the Gulf-stream, and therefore, indirectly, of return cold currents from the polar regions. It seems hardly less certain that, to some extent at least, differences of temperature, and therefore of density, must occasion movements in the mass of the oceanic waters. The discussion of this subject, however, belongs to another part of this work.[1] The main facts for the geological reader to grasp are—that a system of circulation exists in the ocean; that warm currents move round the equatorial regions, and are turned now to the one side now to the other by the form of the continents along and round which they sweep; that cold currents set in from poles to equator; and that, apart from actual currents, there appears to be an extremely slow "creep" of the polar water under the warmer upper layers towards the equator.

3. *Waves and Ground-Swell.*—A gentle breeze curls into ripples the surface of water over which it blows. A strong gale or furious storm raises the surface into waves. The agitation of the water in a storm is prolonged to a great distance beyond the area of the original disturbance, and then takes the form of the long heaving undulations termed ground-swell. Waves which break upon the land are called breakers, and the same name is applied to the ground-swell as it bursts into foam and spray upon the rocks. The concussion of earthquakes sometimes gives rise to very disastrous earthquake-waves, as already explained.

The height and force of waves depend upon the breadth and depth of sea over which the wind has driven them, and the form and direction of the coast-line. The longer the "fetch," and the deeper the water, the higher the waves. A coast directly facing the prevalent wind will have larger waves than a neighbouring shore which presents itself at an angle to this wind or bends round so as to form a lee-shore. The highest waves in the narrow British seas probably never exceed 15 or 20 feet, and usually fall short of that amount. The greatest height observed by Dr Scoresby among the Atlantic waves was 43 feet.[2]

Ground-swell propagated across a broad and deep ocean produces by far the most imposing breakers. So long as the water remains deep and no wind blows, the only trace of the passing ground-swell on the open sea is the huge broad heaving of the surface. But when the water shallows, the superficial part of the swell travelling faster than the bottom begins to curl and crest as a huge billow or wall of water, which finally bursts with enormous force against the shore. Such billows, even when no wind is blowing, often cover the cliffs of the north of Scotland with sheets of water and foam up to heights of 100 or even nearly 200 feet. At Dunnet Head during north-westerly gales the windows of the lighthouse, at a height of upwards of 300 feet above high-water mark, are said to be sometimes broken by stones swept up the cliffs by the sheets of sea water which then deluge the building.

A single roller of the ground-swell 20 feet high falls, according to Mr Scott Russell, with a pressure of about a ton on every square foot. Mr Thomas Stevenson conducted some years ago a series of experiments on the force of the breakers on the Atlantic and North Sea coasts of Britain. The average force in summer was found in the Atlantic to be 611 ℔ per square foot, while in winter it was 2086 ℔, or more than three times as great. But on several occasions, both in the Atlantic and North Sea, the winter breakers were found to exert a pressure of three tons per square foot, and at Dunbar as much as three tons and a half.[3] Besides the waves produced by ordinary wind action, others of an extraordinary size and destructive power are occasionally caused by a violent cyclone-storm. The mere diminution of atmospheric pressure in a cyclone must tend to raise the level of the ocean within the cyclone limits. But the further furious spiral in-rushing of the air towards the centre of the low pressure area drives the sea onward, and gives rise to a wave or succession of waves having great destructive power. Thus, on 5th October 1864, during a great cyclone which passed over Calcutta, the sea rose in some places 24 feet, and swept everything before it with irresistible force, drowning upwards of 48,000 people.

4. *Ice on the Sea.*—In this place may be most conveniently noticed the origin and movements of the ice which in circumpolar latitudes covers the sea. This ice is derived from two sources—(1) the freezing of the sea itself, and (2) the seaward prolongation of land-ice.

1. Three chief types of sea-ice have been observed. (*a.*) In the Arctic sounds and bays the littoral waters freeze along the shores and form a cake of ice which, upborne by the tide and adhering to the land, is thickened by successive additions below, as well as by snow above, until it forms a shelf of ice 120 to 130 feet broad and 20 or 30 feet high. This shelf, known as the ice-foot, serves as a platform on which the abundant debris loosened by the severe frosts of an arctic winter gathers at the foot of the cliffs. It is more or less completely broken up in summer, but forms again with the early frosts of the ensuing autumn. (*b.*) The surface of the open sea likewise freezes over into a continuous solid sheet which in summer breaks up into separate masses sometimes of large extent. This is what navigators term *floe-ice*, and the separate floating cakes are known as *floes*. Ships fixed among these floes have been drifted with the ice for hundreds of miles until at last liberated by its disruption. (*c.*) In the Baltic Sea, off the coast of Labrador and elsewhere, ice has been observed to form on the sea-bottom. It is known as ground-ice or anchor ice. In the Labrador fishing-grounds it forms even at considerable depths. Seals caught in the lines at those depths are brought up sometimes solidly frozen.

2. In the Arctic regions the vast glaciers which drain the snow-fields and descend to the sea extend for some distance from the land until large fragments break off and float away seawards. These detached masses are icebergs. Their shape and size greatly vary, but lofty peaked forms are common, and they sometimes rise from 200 to 300 feet above the level of the sea. As only about a ninth part of the ice appears above water, these larger bergs must sometimes be from 2000 to 3000 feet thick from base to top. They consequently require water of some depth to float them, but they are often seen aground. In the Antarctic regions, where one vast sheet of ice envelops the land and extends into the sea as a high rampart of ice, the detached icebergs often reach a great size, and are characterized by the frequency of a flat tabular form.

II. Geological Work of the Sea.

I. Influence on Climate.—Were there no agencies in nature for distributing temperature, there would be a regular and uniform diminution in the mean annual temperature from equator to poles, and the *isothermal* lines, or lines of equal heat, would coincide with lines of latitude. But no such general correspondence actually exists. If we look at a chart of the globe with the isothermal lines drawn across it, we shall find that their divergences from the parallels are striking, and most so where they approach and cross the ocean. Currents from warm regions raise the

[1] The reader may consult Maury's *Physical Geography of the Sea*, but more particularly Dr Carpenter's papers in the *Proceedings of the Royal Society* for 1869–73, and *Journal of R. Geographical Society* for 1871–77, on the side of temperature; and Herschel's *Physical Geography*, and Dr Croll's *Climate and Time*, on the side of the winds.

[2] *Brit. Assoc. Rep.*, 1850, p. 26. The reader will find a table of the observed heights of waves round Great Britain in Mr T. Stevenson's treatise on *Harbours*, p. 20.

