off to be buried in the delta, or even to be floated out to sea. Hence, in deposits formed at the mouths of rivers, we may always expect to find terrestrial organic remains.

When a river enters upon the delta-portion of its course it assumes a new character. In the previous parts of its journey it is always being augmented by tributaries; but now it begins to split up into branches, which wind to and fro through the flat alluvial land, often coalescing and thus enclosing insular spaces of all dimensions. The feeble current, no longer able to bear along all its weight of sediment, allows much of it to sink to the bottom and to gather over the tracts which are from time to time submerged. Hence many of the channels get choked up, while others are opened out in the plain, to be in turn abandoned, and thus the river restlessly shifts its channels. The seaward ends of at least the main channels grow outwards by the constant accumulation of detritus pushed into the sea, unless this growth chances to be checked by any marine current sweeping past the delta.

The European rivers furnish many excellent illustrations of delta-growth. Thus the Rhine, Meuse, Sambre, Scheldt, and other rivers have formed the wide maritime plain of Holland and the Netherlands. The Rhone has deposited an important delta in the Mediterranean Sea. The upper reaches of the Adriatic Sea are being rapidly shallowed and filled up by the Po, Adige, and other streams. Thus Ravenna, originally built in a lagoon like Venice, is now 4 miles from the sea. The port of Adria, so well known in ancient times as to have given its name to the Adriatic, is now 14 miles inland, while in other parts of that coast-line the breadth of land gained within the last 1800 years has been as much as 20 miles. On the opposite side, also, of the Italian peninsula, great additions have been made to the coast-line within the historical period. It is computed that the Tuscan rivers lay down as much as 12 million cubic yards of sediment every year within the marshes of the Maremma. The "yellow" Tiber, as it was aptly termed by the Romans, owes its colour to the abundance of the sediment which it carries to sea. It has long been adding to the coast-line at its mouth at the rate of from 12 to 13 feet per annum. Hence the ancient harbour of Ostia is now more than 3 miles inland. Its ruins are at present (1879) being excavated, but every flood of the river leaves a thick deposit of mud on the streets and on the floors of the uncovered houses. Whence it would seem that the Tiber has not only advanced its coast-line, but has raised its bed on the plains by the deposit of alluvium, so that it now overflows places which, 2000 years ago, could not have been so frequently under water.[1] In the Black Sea a great delta is rapidly growing at the mouths of the Danube. At the Kilia outlets the water is shallowing so fast that the lines of soundings of 6 feet and 30 feet are advancing into the sea at the rate of between 300 and 400 feet per annum.[2]

The typical delta of the Nile has a seaward border 180 miles in length, the distance from which to the apex of the plain where the river bifurcates is 90 miles. That of the Mississippi contains an area of 40,000 square miles. The united delta of the Ganges and Brahmaputra covers a space of between 50,000 and 60,000 square miles, and has been bored through to a depth of 481 feet.

(*g.*) *Sea-borne Sediment.*—Although more properly to be noticed under the section on the sea, the final course of the materials worn by rains and rivers from the surface of the land may be referred to here. By far the larger part of these materials sinks to the bottom close to the land. It is only the fine mud carried in suspension in the water which is carried out to sea, the distance depending on the velocity of the stream, the specific gravity and shape of the particles of the mud, and the help or hindrance given by marine currents. The sea fronting the Amazon is discoloured for 300 miles by the mud of that river. The soundings taken by the "Challenger" brought up land-derived detritus from depths of 1500 fathoms,—several hundreds of miles distant from the nearest shores.

The amount of material carried by a river into the sea may be taken as the measure or gauge of the general lowering of the surface of the basin drained by the river. If we ascertain the annual quantity of mineral matter thus delivered into the sea, and know the superficial extent of ground from which it has been derived, the one sum divided by the other gives the extent by which the mean level of the country is reduced in one year. Both the fine mud mechanically suspended in the water and the salts dissolved in it should be taken into account, as well as the coarser detritus pushed along the bottom. It is the mechanically suspended mud which has generally been measured. According to the data of Messrs Humphreys and Abbot, already cited, the proportion of sediment in the Mississippi is $\frac{1}{1500}$ by weight, or $\frac{1}{2900}$ by volume. The annual discharge of sediment is 7,459,267,200 cubic feet, and the drainage basin 1,147,000 square miles. This is equal to a loss of $\frac{1}{6000}$ of a foot of rock from the general surface of the drainage basin in 1 year, or 1 foot in 6000 years. Other rivers work faster than this rate. The Ganges has been estimated to remove 1 foot of rock from its drainage area in 2358 years, and the Po 1 foot in 729 years. Such computations are at the best only approximations to the truth, but they are useful in showing how great an amount of change must be effected even within comparatively short geological periods by the various agents which are disintegrating the surface of the land.