[3] *Trans. Roy. Soc. Edin.*, xvi. 25; treatise on *Harbours*, p. 42.

temperature of the tracts into which they flow; those from cold regions lower it. The ocean, in short, is the great distributor of temperature over the globe. As an illustration the two opposite sides of the Atlantic may be taken. The cold arctic current flowing southward along the north-east coast of America reduces the mean annual temperature of that region. On the other hand, the Gulf-stream brings to the shores of the north-west of Europe a temperature much above what they would otherwise enjoy. Dublin and the south-eastern headlands of Labrador, lie in the same parallel of latitude, yet differ as much as 18° in their mean annual temperature, that of Dublin being 50°, and that of Labrador 32° Fahr. Dr Croll has calculated that the Gulf-stream conveys nearly half as much heat from the tropics as is received from the sun by the entire Arctic regions.[1]

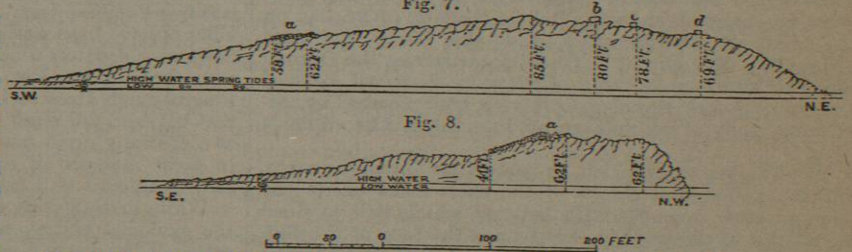
II. Erosion.—The chemical action of the sea upon the rocks of its bed and shores has not yet been properly studied.[2] It is evident, however, that changes analogous to those effected by fresh water on the land must be in progress. Oxidation, and the formation of carbonates, no doubt continually take place. We may judge indeed of the nature and rapidity of some of these changes by watching the decay of stones and material employed in the construction of piers. At the Bell Rock lighthouse, twenty-five different kinds and combinations of iron were exposed to the action of the sea, and all yielded to corrosion. Mr Mallet—as the result of experiments with specimens sunk in the sea—concluded that from $\frac{2}{10}$ths to $\frac{4}{10}$ths of an inch in depth in iron castings 1 inch thick, and about $\frac{6}{10}$ths of an inch of wrought iron, will be destroyed in a century in clear salt water. Mr Stevenson, in referring to these experiments, remarks that he has in his possession specimens of iron which show even a more rapid rate of decay. In castings used at the Bell Rock the loss has been at the rate of an inch in a century. "One of the bars which was free from air holes had its specific gravity reduced to 5·63, and its transverse strength from 7409 to 4797 ℔, and yet presented no external appearance of decay. Another apparently sound specimen was reduced in strength from 4068 ℔ to 2352 ℔, having lost nearly half its strength in fifty years."[3] Similar results were recently observed by Mr Grothe, resident engineer at the railway bridge across the Firth of Tay. A cast-iron cylinder which had been below water for only sixteen months was found to be so corroded that a penknife could be stuck through it in many places.

An examination of the shore will sometimes reveal a good deal of quiet chemical change on the outer crust of rocks exposed to the waves. Such rocks as basalt have their felspar decomposed, and show the presence of carbonates by effervescing briskly with acid. One of their minerals, augite, is occasionally replaced by *pseudomorphs* of carbonate of iron.

It is mainly by its mechanical action that the sea accomplishes its erosive work. This can only take place where the water is in motion, and, other things being equal, is greatest where the motion is strongest. Hence we cannot suppose that erosion to any appreciable extent can be effected in the abysses of the sea, where the only motion possible is that slow creeping of the polar water along the bottom already referred to. But where the currents are powerful enough to move grains of sand and gravel, very slow erosion may take place even at considerable depths. It is in the upper portions of the sea, however, where, owing to currents, tides, and waves, the water suffers most disturbance, that the main mechanical erosion goes on. The depth to which the influence of waves and ground-swell may extend seems to vary greatly according to the situation. The astronomer-royal states that ground-swell may break in 100 fathoms water.[4] It is common to find boulders and shingle disturbed at a depth of 10 fathoms, and even driven from that depth to the shore, and waves may be noticed to become muddy from the working up of the silt at the bottom when they have reached water of 7 or 8 fathoms in depth.[5] Gentle movement of the bottom water is said to be sometimes indicated by ripple-marks on the fine sand of the sea-floor at a depth of 600 feet. A good test for the absence of serious abrasion is furnished by the presence of fine mud on the bottom. Wherever that is found, we may be tolerably sure that the bottom at that place lies beyond the reach of ordinary breaker action.[6] From the upper limit at which the accumulation of mud is possible to high-water mark, and in exposed places up to 100 feet or more above high-water mark, lies the zone within which the sea does its work of abrasion. To this zone, even where the breakers are heaviest, a greater extreme vertical range can hardly be assigned than 300 feet, and in most cases it probably falls far short of that extent.

The mechanical work of erosion by the sea is done in four ways:—(1) the enormous force of the breakers suffices to tear off fragments of the solid rocks; (2) the alternate compression and expansion of the air in the crevices of rocks exposed to heavy breakers dislocates rocks even above the limits of wave-action; (3) the hydraulic pressure of those portions of large waves which enter fissures and cavities forces asunder masses of rock; (4) the waves make use of the loose fragments within their reach in battering down the cliffs exposed to their fury.

(1.) Abundant examples of the dislodgement of huge blocks of rock from their parent masses are furnished by the precipitous shores of Caithness, and of the Orkney and Shetland Islands. It sometimes happens that demonstration of the height to which the effective force of breakers may reach is furnished at lighthouses built on exposed parts of the coast. Thus, at Unst, a door was broken open at a height of 195 feet above the sea, and at the Bishop Rock lighthouse a bell was wrenched off at a level of 100 feet above high-water mark.[7] Some of the most remarkable instances of the power of breakers have been observed by Mr Thomas Stevenson among the islands of the Shetland group. On the Bound Skerry he found that blocks of rock up to $9\frac{1}{2}$ tons in weight had been washed together at a height of nearly 60 feet above the sea, that blocks weighing from 6 to $13\frac{1}{2}$ tons had been actually quarried out of their original bed, at a height of from 70 to 75 feet, and that a



Figs. 7 and 8.—Sections of the Bound Skerry of Whalsey, Shetland (from Stevenson's *Harbours*, p. 32): *a*, *b*, *c*, and *d*, positions of blocks moved by the sea.