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[1] See an interesting article by Professor Charles Martins on the Aigues-Mortes, in *Revue des Deux Mondes*, 1874, p. 780. The present writer accompanied the distinguished French geologist on the occasion of his visit to Ostia in the spring of 1873, and was much struck with the proofs of the rapidity of deposit in favourable situations. In the article just cited some valuable information is given regarding the progress of the delta of the Rhone in the Mediterranean.

[2] Hartley, *Min. of Proc. Inst. Civ. Engin.*, xxxvi. 216.

§ 4. *Lakes.*

Depressions filled with water on the surface of the land, and known as lakes, occur abundantly in the northern parts of both hemispheres, and more sparingly, but often of large size, in warmer latitudes. They do not belong to the normal system of erosion in which running water is the prime agent, and to which the excavation of valleys and ravines must be attributed. On the contrary, they are exceptional to that system, and the constant tendency of running water is to fill them up. Their origin, therefore, must be sought among some of the other geological processes. See part vii.

Lakes are conveniently classed as fresh or salt. Those which possess an outlet contain in almost all cases fresh water; those which have none are usually salt.

1. *Fresh-water Lakes.*—These, in a vast number of cases, are simply depressions or expansions of the valleys in which they lie. They receive a river at the upper end, together probably with many minor tributaries from the sides, and let the accumulated waters overflow at the lower end. In all these cases, they act as filters for the river water, allowing its sediment to settle, and discharging it purified at the outflow, to continue its course of erosion and mud-making down the valley. A river which flows through a succession of lakes cannot carry much sediment to the sea, unless it has a long course to run after it has passed the lowest lake, and receives one or more muddy tributaries. But the sediment which would have reached the sea and gone to form a delta or deposit on the sea-bed serves its purpose in contributing to fill up the lakes. Hence it is rare to find any lake with an inflowing and outflowing river, where proofs of the gradual encroachment of the land upon the water may not be gathered.

In other cases lakes do not lie in the natural drainage lines of a country, but are scattered apparently at random over the surface, fed by springs, rains, and streamlets from the slopes, or, if of large size, lying as great basins, receiving the collected waters of a wide region, and forming in this way the source out of which full-formed rivers emerge. From the little tarns of Wales and the lochans of Scotland a series may be traced, through innumerable grades of size and form, in Scandinavia, Finland, and Canada, till we reach such vast sheets of inland water as Lakes Huron, Erie, and Superior, and the great equatorial lakes of Africa. In lakes of this kind also the process of filling up may often be traced. Each tributary stream pushes its delta into the water. Where the lakes are shallow, and lie in temperate countries, vegetation comes in to aid in the conversion of the water, first into marsh, then into peat-bog, and finally into dry ground. In Scotland during the last few centuries great changes of this kind have been going on.

On large lakes the wind throws the water into waves which almost rival those of the ocean in size and destructive power. Beaches, sand-dunes, shore-cliffs, and the other familiar features of the meeting line between land and sea reappear along the margins of such great fresh-water seas as Lake Superior.

Three geological functions of lakes are (1) to arrest and equalize the drainage by regulating the outflow and preventing or lessening the destructive effects of floods[1]; (2) to filter river water and permit of the undisturbed accumulation of new deposits, which in some modern cases may cover thousands of square miles of surface, and might attain a thickness of nearly 3000 feet (Lake Superior has an area of 32,000 square miles; Lago Maggiore is 2800 feet deep); (3) to furnish an abode for a lacustrine fauna and flora, to receive the remains of the plants and animals washed down from the surrounding country, and to entomb all these organisms in the growing deposits, so as to preserve a record of the terrestrial life of the period. The deposits in lakes consist of alternations of sand, silt, mud, and gravel, with occasional irregular seams of vegetable matter, and layers of calcareous marl formed from the accumulation of lacustrine shells, *Entomostraca*, &c. In a lake receiving much sediment there will be little or no marl formed, at least not during the time when the sediment is being deposited. In clear lakes, on the other hand, where there is very little sediment or where it only comes occasionally at wide intervals of flood, beds of white marl, formed entirely of organic remains, may gather on the bottom to a depth of many yards.