[1] See papers by Dr Croll on "Gulf-stream and Ocean-currents," in *Geol. Mag.* and *Phil. Mag.* for 1869, 1870–74, and *Climate and Time*.

[2] See Bischof's *Chemical Geology*, vol. i. chap. vii.

[3] T. Stevenson on *Harbours*, p. 47.

[4] *Encyclopædia Metropolitana*, art. "Waves."

[5] T. Stevenson on *Harbours*, p. 15. [6] *Ibid.* [7] *Ibid.*, p. 31.

block of nearly 8 tons had been driven before the waves at the level of 20 feet above the sea, over very rough ground, to a distance of 73 feet (figs. 7 and 8). He likewise records the moving of a 50-ton block by the waves at Barrahead, in the Hebrides.[1] At Plymouth also, blocks of several tons in weight have been known to be washed about the breakwater like pebbles.[2]

(2.) But, besides their mechanical force, waves acquire a singular and most effective aid from the air. It is a fact familiar to engineers that, even from a vertical and apparently perfectly solid wall of well-built masonry exposed to heavy seas, stones will sometimes be started out of their places, and that when this happens a rapid enlargement of the cavity may be effected, as if the walls were breached by a severe bombardment. At the Eddystone lighthouse, during a storm in 1840, a door which had been securely fastened against the force of the surf from without, was actually driven outward by a pressure acting from within the tower, in spite of the strong bolts and hinges, which were broken. We may infer that, by the sudden sinking of a mass of water hurled against the building, a partial vacuum was formed, and that the air inside forced out the door in its efforts to restore the equilibrium.[3] This explanation may partly account for the way in which the stones are started from their places in a solidly built sea-wall. But besides this cause we must also consider a perhaps still more effective one in the condensation of the air driven before the wave between the joints and crevices of the stones, and its subsequent instantaneous expansion when the wave drops. During gales when large waves are driven to shore, many tons of water are poured suddenly into each cleft and cavern within reach. These volumes of water, as they rush in, compress the air into every joint and pore of the rock at the further end, and then quickly retiring, exert such a suction as from time to time to bring down part of the walls or roof. The sea may thus gradually form an inland passage for itself to the surface above, in a "blow-hole" or "puffing-hole," through which spouts of foam and spray are in storms shot high into the air. On the more exposed portions of the west coast of Ireland numerous examples of such blow-holes occur. In Scotland, likewise, they may often be observed, as in the Bullers (boilers) of Buchan on the coast of Aberdeenshire, and the Geary Pot near Arbroath. Magnificent instances occur among the Orkney and Shetland Islands, some of the more shattered rocks of these northern coasts being, as it were, honeycombed by sea-tunnels, many of which open up into the middle of fields or moors.

(3.) The sea-water which, as part of an inrushing wave, fills the gullies and chinks of the shore-rocks exerts the same pressure upon the walls between which it is confined as the rest of the wave is doing upon the face of the cliff. Each cleft so circumstanced becomes a kind of hydraulic press, the potency of which is to be measured by the force with which the waves fall upon the rocks outside—a force which often amounts to three tons on the square foot. There can be little doubt that by this means considerable pieces of a cliff are from time to time dislodged.

(4.) But probably by far the largest amount of erosion accomplished by the sea is due not to its own direct mechanical impetus, but to the blows dealt by the boulders, gravel, or sand which it hurls against the shores. This action was aptly compared by Playfair to a kind of artillery.[4] During a storm upon a shingly coast we may hear, at a distance of several miles, the grind of the stones against each other, as they are dragged back by the recoil of the waves which had launched them forward. In this tear and wear the loose stones are ground smaller, and acquire the smooth round form so characteristic of a surf-beaten beach. At the same time they bruise and wear down the solid cliffs against which they may be driven. Wherever the rock is much jointed, or from any cause presents less resistance to attack, it is excavated into gullies, creeks, and caves; its harder parts standing out as promontories are pierced; gradually a series of detached buttresses and sea-stacks appears as the cliff recedes, and these in turn are wasted until they become mere skerries and sunken surf-beaten reefs. Of this progress of destruction the more exposed parts of the British coast-line furnish many admirable examples. The west coast of Ireland, exposed to the full swell of the Atlantic, is in innumerable localities completely undermined by caverns, into which the sea enters from both sides. In many places the cliffs are as vertical as walls, this feature depending upon their joints, which enable slice after slice to be undermined and removed. The precipitous coasts of Skye, Sutherland, Caithness, Forfar, Kincardine, and Aberdeenshire abound in the most impressive lessons of the waste of a rocky sea-margin; while the same picturesque features are prolonged into the Orkney and Shetland Islands, the magnificent cliffs of Hoy towering as a vast wall some 1200 feet above the Atlantic breakers, which are tunnelling and fretting their base.

If such is the progress of waste where the materials consist of the most solid rocks, we may expect to meet with at least equally impressive proofs of decay where the coast-line can oppose only soft sand or clay to the march of the breakers. Again, the geological student in Britain can examine for himself many illustrations of this kind of destruction around the shores of these islands. Within the last few hundred years entire parishes with their towns and villages have been washed away, and the tide now ebbs and flows over districts which in old times were cultivated fields and cheerful hamlets. The coast of Yorkshire between Flamborough Head and the mouth of the Humber, and also that between the Wash and the mouth of the Thames, suffer at a specially rapid rate, for the cliffs in these parts consist in great measure of soft clay. In some places this loss is said to amount to 3 feet per annum.

While investigating the proofs of decay along the shore, the geologist endeavours to ascertain to what extent the action of the waves is assisted by that of rain, springs, frosts, and general atmospheric disintegration. He often finds that the progress of the waves depends not so much upon their own labours as upon those of the terrestrial agencies already described. A crumbling cliff, battered and wasted by the breakers, will yield to him abundant evidence of the manner in which the other agents of destruction prepare the way for its final demolition and removal by the sea; and he will learn that the very blocks of stone which give the waves so much of their efficacy are in great measure furnished to them by these co-operating agents. If the cutting back of a cliff were mainly the work of the sea, we ought to find the cliff overhanging, because the sea acts only at its base. But the fact that in the vast majority of cases sea-cliffs, instead of overhanging, slope backward, at a greater or less angle, from the sea, shows that the waste from subaerial action is

[1] Stevenson, *op. cit.*, pp. 21–37.