2. *Salt Lakes* may be divided into two classes—(*a*) those which owe their saltness to the evaporation and concentration of the fresh water poured into them by their feeders; and (*b*) those which were originally parts of the ocean. Salt lakes of the first kind are abundantly scattered over the inland areas of drainage in the heart of continents, as in the great Lake of Utah, and numerous other minor lakes in North America, and the abundant salt lakes of the great plateau of Central Asia. These sheets of water were doubtless fresh at first, but they have progressively increased in salinity, because though the water is evaporated as fast as it is received, there is no escape for the dissolved salts, which consequently remain in the increasingly concentrated liquid. Salt lakes of the second class are comparatively few in number. In their case portions of the sea have been isolated by movements of the earth's crust, and these detached areas, exposed to evaporation, which is only partially compensated by inflowing rivers, have shrunk in level, and at the same time have sometimes grown much salter than the parent ocean. The Caspian Sea, 180,000 square miles in extent, and with a maximum depth of from 2000 to 3000 feet, is a magnificent example. The shells are chiefly the same as those still living in the Black Sea. Banks of them may be traced between the two seas, with salt lakes and marshes and other evidence to prove, not only that the Caspian was once joined to the main ocean, but that a great firth ran up between Europe and Asia, and possibly stretched completely across what are now the steppes and plains of the Tundras till it merged into the Arctic Sea. Even at present, by means of canals connecting the rivers Volga and Dwina, vessels can pass from the Caspian into the White Sea. But the surface of the Caspian is now more than 80 feet below that of the Black Sea. At present the amount of water supplied by rivers to the Caspian just balances that removed by evaporation, so that the level appears to be no longer sinking. But though, owing to the enormous volume of fresh water poured into it by these rivers, the Caspian is not as a whole so salt as the main ocean, and still less so than the Mediterranean, nevertheless the inevitable result of evaporation is there manifested. Along the shallow pools which border this sea a constant deposition of salt is taking place, forming sometimes a pan or layer of rose-coloured crystals on the bottom, or gradually getting dry, and covered with drift sand. This concentration of the water is still more marked in the great offshoot called the Karaboghaz, which is connected with the middle basin of the Caspian by a channel 150 yards wide and 5 feet deep. Through this narrow mouth there flows from the main sea a constant current, which Von Baer estimated to carry daily into the Karaboghaz 350,000 tons of salt. An appreciable increase of the saltness of that gulf has been noticed: seals, which once frequented it, have forsaken its barren shores. Layers of salt are gathering on the mud at

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[1] Winds, by blowing strongly down the length of a lake, sometimes considerably increase for the time being the volume of the outflow. If this takes place coincidently with a heavy rainfall, the flood of the river is greatly augmented. These features are noticed in Loch Tay (D. Stevenson, *Reclamation of Land*, p. 14). Hence, though, on the whole, lakes tend to moderate floods in the outflowing rivers, they may by a combination of circumstances sometimes increase them.

the bottom, and the sounding-line, when scarcely out of the water, is covered with saline crystals.[1] These facts furnish an illustration of the circumstances under which the rock-salt deposits in the New Red Sandstone and other geological formations were probably accumulated.

The following table shows the proportion of the saline materials in the waters of some salt lakes :—

	Elton Lake, Kirghis Steppe, in Summer. (Erdmann.)	Indertsch Lake. (Göbel.)	Dead Sea. (C. G. Gmelin.)	Caspian Sea. (Göbel.)
Chloride of Sodium	7·4	23·9	7·1	0·3673
„ Magnesium	16·3	1·7	11·8	0·0632
„ Calcium	...	...	3·2	0·0013 Bicarb. Magn.
„ Potassium	...	0·1	1·7	0·0076
„ Manganese	...	...	0·2	...
„ Aluminium	...	...	0·1	...
Bromide of Magnesium	...	...	0·4	... trace
„ Potassium	...	...	...	...
Sulphate of Calcium	..	...	0·05	0·0490
„ Potassium	0·04	0·04	...	0·0171 Bicarb. Lime.
„ Magnesium	2·2	0·3	...	0·12[illegible]
Water	73·5	73·8	74·5	99·3806
	99·44	99·84	99·05	100·0000

II. FRESH WATER IN THE SOLID STATE—ICE.

Fresh water under ordinary circumstances, when it reaches a temperature of 32° Fahr., passes into the solid state by crystallizing into ice. In this condition it performs a series of important geological operations before being again melted and relegated to the general mass of liquid terrestrial waters. Five conditions under which ice occurs on the land deserve notice, viz., frost, frozen rivers and lakes, hail, snow, and glaciers.

1. *Frost.*—Water in freezing expands. If it be confined in such a way that expansion is impossible, it remains liquid even at temperatures far below the freezing point; but the instant that the pressure is removed this chilled water becomes solid ice. There is a constant effort on the part of the water to become solid, and very considerable pressure is needed to counterbalance its expansive power. The lower the temperature the greater this exerted pressure becomes. At a temperature of 30° Fahr. the pressure must amount to 146 atmospheres, or the weight of a column of ice a mile high, or 138 tons on the square foot. Consequently when the water freezes at a lower temperature its pressure on the walls of its enclosing cavity must exceed 138 tons on the square foot. Bomb-shells and cannon filled with water and hermetically sealed have been burst in strong frosts by the expansion of the freezing water within them. It is easy to see, therefore, that we have here a geological agent of great potency. It is true that in nature the enormous pressures which can be obtained artificially occur rarely or not at all, because the spaces into which water penetrates can hardly ever be so securely closed as to permit the water to be cooled down very considerably below 32° Fahr. before freezing. Still ice forming at even two or three degrees below the freezing point exerts an enormous disruptive force.

Soils and rocks are all porous, and usually contain a good deal of moisture. When frost congeals this interstitial water, the particles of the soil or rock are pushed asunder by the expanding ice; their cohesion is loosened or destroyed, so that when a thaw comes, they seem as if they have been ground down in a mortar. Water lodges also in the numerous joints and crevices of rocks. Freezing there, it exerts great pressure upon the walls between which it lies, pushing them asunder as if a wedge were driven between them. When this ice melts, the separated masses do not return to their original position. Their centre of gravity in successive winters becomes more and more displaced, until the sundered masses fall apart. In mountainous districts, where the winters are severe, and in high latitudes, a great deal of waste is thus produced on exposed cliffs and loose blocks of rock. Some measure of its magnitude may be seen in the heaps of angular rubbish which in these regions are so frequently to be met with at the foot of crags and steep slopes. At Spitzbergen and on the coast of Greenland the amount of destruction caused by frost is enormous. The short and warm summer, melting the snow, fills the pores and joints of the rocks with water, which when it freezes splits off large blocks of rock from the hills, and sends them to the base of the declivities, where they are further broken up by the same cause.

2. *Frozen Rivers and Lakes.*—In countries where the winter temperature falls considerably below 32° Fahr., the lakes and rivers become solidly frozen over. The amount of geological change effected during the process is probably hardly appreciable. But when the ice breaks up in spring its power as a geological agent becomes apparent. In lakes, such as Lake Superior, the ice in forming encloses beach-pebbles and boulders, and when thaw sets in, floats these off, so as either to drop them in deeper water or to strand them on some other part of the coast. Should a gale arise during the breaking up of the ice, vast piles of the latter, with mingled gravel and boulders, may be driven ashore and pushed up the beach. By this means blocks of stone, even of considerable size, are sometimes forced to a great height inland on some of the Canadian lakes, tearing up the soil on their way, and helping to form a bank above the water level. It has been observed that during a severe frost ice occasionally forms on the bottoms of rivers where it encloses stones and large boulders. These are borne up to the surface in cakes of ground-ice to join the rest of the superficial ice-borne detritus. Great damage is frequently done to quays and bridges in Canada by masses of river-ice driven against them on the arrival of spring. Reference has already been made to the increased power of transport and erosion acquired by rivers liable to be frozen over, and especially when their ice is broken up in the higher parts of their courses, before it gives way in the lower.

3. *Hail.*—When rain or aqueous vapour is cooled down in the atmosphere to the freezing point of water, it is frozen, and falls to the earth as hail or snow. The formation of hail is not yet well understood. It is chiefly in summer and during thunderstorms that hail falls. When the pellets of ice are frozen together so as to reach the ground in lumps as large as a pigeon's egg, or larger, great damage is often done to cattle, flying birds, and vegetation. Trees have their leaves and fruit torn off. and farm crops are beaten down.

4. *Snow.*—In those parts of the earth's surface where, either from geographical position or from elevation into the upper cold regions of the atmosphere, the mean annual temperature is below the freezing point, the condensed moisture falls chiefly as snow, and remains in great measure unmelted throughout the year. A line can be traced below which the summer heat suffices to cause the disappearance of the snow, but above which the snow continues to cover the whole or great part of the surface. This line has received the name of the snow-line, or line of perpetual snow. It comes down to the sea within the polar circles. Between these limits it rises gradually in level till it reaches its highest elevation in tropical latitudes. In northern Scandinavia it is less than 3000 feet above the sea. None of the British mountains quite reach it. In the Alps it stands at 8500 feet, on the Andes at 18,000 feet, and on the northern slopes of the Himalayas at 19,000 feet.

Snow exhibits two different kinds of geological behaviour, one conservative, the other destructive. Lying stationary and unmelted it exercises a protective influence on the face of the land, shielding rocks, soils, and vegetation from the effects of frost. On low grounds this is doubtless its chief function. When snow falls in a partially melted state it is apt to accumulate on branches and leaves, until by its weight it breaks them off, or even bears down entire trees. Snow which falls thickly on steep mountain slopes is frequently during spring and summer detached in large sheets. These rush down the declivities as *avalanches*, and often create much destruction of trees, soil, crops, and houses in their course. Another indirect effect of snow is seen in the sudden rise of the rivers when warm weather rapidly melts the mountain snows. Many summer floods are caused in this way in Switzerland.