[2] The reader will bear in mind that the specific gravity of bodies is greatly reduced when in water, and still more in sea-water. The following examples will illustrate this fact (Stevenson on *Harbours*, p. 107):—

	Spec. Grav.	No. of cub. feet to a ton in air.	No. of feet to a ton in sea-water of sp. grav. 1·028.
Basalt	2·99	11·9	18·26
Red granite	2·71	13·2	21·30
Sandstone	2·41	14·8	26·00
Cannel coal	1·54	23·3	70·00

[3] Walker, *Proc. Inst. Civ. Engin.*, i. 15: Stevenson's *Harbours*, p. 10

[4] *Illustrations of the Huttonian Theory*.

really greater than that from the action of the breakers. What the sea chiefly does is to break down and wash away the rubbish that falls from the cliffs, and thus to leave an ever fresh surface for renewed denudation.

(5.) Among the erosive operations of the sea must be included what is performed by floating ice. Along the margin of arctic lands a good deal of work is done by the broken up floe-ice and ice-foot. These cakes of ice, driven ashore by storms, tear up the soft shallow-water or littoral deposits, rub and scratch the rocks, and push gravel and blocks of rock before them as they strand on the beach. Icebergs also, when they get aground in deep water, must greatly disturb the sediment accumulating there, and must grind down any submarine rock on which they grate as they are driven along.

The general result of the erosive action of the sea on the land is the production of a submarine plain. As the sea advances by cutting slice after slice away from the coast, successive lines of beach pass under low-water mark. The whole of the littoral belt, as far down as wave action has influence, is continually being ground down by the moving detritus. If no change of level between sea and land should take place, the sea might conceivably eat its way slowly far into the land, and produce a gently sloping yet almost horizontal selvage of plain covered permanently by the waves. In such a submarine plain the influence of geological structure, and notably of the relative powers of resistance of different rocks, would make itself conspicuous. The present promontories caused by the superior hardness of their component rocks would no doubt be represented by ridges on the subaqueous plateau, while the existing bays and creeks worn out of softer rocks would be marked by lines of valleys or hollows.

III. TRANSPORT.—The sea by means of its surface-drifts and currents carries sedimentary material to great distances and strews them over its floor. Near land, where the movements of the water are active, much coarse detritus is transported along shore or swept farther out to sea. A prevalent wind, by creating a current in a given direction along a coast-line, will cause the shingle to travel coastwise, the stones getting more and more rounded and reduced in size as they recede from their sources. The Chesil Bank, which runs as a natural breakwater 16 miles long connecting the Isle of Portland with the mainland of Dorsetshire, consists of rounded shingle which is constantly being driven westwards. On the Moray Firth the reefs of quartz-rock about Cullen furnish abundance of shingle, which moves westwards along the coast for more than 15 miles. The coarser sediment probably seldom goes much beyond the littoral zone. Fine gravel, however, is pushed along the bottom by currents even at 600 fathoms; for at that depth in the North Atlantic between the Faroe Islands and Scotland small pebbles of volcanic and other rocks are dredged up which have probably been carried by an arctic under-current from the north. At greater depths the force of currents at the bottom must be too feeble to push along any detritus. But much fine sediment is carried in suspension by the sea for long distances from land. Some rivers, as the Amazon, pour so much silt into the sea as to discolour its water for several hundred miles away from land. After wet weather the coast-waters round the shores of the British Islands are sometimes made turbid from the quantity of mud brought down from the land. Dr Carpenter found the bottom waters of the Mediterranean to be everywhere permeated by an extremely fine mud, derived no doubt from the rivers and shores of that sea, borne away out far from land, and settling slowly down upon the bottom. He remarks that the characteristic blueness of the Mediterranean may be explained, like that of the Lake of Geneva (as shown by Dr Tyndall), by the diffusion of those exceedingly minute sedimentary particles through the water.

But the most startling evidence of the wide extent to which transport takes place in the ocean is that supplied by the observations made during the voyage of the "Challenger." From the abysses of the Pacific Ocean, at the furthest distances from land, the dredge brought up bushels of rounded pieces of pumice of all sizes up to blocks a foot in diameter. These fragments were all evidently water-worn, and almost certainly were derived from the land. Some small pieces indeed were taken on the surface in the tow-net. Round volcanic islands, and off the coasts of volcanic tracts of the mainland, the sea is sometimes covered with floating pieces of water-worn pumice swept out by flooded rivers. These fragments drift away for hundreds or even thousands of miles until, becoming water-logged, they sink to the bottom. Their universal distribution was one of the most noticeable features in the dredgings of the "Challenger." The clay which is found on the bottom of the ocean at the greatest distances from any shore may be partly due to its transport in that condition from land, but more probably to the decomposition of the drifted pumice.[1]

Another not unimportant process of marine transport is that performed by floating ice. Among the arctic glaciers moraine stuff is of rare occurrence; but occasional blocks of rock and heaps of earth and stones fall from the cliffs which rise above the general waste of snow. Hence on the icebergs that float off from these glaciers, rock debris sometimes may be observed. It is transported southward for hundreds of miles until, by the shifting or melting of the bergs, it is dropped into deep water. The floor of certain portions of the North Atlantic in the pathway of the bergs must be plentifully strewn with this kind of detritus. By means of the ice-foot also, an enormous quantity of earth and stones is every year borne away from the shore as the ice breaks up, and strewn over the floor of the sounds, bays, and channels.

IV. REPRODUCTION.—The sea being the receptacle for the material worn away from the land must receive and store up in its depths all that vast amount of detritus by the removal of which the level and contours of the land are in the course of time so greatly changed. The deposits which take place within the area covered by the sea may be divided into two groups—the inorganic and organic. It is the former with which we have at present to deal; the latter will be discussed with the other geological functions of plants and animals. The inorganic deposits of the sea-floor are partly (*a*) land-derived or terrigenous, partly (*b*) abyssal.

(*a*.) *Land-derived or Terrigenous.*—These may be conveniently grouped according to their relative places on the sea-bed.