5. *Glaciers.*—(1.) Nature and Origin.—A glacier is a river of ice formed by the slow movement and compression of the snow which by gravitation creeps downward into a valley descending from a snow-field. The structure and physics of glaciers are described elsewhere (see GLACIERS). From a geological point of view these ice-rivers may be regarded as the drainage of the snow-fall above the snow-line, as rivers are the drainage of the rainfall. In a mountainous region, such as the Alps, or a table-land like Scandinavia, where a considerable mass of ground lies above the snow-line, three varieties of glaciers have been observed. (*a.*) Glaciers of the first order, where the ice-river comes down well below the snow and extends into the valley, even it may be far below the upper limits of cultivation, or in northern regions approaches or even reaches the sea. In the Alps such glaciers may be 20 or 30 miles long, by a mile or more wide, and 600 feet or more deep. (*b.*) Glaciers of the second order, which hardly creep beyond the high recesses wherein they are formed, and do not therefore reach as far as the nearest valley. Many beautiful examples of this type may be seen along the steep declivities which intervene between the snow-covered plateau of Arctic Norway and the sea. (*c.*) Re-cemented glaciers, consisting of fragments which fall from an ice-cliff crowning precipices of rock, and are re-frozen at the bottom into a solid mass, creeping downward as a glacier usually of the second order. Probably the best illustrations in Europe are furnished by the Nus Fjord, and other parts of the north of Norway. In some cases a cliff of blue ice appears at the top of the precipice,—the edge of the great "snee-fond," or snow-field,—while several hundred feet below, in the corrie or cwm at the bottom, lies the re-cemented glacier (*glacier remanié* of the Swiss), white at its upper edge, but acquiring somewhat of the characteristic blue gleam of compact ice as it moves towards its lower margin.

But it is in high Arctic, and still more in Antarctic, latitudes that land-ice, formed from the drainage of a great snow-field, attains its greatest dimensions. The land in these regions is completely buried under an ice-cap, which ranges in thickness up to a depth (in the South Polar circle) of 10,000 feet (2 miles) or even more. Greenland lies under such a pall of snow that all its inequalities, save the mere steep mountain peaks, are concealed. The snow creeping down the slopes, and mounting over the minor hills, passes beneath by pressure into compact ice. From the main valleys great glaciers like vast tongues of ice, 2000 or 3000 feet thick, and sometimes 50 miles or more in breadth, push out to sea, where they break off in huge fragments, which float away as icebergs.

A glacier, like a river, is always in motion, though so slowly that it seems to be solid and stationary. The motion also, like that of a river, and for the same reason, is unequal in the different parts, the centre moving faster than the sides and bottom. This important fact was first ascertained through accurate measurement by J. D. Forbes, who found that in the Mer de Glace of Chamouni, the mean daily rate of motion in the summer and autumn was from 20 to 27 inches in the centre, and from 13 to 19½ near the side. The consequence of this differential motion is seen in the arrangement of the lines of rubbish thrown down at the end of a glacier, which often present a horse-shoe shape, corresponding to that of the end of the ice by which they were discharged.

There are some features of geological importance also in the behaviour of the ice as it descends its valley. When it has to travel over a very uneven floor, some portions may get embayed, while overlying parts slide over them. A massive ice-sheet may thus have many local eddies in its lower portions, the ice there even travelling for various distances, according to the nature of the ground, obliquely to the general flow of the main mass. In descending by a steep slope from an upper to a lower and more level part of its course, a glacier becomes a mass of fissured ice in great confusion. It descends by a slowly creeping ice-fall, where a river would shoot over in a rushing waterfall. A little below the fall the fractured ice is pressed together again into a solid mass as before. The body of the glacier throughout its length is traversed by a set of fissures called *crevasses*, which, though at first as close-fitting as cracks in a sheet of glass, widen by degrees as the glacier moves on, till they form wide yawning chasms, reaching, it may be, to the bottom of the ice, and travelling down with the glacier, but apt to be effaced by the pressing of their walls together again as the glacier winds down its valley. The glacier continues to descend until it reaches that point where the supply of ice is just equalled by the liquefaction. There it ends, and its place down the rest of the valley is taken by the tumultuous river of muddy water which escapes from under the melting extremity of the ice. A prolonged augmentation of the snow-fall will send the foot of the glacier further down the valley; a diminution of the snowfall with a general rise of temperature will cause it to retreat farther up.

(2.) Work done by Glaciers.—Glaciers have two important geological tasks to perform,—(1) to carry the debris of the mountains down to lower levels; and (2) to erode their beds.

a. Transport.—This takes place chiefly on the surface of the glacier. Descending its valley, the glacier receives and bears along on its margin the earth, stones, and rubbish which, loosened by frost, or washed down by rain and rills, slip from the cliffs and slopes to the level of the ice. In this part of its work the glacier resembles a river which carries down branches and leaves from the woods on its banks. Most of the detritus rests on the surface of the ice. It includes huge masses of rock, sometimes as big as a large cottage, all which, though seemingly at rest, are slowly travelling down the valley with the ice, and liable at any moment to slip into the crevasses which may open below them. When they thus disappear they may descend to the bottom of the ice, and move with it along the rocky floor, which is no doubt the fate of the smaller stones and sand. Bnt the large stones seem sometimes at least to be cast up again by the ice to the surface of the glacier at a lower part of its course. Whether, therefore, on the ice, in the ice, or under the ice, a vast quantity of detritus is continually travelling with the glacier down towards the plains. The rubbish lying on the surface is called *moraine stuff.* Naturally it accumulates on either side of the glacier, where it forms the so-called *lateral moraines.* When two glaciers unite, their two adjacent lateral moraines are brought together, and travel thereafter down the centre of the glacier as a *medial moraine.* A glacier, formed by the union of many tributaries in its upper parts, may have

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[1] Carpenter, *Journ. Geog. Soc.*, vol. xviii., No. 4, quoting from Von Baer's "Kaspische Studien," in *Bull. Acad. Sci. St Petersburg*, 1855–6.

many medial lines of moraine, so many indeed as sometimes to be entirely covered with debris to the complete concealment of the ice. At such parts the glacier resembles a bare field or earthy plain rather than a solid mass of clear ice of which only the surface is dirty with rubbish. At the point where the glacier ends, the pile of loose materials is tumbled upon the valley in what is called the *terminal moraine.*

In such comparatively small and narrow ice-sheets as the present glaciers of Switzerland, the rock-bottom on which the ice moves is usually, as far as it can be examined, swept clean by the trickle or rush of water over it from the melting ice. But when the ice does not flow in a mere big drain (which, after all, the largest Alpine valley really is), but overspreads a wide area of uneven ground, there cannot fail to be a great accumulation of rubbish here and there underneath it. When the broad central plain of Switzerland between the Alps and the Jura was filled with ice, the latter certainly pushed a vast deal of mud, sand, and stones over the floor of the valley. This material is known to Swiss geologists as the *moraine profonde* or *Grundmoräne.*[1]

When from any cause a glacier diminishes in size, it may drop its blocks upon the sides of its valley, and leave them there sometimes in the most threatening positions. Such stranded stones are known as *perched blocks.* They abound in the Swiss valleys, extending even across the great plain of Switzerland, and appearing in numbers high upon the flanks of the Jura. Since the latter mountains consist chiefly of limestone, and the blocks are of various crystalline rocks belonging to the higher parts of the Alps, the proof of transport is irrefragable. The agent of removal is now recognized to have been an enormous extension of the glacier system of the Alps, whereby the whole country was buried under snow and ice. Similar evidence abounds in the valleys among the mountainous parts of Britain, as well as in other parts of Europe and America, no longer the abode of glaciers.

b. Erosion.—The manner in which glacier ice erodes its channel differs in many respects from that in use by any other geological agent, and forms therefore one of the distinguishing features of ice-action. This erosion is effected not by the mere contact and pressure of the ice upon the rocks, though undoubtedly fragments of rock must now and then be detached from this cause. It is by means of the fine sand, stones, and blocks of rock, which fall between the ice and the rocks on which it moves, that the grinding work of the glacier is done. These materials, held by the ice as it creeps along, are pressed against the rocky sides and bottom of the valley so firmly and persistently as to descend into each little hollow and mount over each ridge, yet all the while moving along steadily in one dominant direction with the general movement of the glaciers. As a result, the most compact resisting rocks are ground down, smoothed, polished, and striated. The striæ vary from such fine lines as may be made by the smallest grains of quartz up to deep ruts and grooves. They sometimes cross each other, one set partially effacing an older one, and thus pointing to shiftings in the movement of the ice. On the retirement of the glacier, hummocky bosses of rock having smooth undulating forms like dolphins' backs are conspicuous. These have received the name of *roches moutonnées.* The stones by which this scratching and polishing are effected suffer in exactly the same way. They are ground down and striated, and since they must move in the line of least resistance, or "end on," their striæ run in a general sense lengthwise. It will be seen, when we come to notice the traces of former glaciers, how important is the evidence given by these striated stones.