(1.) Shore Deposits.—The most conspicuous and familiar are the layers of gravel and sand which accumulate between tide-marks. As a rule, the coarse materials are thrown up about the upper limit of the beach. They seem to remain stationary there; but if watched and examined from time to time, they will be found to be continually shifted by high tides and storms, so that the bank or bar of shingle retains its place though its component pebbles are being constantly moved. Below the limit of coarse shingle upon the beach lies the zone of fine gravel, and then that of sand. These zones are far from being constant; yet when they all occur on the same beach, they tend to range themselves according to their relative coarseness, the rougher detritus lying at the upper, and the finer towards the lower edge of the shore. The nature of the littoral accumulations on any

[1] Murray, *Proc. Roy. Soc. Edin.*, 1876–7, p. 247.

given part of a coast-line must depend either upon the character of the shore-rocks which at that locality are broken up by the waves, or upon the set of the shore-currents and the kind of detritus they bear with them. Coasts exposed to heavy surf, especially where of a rocky character, are apt to present beaches of coarse shingle between their projecting promontories. Sheltered bays, on the other hand, where wave action is comparatively feeble, afford a gathering ground for fine sediment such as sand and mud. Estuaries and inlets into which rivers enter frequently show wide muddy flats at low water. The mud brought down by the fresh water is allowed to sink to the bottom when the motion of the current is checked as it enters the sea.

(2.) Infra-Littoral and Deeper-Water Deposits.—These extend from below low-water mark to a depth of sometimes as much as 2000 fathoms, and reach a distance from land varying up to 200 miles or even more. Near land, and in comparatively shallow water, they consist of banks or sheets of sand more rarely mixed with gravel. The bottom of the North Sea, for example, which between Britain and the continent of Europe lies at a depth never reaching 100 fathoms, is irregularly marked by long ridges of sand enclosing here and there hollows where mud has been deposited. In the English Channel large banks of gravel extend through the Straits of Dover as far as the entrance to the North Sea. These features seem to indicate the line of the chief mud-bearing streams from the land, and the general disposition of currents and eddies in the sea which covers that region, the gravel ridges marking the tracks of the more rapidly moving currents, while the muddy hollows point to the eddies where the fine sediment is permitted to settle on the bottom. It is possible, however, that the inequalities on the floor of the North Sea, and their peculiarities of sediment, may not be due wholly to modern accumulations, but partly to the contour of the ground before it was submerged and the land connexion between Britain and Europe was destroyed

During the course of the voyage of the "Challenger," the approach to land could always be foretold from the character of the bottom, even at distances of 150 and 200 miles from land. The deposits were found to consist of blue and green muds derived from the degradation of older crystalline rocks. At depths of 100 to 700 fathoms they are often coloured green by glauconite. At greater depths they consist of blue or dark slate-coloured mud with a thin upper layer of red or brown. Throughout these land-derived sediments particles of mica, quartz, and other minerals are distributed, the materials becoming coarser towards land. Pieces of wood, portions of fruits, and leaves of trees occur in them, and further indicate the reality of the transport of material from the land. Shells of pteropods, larval gasteropods, and lamellibranchs are tolerably abundant in these muds, with many infra-littoral species of *Foraminifera*, and diatoms. Below 1500 or 1700 fathoms pteropod shells seldom appear, while at 3000 fathoms hardly a foraminifer or any calcareous organism remains (Murray, *Proc. Roy. Soc. Edin.*, 1876, p. 519). Round volcanic islands the bottom is found to be covered with grey mud and sand derived from the degradation of volcanic rocks. These deposits can be traced to great distances, as at Hawaii for 200 miles or more. Pieces of pumice, scoriæ, &c., occur in them, mingled with marine organisms, and more particularly with abundant grains, incrustations, and nodules of an earthy peroxide of manganese. Near coral-reefs the sea-floor is coated with a white calcareous mud derived from the abrasion of the coral. The east coast of South America supplies a peculiar red mud which is spread over the Atlantic slope down to depths of more than 2000 fathoms.

(*b.*) *Abyssal.*—Passing over at present the organic deposits which form so characteristic a feature on the floor of the deeper and more open parts of the ocean, we come to certain red and grey clays found at depths of more than 2000 fathoms down to the bottoms of the deepest abysses. These consist of exceedingly fine clay, coloured sometimes red by iron-oxide, sometimes of a chocolate tint from manganese oxide, with grains of quartz, mica, pumice, scoriæ, peroxide of manganese, and other mineral substances, together with *Foraminifera*, and in some regions a large proportion of siliceous *Radiolaria*. Mr Murray has shown the high probability that these clays result from the decomposition of pumice and fine volcanic dust transported from volcanic islands into mid-ocean. The extreme slowness of their deposit is strikingly brought out in the tracts farthest removed from land. From these localities great numbers of sharks' teeth, with ear-bones and other bones of whales, were dredged up in the "Challenger" expedition.—some of them quite fresh, others partially crusted with peroxide of manganese, and some completely and thickly surrounded by that substance. We cannot suppose that sharks and whales so abound in the sea as to cover the floor of the ocean with a continuous stratum of their remains. No doubt each haul of the dredge which brought up so many bones represented the droppings of many generations. The successive stages of manganese incrustation point to a long, slow, undisturbed period, when so little sediment accumulated that the bones dropped at the beginning remained at the end still uncovered, or only so slightly covered as to be easily scraped up by the dredge. In these deposits, moreover, Mr Murray has found numerous minute spherular particles of metallic iron which there is every reason to believe are of cosmic origin—portions of the dust of meteorites which in the course of ages have fallen upon the sea-bottom. Such particles no doubt fall all over the ocean; but it is only on those parts of the bottom which, by their distance from any land, receive accessions of deposit with extreme slowness, and where therefore the present surface may contain the dust of a long succession of years, that it has been possible to detect them.

The abundant deposit of peroxide of manganese over the floor of the deep sea is one of the most singular features of recent discovery. It occurs as an earthy incrustation round bits of pumice, bones, and other objects. The nodules possess a concentric arrangement of lines not unlike those of urinary calculi. That they are formed on the spot, and not drifted from a distance, was made abundantly clear from their containing abyssal organisms, and enclosing more or less of the surrounding bottom, whatever its nature might happen to be. Mr Murray refers their origin to the decomposition of the manganese-bearing minerals in the universally diffused volcanic detritus. Quite recently Mr J. Y. Buchanan has dredged similar manganese concretions from some of the deeper parts of Loch Fyne. In connexion with the chemical reactions indicated by these nodules as taking place on the sea-bottom, reference may be made to a still more remarkable but yet unpublished discovery made by Mr Murray in the course of his examinations of the materials brought up from the same abyssal deposits. He has detected abundant minute concretions or bundles of crystals which on analysis are found to resemble olivine in composition. These silicates (there may be several of them) have certainly been formed directly on the sea-bottom, for they are found gathered round abyssal organisms. It is difficult to overestimate the importance of this fact in reference to the chemistry of marine deposits.

From a comparison of the results of the dredgings made in recent years in all parts of the oceans, it is impossible to resist the conclusion that there is nothing in the character of the deep-sea deposits which finds a parallel among the marine geological formations visible to us on the land. It is only among the comparatively shallow water accumulations

of the existing sea that we encounter analogies to the older formations. And thus we reach by another and a new approach the conclusion which on very different grounds has been arrived at, viz., that the present continental ridges have existed from the remotest times, and that the marine strata which constitute so large a portion of their mass have been accumulated not as deep water formations, but in comparatively shallow water along their flanks.

Section III.—Life.

Among the agents by which geological changes are carried on upon the surface of the globe living organisms must be enumerated. Both plants and animals co-operate with the inorganic agents in promoting the degradation of the land; and in some cases, on the other hand, they protect rocks from decay. Again by the accumulation of their remains they form extensive formations both upon the land and in the sea. Their operations may hence be described as alike destructive, conservative, and reproductive. Under this heading also we may notice the influence of man as a geological agent.

I. Destructive Action.—Plants aid in the general progress of disintegration in various ways. 1. By keeping the surfaces of rocks moist, and thus promoting both the mechanical and chemical dissolution of the rocks. This action is especially shown by liverworts, mosses, and other plants which only thrive in copious moisture. 2. By producing through their decay carbonic and other acids, which, with decaying organic matter taken up by passing moisture, become potent in effecting the chemical decomposition of rocks, and in promoting the disintegration of soils. 3. By inserting their roots or branches between joints of rock, which are thereby loosened, so that large slices may be eventually wedged off. On the sides of wooded hills and cliffs this process may often be seen; even among old ruins an occasional sapling ash or elm may be found to have cast its roots round a portion of the masonry and to be slowly detaching it from the rest of the wall. 4. By attracting rain, as thick woods, forests, and mosses do, and thus accelerating the general scouring of a country by running water. The indiscriminate destruction of the woods in the Levant has been assigned with much plausibility as the main cause of the present desiccation of that region. 5. By promoting the decay of diseased and dead plants and animals, as when fungi overspread a damp rotting tree or the carcase of a dead animal.

Of the destructive influences of animal life numerous illustrations might be given. 1. The composition and arrangement of soil are affected. Worms are continually engaged in bringing up the lower portions of the soil to the surface, and thus increase its fertility and its capability of being washed away by rain. Burrowing animals, by throwing up the soil and subsoil, expose these to be dried and blown away by the wind. At the same time their subterranean passages serve to drain off the superficial water and to injure the stability of the surface of the ground above them. In Britain the mole and rabbit are familiar examples. In North America the prairie dog has undermined extensive tracts of pasture land in the west. In Cape Colony wide areas of open country seem to be in a constant state of eruption from the burrowing operations of multitudes of *Bathyergi* and *Chrysochloris*—small mole-like animals which bring up the soil and bury the grassy vegetation under it. 2. The flow of streams is sometimes interfered with, or even diverted, by the operations of animals. Thus the beaver, by constructing dams, checks the current of water-courses, intercepts floating materials, and sometimes even diverts the water into new channels. This action is typically displayed in Canada and other parts of North America. The embankments of the Mississippi are sometimes weakened to such an extent by the burrowings of the cray-fish as to gave way and allow the river to inundate the surrounding country. Similar results have happened in Europe from the subterranean operations of rats. 3. Some Mollusca (*Pholas*, *Saxicava*, *Teredo*, &c.) bore into stone or wood, and by the number of contiguous perforations greatly weaken the material. Pieces of drift-wood are soon riddled with long holes by the teredo; while wooden piers, and the bottom of wooden ships, are often rapidly perforated. The saxicavous shells, by piercing rocks and leaving open cavities for rain and sea water to fill, promote the decay of the stone. 4. Many animals exercise a ruinously destructive influence upon vegetation. Of the many insect plagues of that kind it will be enough to enumerate the locust, phylloxera, and Colorado beetle. The pasture in some parts of the south of Scotland has in recent years been much damaged by mice, which have increased in numbers owing to the indiscriminate shooting and trapping of owls, hawks, and other predaceous creatures. Grasshoppers cause the destruction of vegetation in some parts of Wyoming and other western territories of the United States. The way in which animals destroy each other, often on a great scale, may likewise be included among the geological operations now under description.

II. Conservative Action.—This is admirably shown by many kinds of vegetation. 1. The formation of a stratum of turf protects the soil and rocks from being rapidly disintegrated and washed away by atmospheric action. Hence the surface of a district so protected is denuded with extreme slowness except along the lines of its water-courses. 2. Many plants, even without forming a layer of turf, serve by their roots or branches to protect the loose sand or soil on which they grow from being removed by wind. The common sand-carex and other arenaceous plants bind the loose sand-dunes of our coasts, and give them a permanence which would at once be destroyed were the sand laid bare again to storms. In North America the sandy tracts of the western territories are in many places protected by plants known as sage-brush and grease-wood. The growth of shrubs and brushwood along the course of a stream not only keeps the alluvial banks from being so easily undermined and removed as would otherwise be the case, but serves to arrest the sediment in floods, filtering the water, and thereby adding to the height of the flood plain. On some parts of the west coast of France extensive ranges of sand-hills have been gradually planted with pine woods which, while preventing the destructive inland march of the sand, also yield a large revenue in timber, and have so improved the climate as to make these districts a resort for pulmonary invalids. In tropical countries the mangrove grows along the margin of the sea, and not only protects the land, but adds to its breadth, by forming and increasing an alluvial belt along the coast. 3. Some marine plants likewise afford protection to shore rocks. This is done by the calcareous nullipores, which form upon them a hard incrustation; likewise by the tangles and smaller fuci which grow abundantly on the littoral zone and break the force of the waves, or diminish the effects of ground swell. 4. Forests and brushwood protect the soil, especially on slopes, from being washed away by rain. This is shown by the disastrous results of the thoughtless destruction of such woods. According to Reclus (*La Terre*, p. 410), in the three centuries from 1471 to 1776, the "vigueries," or provostry-districts of the French Alps, lost a third, a half, and even three-fourths of their cultivated ground, and the population has diminished in somewhat similar proportions. From 1836 to 1866 the departments of Hautes and Basses Alpes lost 25,000 inhabitants, or nearly one-tenth of their population—a diminution which has with plausibility been assigned to the reckless removal of the pine forests, whereby the steep mountain sides have been washed bare of their soil. The desiccation of the countries bordering the eastern Mediterranean has been ascribed to a similar cause. 5. In mountain districts pine forests exercise also an important conservative function in preventing the formation or arresting the progress of avalanches. In Switzerland some of the forests which cross the lines of frequent snow-falls are carefully preserved.