As rocks present great diversities of structure and hardness, and consequently vary much in the resistance they offer to denudation, they are necessarily worn down unequally. The softer, more easily eroded portions are scooped out by the grinding action of the ice, and basin-shaped or various irregular cavities are dug out below the level of the general surface. Similar effects may be produced by an augmented excavating power of a glacier, as where the ice is strangled in some narrow part of a valley, or where, from change in declivity, it is allowed to accumulate in greater mass as it moves more slowly onward. Such hollows, on the retirement of the ice, become receptacles for water, and form pools, tarns, or lakes, unless indeed they chance to have been already filled up with glacial rubbish. It is now some years since Professor A. C. Ramsay drew attention to this peculiar power of land-ice, and affirmed that the abundance of excavated rock-basins in northern Europe and America was due to the fact that these regions had been extensively eroded by sheets of land-ice. This glaciation was due not to independent glaciers but to the pressure and grinding power of vast masses of continental ice. In short the more northern parts of Europe and North America must have been in a condition like that of North Greenland at the present day. It is therefore among the ice-fields of Greenland rather than among the valley glaciers of isolated mountain-groups that we ought to look for analogies to the operations which produced the widespread general glaciation of the period of the rock-basins. A single valley-glacier retires towards its parent snow-field as the climate ameliorates, leaving its *roches moutonnées*, moraine-mounds, and rock-basins, yet at times discharging its water-drainage in such a way perhaps as to sweep down the moraine-mounds, fill up the basins, bury the ice-worn hummocks of rock, and strew the valley with gravel, earth, sand, and big blocks of rock. Hence the actual floor of the glacier is apt to be very much obscured. But in the case of a vast sheet of land-ice covering continuously a wide region, there can be but little superficial debris. When such a mass of ice retires it must leave behind it an ice-worn surface of country more or less strewn with the subsoil which accumulated under the ice and was pushed along by it. This infra-glacial detritus forms the *Grundmoräne* (*moraine profonde*) or bottom moraine. We know as yet very little regarding its formation in Greenland. Most of our knowledge regarding it is derived from a study of the till or boulder-clay of Britain, which is believed to represent the bottom moraine of an ancient ice-sheet. In countries where true boulder-clay occurs, numerous rock-basins are commonly to be met with among the uncovered portions of the rocks.

The abundant fine sediment which gives the characteristic milky turbidity to all streams that escape from the melting ends of glaciers is an index of the amount of erosion unceasingly effected by the ice. From the end of the Aar glacier, for example, though by no means one of the largest in Switzerland, it has been estimated that there escape every day in the month of August 2 million cubic metres (440 million gallons) of water. containing 284,374 kilogrammes (280 tons) of sand.

B. OCEANIC WATERS.

The area, depth, temperature, density, and composition of the sea have been already treated of in part ii. Viewed as a dynamical agent in geology, the ocean may be studied under two aspects—(1) its movements, and (2) its geological work.

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[1] The present writer examined in 1869 a characteristic section of it near Solothurn, full of scratched stones, and lying on the striated pavement of rock to be immediately described as further characteristic of ice-action.

I. MOVEMENTS OF THE OCEAN.

These may be grouped as—(1) tides, (2) currents, and (3) waves.

1. *Tides.*—These are oscillations of the mass of the oceanic waters caused by the attraction of the sun and moon. We have at present to deal with them merely in so far as their geological bearings are concerned. In a wide deep ocean the tidal elevation probably produces no perceptible geological change. It passes at a great speed; in the Atlantic its rate is 500 geographical miles an hour. But as this is merely the passing of an oscillation whereby the particles of water are gently raised up and let down again, there can hardly be any appreciable effect upon the deep ocean bottom. When, however, the tidal wave enters a narrow and shallow sea, it has to accommodate itself to a smaller channel, and encounters more and more the friction of the bottom. Hence, while its rate of motion is diminished, its height and force are increased. It is in shallow water and along the shores of the land that the tides acquire their main geological importance. They there show themselves in an alternate advance upon and retreat from the coast. Their upper limit has received the name of *high-water mark*, their lower that of *low-water mark*, the space between being termed the *beach.* If the coast is precipitous, a beach can only occur in the shelving bays and creeks, since elsewhere the tides will rise and fall against a face of rock, as they do on the piers and bulwarks of a port. On such rocky coasts the line of high water is sometimes admirably defined by the grey crust of barnacles adhering to the rocks. Where the beach is flat, and the rise and fall of the tide great, an area of several hundred square miles of sand or mud may be laid bare in one bay at low-water.