Animals do not exert any important conservative action upon the earth's surface, save in so far as they form new deposits, as will be immediately referred to. In the prairie regions of Wyoming and other tracts of North America, some interesting minor effects are referable to the herds of roving animals which migrate over these territories. Professor Comstock describes the trails made by the bison, the elk, and the big-horn or mountain-sheep as firmly-trodden tracks on which vegetation will not grow for many years. All over the region traversed by the bison numerous circular patches of grass are to be seen which have been formed on the hollows where this animal has wallowed. Originally they are shallow depressions formed in great numbers where a herd of bisons has rested for a time. On the advent of the rains they become pools of water; thereafter grasses spring up luxuriantly, and so bind the soil together that these grassy patches, or "bison-wallows," may actually become slightly raised above the general level if the surrounding ground becomes parched and degraded by the winds (*Reconnaissance of N.W. Wyoming*, 1875, p. 175).

III. Reproductive Action.—Both plants and animals contribute materials towards new geological formations. Their remains are enclosed in deposits of sand and mud and there preserved. But they form of themselves not unimportant accumulations. Of plant formations the following illustrative examples may be given. (1.) *Peat-Mosses.*—These are accumulations of marshy vegetation which occur in temperate and arctic latitudes, sometimes to a depth of 40 feet or more. In Europe they have been largely formed by plants of the genus *Sphagnum*, which, growing as a spongy fibrous mass over wet ground, die in their lower parts and send out new fibres above. It is this lower decaying stratum which forms the peat. Every stage of the process may be seen in a large moss, from the green living plants at the top, through fibrous brown turf full of the scarcely decayed rootlets of the *Sphagnum*, down to the compact brown or almost black peat at the bottom. Many peat-mosses were at one time lakes which have been gradually filled up by the accumulation of marsh-plants. Peat possesses a great antiseptic power; the bodies of animals which have been entombed in it are sometimes preserved for many centuries. (2.) *Mangrove Swamps.*—On the low moist shores and river mouths of tropical countries, the mangrove tree plays an important geological part. It grows in such situations in a dense jungle, sometimes 20 miles broad, which fringes the coast as a green selvage, and runs up if it does not quite occupy creeks and inlets. The mangrove flourishes in sea-water even down to low-water mark, forming there a dense thicket which, as the trees drop their radicles and take root, grows outward into the sea. It is singular to find terrestrial birds nestling in the branches above and crabs and barnacles living among the roots below. By this network of subaqueous radicles and roots the water is filtered of its sediment, which, retained among the vegetation, helps to turn the spongy jungle into a firm soil. On the coast of Florida the mangrove swamps stretch for long distances as a belt from 5 to 20 miles broad, which winds round the creeks and inlets. At Bermuda the mangroves co-operate with grasses and other plants to choke up the creeks and brackish lakes. In these waters calcareous algæ abound, and as their remains are thrown up amidst the sand and vegetation they form a remarkably calcareous soil. (3.) *Diatom Mud or Earth.*—As the minute siliceous plants called diatoms occur both in fresh and salt water, the deposit formed from their congregated remains is found both on the sites of lakes and on the sea-floor. "Infusorial" earth and "tripoli powder" consist mainly of the frustules and fragmentary debris of diatoms which have accumulated on the bottoms of lacustrine areas. Towards the Antarctic circle the "Challenger" met with *Diatomaceæ* in abundance, both in the surface waters of the ocean and on the bottom. They form at depths of from 1260 to 1975 fathoms a pale straw-coloured deposit, which when dried is white and very light.

Animal formations are chiefly composed of the remains of the lower grades of the animal kingdom, especially of *Mollusca, Actinozoa*, and *Foraminifera*. (1.) In some cases they are *calcareous*. Lime, chiefly in the form of carbonate, is the mineral substance of which the solid parts of animals are mainly built up. Hence the great majority of the accumulations formed of animal remains are calcareous. In fresh water they are represented by the *marl* of lakes—a white, chalky deposit consisting of the mouldering remains of *Mollusca, Entomostraca*, and partly of fresh-water algæ. On the sea-bottom in shallow water they consist of beds of shells, such as the oyster-banks of English seas. The fringing, barrier, and atoll coral-reefs of warm seas are conspicuous examples of wide and thick masses of rock formed from the accumulated growth of animal organisms. The great reef of Australia, for example, is 1250 miles long, from 10 to 90 miles broad, and more than 1800 feet thick. The coral rock, though formed by the continuous growth of the polyps, gradually loses any distinct organic structure, and acquires an internal crystalline character owing to the infiltration of water through its mass, whereby carbonate of lime is carried down and deposited in the pores and crevices as in a growing stalactite. Great quantities of calcareous mud are produced by the breakers which beat upon the outer edge of the reefs. This mud is partly washed up upon the reefs and aids in their consolidation, but in great measure it is swept away by the ocean currents and distributed over many thousands of square miles of the sea-floor. In deep water over the bed of the Atlantic and other oceans a remarkable calcareous ooze occurs which is formed of the remains of *Foraminifera*, and chiefly of species of the genus *Globigerina*. It is next in abundance to the red and grey clays of the deep sea. It is a pale-grey marl, sometimes red from peroxide of iron, or brown from peroxide of manganese; and it usually contains more or less clay, even with occasional fragments of pumice. (2.) *Siliceous* deposits formed from animal exuviæ are illustrated by another of the deep-sea formations brought to light by the "Challenger" researches. In certain regions of the western and middle Pacific Ocean, the bottom was found to be covered with an ooze consisting almost entirely of *Radiolaria*. These minute organisms occur, indeed, more or less abundantly in almost all deep oceanic deposits. From the deepest sounding yet taken (4575 fathoms, or more than 5 miles) a radiolarian ooze was obtained. The spicules of sponges likewise furnish materials towards these siliceous accumulations. (3.) *Phosphatic* deposits, in the great majority of cases, betoken some of the vertebrate animals, seeing that phosphate of lime enters largely into the composition of their bones and occurs in their excrement. The most typical modern accumulations of this nature are the guano beds of rainless islands off the western coasts of South America and Southern Africa. In these regions immense flocks of sea-fowl have in the course of centuries covered the ground with an accumulation of their droppings to a depth of sometimes 30 to 80 feet, or even more. This deposit, consisting chiefly of organic matter and ammoniacal salts, with about 20 per cent. of phosphate of lime, has acquired a high value as a manure, and is being rapidly cleared off. It could only have been

preserved in a rainless or almost rainless climate. On the west of Europe isolated stacks and rocky islands in the sea are often seen to be white from the droppings of clouds of sea birds; but it is merely a thin crust, which is not allowed to grow thicker in a climate where rains are frequent and heavy.