The height of the tide varies from zero up to 60 or 70 feet. It is greatest where, from the form of the land, the tidal wave is cooped up within a narrow inlet or estuary. Under such circumstances the advancing tide sometimes gathers itself into one or more large waves, and rushes furiously up between the converging shores. This is the origin of the "bore" of the Severn, which rises to a height of 9 feet, while the rise and fall of the tide there amounts to 40 feet. In like manner the tides which enter the Bay of Fundy, between Nova Scotia and New Brunswick, get more and more cooped up as they ascend that strait, till they reach a height of 70 feet.

While the tidal swelling is increased in height by the shallowness and convergence of the shores, it gains at the same time force and rapidity. No longer a mere oscillation or pulsation of the great ocean, the tide acquires a true movement of translation, and gives rise to currents which rush past headlands and through narrows in powerful currents and eddies. The rocky and intricate navigation of the west of Scotland and Scandinavia furnishes many admirable illustrations of the rapidity of these tidal currents. The famous whirpool of Corryvreckan, the lurking eddies in the Kyles of Skye, the breakers at the Bore of Duncansbay, and the tumultuous tideway, grimly named by the northern fishermen the Merry Men of Mey, in the Pentland Firth, bear witness to the strength of these sea rivers. At the last-mentioned strait the current at its strongest runs at the rate of 10 miles an hour, which is fully three times the speed of most of our larger rivers.

2. *Currents.*—Recent researches in ocean-temperature have disclosed the remarkable fact that beneath the surface layer of water affected by the temperature of the latitude there lies a vast mass of cold water, the bottom temperature of every ocean in free communication with the poles being little above and sometimes actually below the freezing point of fresh water. In the North Atlantic a temperature of 40° Fahr. is reached at an average depth of about 800 fathoms, all beneath that depth being progressively colder. In the equatorial parts of the same ocean the same temperature comes to within 300 fathoms of the surface. In the South Atlantic, off Cape of Good Hope, the mass of cold water (below 40°) comes likewise to about 300 fathoms from the surface This distribution of temperature proves that there must be a transference of cold polar water towards the equator, for in the first place the temperature of the great mass of the ocean is much lower than that which is normal to each latitude, and in the second place it is lower than that of the superficial parts of the earth's crust underneath. On the other hand, the movement of water from the poles to the equator requires a return movement of compensation from the equator to the poles, and this must take place in the superficial strata of the ocean. Apart therefore from those rapid river-like streams which traverse the ocean, and to which the name of currents is given, there must be a general drift of warm surface water towards the poles. This is doubtless most markedly the case in the North Atlantic, where besides the current of the Gulf-stream there is a prevalent set of the surface waters towards the north-east. As the distribution of life over the globe is everywhere so dependent upon temperature, it becomes of the highest interest to know that a truly arctic submarine climate exists everywhere in the deeper parts of the sea. With such uniformity of temperature we may anticipate that the abyssal fauna will be found to possess a corresponding sameness of character, and that arctic types may be met with even on the ocean-bed at the equator.

But besides this general drift or set, a leading part in oceanic circulation is taken by the more defined streams termed currents. The tidal wave only becomes one of translation as it passes into shallow water, and is thus of but local consequence. But a vast body of water, known as the Equatorial Current, moves in a general westerly direction round the globe. Owing to the way in which the continents cross its path, this current is subject to considerable deflexions. Thus that portion which crosses the Atlantic from the African side strikes against the mass of South America and divides, one portion turning towards the south and skirting the shores of Brazil, the other bending north-westward into the Gulf of Mexico, and issuing thence as the well-known Gulf-stream. This equatorial water is comparatively warm and light. At the same time the heavier and colder polar water moves towards the equator, sometimes in surface currents like those which skirt the eastern and western shores of Greenland, but more generally as a cold under-current which creeps over the floor of the ocean even as far as the equator.

Much discussion has arisen in recent years as to the cause of oceanic circulation. Two rival theories have been given. According to one of these the circulation entirely arises from that of the air. The trade-winds blowing from either side of the equator drive the water before them until the north-east and south-east currents unite in equatorial latitudes into one broad westerly-flowing current. Owing to the form of the land portions of this main current are deflected into temperate latitudes, and, as a consequence, portions of the polar water require to move towards the equator to restore the equilibrium. According to the other view the currents arise from differences of temperature (and according to some, of salinity also); the warm and light equatorial water is believed to stand at a higher level than the colder and heavier polar water; the former, therefore, flows down as it were polewards, while the latter moves as a bottom inflow towards the equator; the cold bottom water under the tropics is constantly ascending to the surface, whence, after being heated, it drifts away towards the pole, and on being cooled down there, descends and begins another journey to the equator. There can be no doubt that the winds are directly the cause of such currents as