IV. Man as a Geological Agent.—No survey of the geological workings of plant and animal life upon the surface of the globe can be complete which does not take account of the influence of man—an influence of enormous and increasing consequence in physical geography, for man has introduced, as it were, an element of antagonism to nature. Not content with gathering the fruits and capturing the animals which she has offered for his sustenance, he has, with advancing civilization, engaged in a contest to subdue the earth and possess it. His warfare indeed has often been a blind one, successful for the moment, but leading to sure and sad disaster. He has, for instance, stripped off the woodland from many a region of hill and mountain, gaining his immediate object in the possession of their stores of timber, but thereby laying bare the slopes to parching droughts or fierce rains. Countries once rich in beauty, and plenteous in all that was needful for his support, are now burnt and barren, or washed bare of their soil. It is only in comparatively recent years that he has learnt the truth of the aphorism—"*Homo Naturæ minister et interpres.*"

But now, when that truth is coming more and more to be recognized and acted on, man's influence is none the less marked. His object still is to subdue the earth, and he attains it, not by setting nature and her laws at defiance, but by enlisting her in his service. Within the compass of this article it is impossible to give more than merely a reference to this vast subject. The action of man may be witnessed on climate, on the flow of water, on the character of the terrestrial surface, and on the distribution of life.[1]

1. *On Climate.*—Human interference affects meteorological conditions—(1) by removing forests and laying bare to the sun and winds areas which were previously kept cool and damp under trees, or which, lying on the lee side, were protected from tempests; as already stated, it is supposed that the wholesale destruction of the woodlands formerly existing in countries bordering the Mediterranean has been in part the cause of the present desiccation of these districts; (2) by drainage, the effect of this operation being to remove rapidly the discharged rainfall, to lessen the evaporation, and thereby to diminish the rainfall and somewhat increase the general temperature of a country; (3) by the other processes of agriculture, such as the transformation of moor and bog into cultivated land, and the clothing of bare hillsides with green crops or plantations of coniferous and hardwood trees.

2. *On the Flow of Water.*—1. By increasing or diminishing the rainfall man directly affects the course of the waters over the land. 2. By his drainage operations he makes the rain to run off more rapidly than before, and thereby increases the floods in the rivers. 3. By wells, bores, mines, or other subterranean works he interferes with the underground waters and consequently with the discharge of springs. 4. By embanking rivers he confines them to narrow channels, sometimes increasing their scour, and enabling them to carry their sediment further seaward, sometimes causing them to deposit it over the plains and raise their level.

3. *On the Surface of the Land.*—Man's operations alter the aspect of a country in many ways:—(1) by changing forest into bare mountain, or clothing bare mountains with forest; (2) by promoting the growth or causing the removal of peat-mosses; (3) by heedlessly uncovering sand-dunes, and thereby setting in motion a process of destruction which may convert hundreds of acres of fertile land into waste sand, or by prudently planting the dunes with sand-loving vegetation or pines, and thus arresting their landward progress; (4) by so guiding the course of rivers as to make them aid him in reclaiming waste land, and bringing it under cultivation; (5) by piers and bulwarks, whereby the ravages of the sea are stayed, or by the thoughtless removal from the beach of stones which the waves had themselves thrown up, and which would have served for a time to protect the land; (6) by forming new deposits either designedly or incidentally. The roads, bridges, canals, railways, tunnels, villages, and towns with which man has covered the surface of the land will in many cases form a permanent record of his presence. Under his hand the whole surface of civilized countries is very slowly covered by a stratum, either formed wholly by him, or due in great measure to his operations, and containing many relics of his presence. The soil of old cities has been increased to a depth of many feet by the rubbish of his buildings; the level of the streets of modern Rome stands high above that of the pavements of the Cæsars, and that again above the roadways of the early republic. Over cultivated fields his potsherds are turned up in abundance by the plough. The loam has risen within the walls of his graveyards, as generation after generation has mouldered there into dust.

4. *On the Distribution of Life.*—It is under this head, perhaps, that the most subtle of human influences come. Some of man's doings in this domain are indeed plain enough, such as the extirpation of wild animals, the diminution or destruction of some forms of vegetation, the introduction of plants and animals useful to himself, and especially the enormous predominance given by him to the cereals and to the spread of sheep and cattle. But no such extensive disturbance of the normal conditions of the distribution of life can take place without carrying with it many secondary effects, and setting in motion a wide cycle of change and of reaction in the animal and vegetable kingdoms. For example, the incessant warfare waged by man against birds and beasts of prey in districts given up to the chase leads sometimes to unforseen results. The weak game is allowed to live, which would otherwise be killed off and give more room for the healthy remainder. Other animals which feed perhaps on the same materials as the game are by the same cause permitted to live unchecked, and thereby to act as a further hindrance to the spread of the protected species. But the indirect results of man's interference with the *régime* of plants and animals still require much prolonged observation.

From this brief and imperfect outline the reader may perceive that man takes an important place as a geological agent, and that in future ages the traces of his interference will introduce a new element of difficulty into the study of geological phenomena.

PART IV.—STRUCTURAL GEOLOGY,

OR THE ARCHITECTURE OF THE EARTH'S CRUST.

Having considered the nature of the materials constituting the crust of the earth, and the operation of the different agencies by which these materials are produced, arranged, and modified, we may now proceed to examine the structure of the crust itself with the view of marking how its component parts have been put together. Since by far the largest portion of the crust consists of sedimentary or

[1] The reader will find much suggestive matter in Marsh's *Man and Nature*, a work which, as its title denotes, specially treats of this subject. A new and enlarged edition of this volume was published in 1874 under the title of *The Earth as Modified by Human Action*.