TEXT-BOOK OF GEOLOGY

BY

SIR ARCHIBALD GEIKIE, F.R.S.

PART TWO

NEW YORK
P. F. COLLIER & SON
MCMII
30

TEXT-BOOK OF GEOLOGY

BOOK III

DYNAMICAL GEOLOGY
(CONTINUED)

Section iv. Hypogene Causes of Changes in the Texture, Structure, and Composition of Rocks

THE phenomena of hypogene action considered in the foregoing pages relate almost wholly to the effects produced at the surface. It is evident, however, that these phenomena chiefly arise from movements within or beneath the earth's crust, and must be accompanied by very considerable internal changes in the rocks which form that crust. These rocks, subjected to enormous pressure, have been contorted, crumpled, and folded back upon themselves, as if thousands of feet of solid limestones, sandstones, and shales had been merely a few layers of carpet; they have been shattered and fractured; they have in some places been pushed far above their original position, in others depressed far beneath it: so great has been the compression which they have undergone that their component particles have in many places been rearranged, and even crystallized. They have here and there probably been reduced to actual fusion, and have been abundantly invaded by masses of molten rock from below.

In the present section, the student is asked to consider chiefly the nature of the agencies by which such changes can be effected; the results achieved, in so far as they constitute part of the architecture or structure of the earth's crust, will be discussed in Book IV. At the outset, it is evident that we can hardly hope to detect many of these processes of subterranean change actually in progress and watch their effects. The very vastness of some of them places them beyond our direct reach, and we can only reason regarding them from the changes which we see them to have produced. But a good number are of a kind which can in some measure be imitated in laboratories and furnaces. It is not requisite, therefore, to speculate wholly in the dark on this subject. Since the early and classic researches of Sir James Hall, great progress has been made in the investigation of hypogene processes by experiment. The conditions of nature have been imitated as closely as possible, and varied in different ways, with the result of giving us an increasingly clear insight into the physics and chemistry of subterranean geological changes. The following pages are chiefly devoted to an illustration of the nature of hypogene action, in so far as that can be inferred from the results of actual experiment. The subject may be conveniently treated under three heads—1, the effects of mere heat; 2, the influence of the co-operation of heated water; 3, the effects of compression, tension, and fracture.

§ 1. Effects of Heat

The importance of heat among the transformations of rocks has been fully admitted by geologists, since it used to be the watchword of the Huttonian or Vulcanist school at the end of the 18th century. Three sources of subterranean heat may have at different times and in different degrees co-operated in the production of hypogene changes—the original internal heat of the globe, the heat arising from chemical changes within the crust or beneath it, and the heat due to the transformation of mechanical energy in the crumpling, fracturing, and crushing of the rocks of the crust.

Rise of temperature by depression.—As stated above (p. 500), the mere recession of rocks from the surface owing to superposition of newer deposits upon them will cause the isogeotherms, or lines of equal subterranean temperature, to rise—in other words, will raise the temperature of the masses so withdrawn. This can take place, however, to but a limited extent, unless combined with such depression of the crust as to admit of thick sedimentary formations. From the rate of increment of temperature downward it is obvious that, at no great depth, the rocks must be at the temperature of boiling water, and that further down, but still at a distance which, relatively to the earth's radius, is small, they may reach and exceed the temperatures at which they would fuse at the surface. Mere descent to a great depth, however, will not necessarily result in any marked lithological change, as has been shown in the cases of the Nova Scotian and South Welsh coal-fields, where sandstones, shales, clays, and coal-seams can be proved to have been once depressed 14,000 to 17,000 feet below the sea-level, under an overlying mass of rock, and yet to have sustained no more serious alteration than the partial conversion of the coal into anthracite. They have been kept for a long period exposed to a temperature of at least 212° Fahr. Such a temperature would have been sufficient to set some degree of internal change in progress, had any appreciable quantity of water been present, whence the absence of alteration may perhaps be explicable on the supposition that these rocks were comparatively dry (p. 519).

Rise of temperature by chemical transformation.—To what extent this cause of internal heat may be operative, forms part of an obscure problem. But that the access of water from the surface, and the consequent hydration of previously anhydrous minerals must produce local augmentation of temperature, cannot be doubted. The conversion of anhydrite into gypsum, which takes place rapidly in some mines, gives rise to an increase of volume of the substance (p. 588). Besides the remarkable manner in which the rock is torn asunder by minute clefts, crystals of bitter-spar and quartz are reduced to fragments.[1] The amount of heat evolved during this process is capable of measurement. The conversion of limestone into dolomite, on the other hand, which involves a diminution of volume, might likewise be made the subject of similar experimental inquiry. Experiments with various kinds of rocks, such as clay-slate, clay, and coal, show that when these substances are reduced to powder and mixed with water, they evolve heat.[2]

Rise of temperature by rock-crushing.—A further store of heat is provided by the internal crushing of rocks during the collapse and readjustment of the crust. The amount of heat so produced has been made the subject of direct experiment. Daubrée has shown that, by the mutual friction of its parts, firm brick-clay can be heated in three-quarters of an hour from a temperature of 18° to one of 40° C. (65° to

---

[1] The microscopic structure of the stages in the conversion of anhydrite into gypsum is described by F. Hammerschmidt, Tschermak's Mineral. Mittheil. v. (1883), p. 272.

[2] W. Skey, Chem. News, xxx. p. 290.

104° Fahr.).[3] The most elaborate and carefully conducted series of experiments yet made in this subject are those conducted by Mallet. He subjected 16 varieties of stone (limestone, marble, porphyry, granite, and slate) in cubes averaging rather less than 1½ inches in height to pressures sufficient to crush them to fragments, and estimated the amount of pressure required, and of heat produced. The following examples may be selected from his table:[4]

Rock	Temperature (Fahr.) in 1 cubic foot of rock due to work of crushing	Number of cubic feet of water at 32 deg. evaporated into steam at 212 deg.	Volume of ice at 32 deg. melted to water at 32 deg. by one volume of rock
Caen Stone, Oolite..................	8°·004	0·0046	0·04008
Sandstone, Ayre Hill, Yorkshire	47°·79	0·0234	0·2026
Slate, Conway........................	132°·85	0·07	0·596
Granite, Aberdeen..................	155°·94	0·072	0·617
Scotch furnace-clay porphyry....	198°·97	0·083	0·724
Rowley Rag (basalt)................	213°·23	0·109	0·925

Within the crust of the earth, there are abundant proofs of enormous stresses under which the rocks have been crushed. The weight of rock involved in these movements has often been that of masses several miles thick. We can conceive that the heat thus generated may have been sufficient to promote many chemical and mineralogical rearrangements through the operation of water (postea, p. 519), and

[3] "Geol. Experimentale," p. 448 *et seq.* This distinguished chemist and geologist has during the last forty years devoted much time to researches designed to illustrate experimentally the processes of geology. His numerous important memoirs are scattered through the Annales des Mines, Comptes Rendus de l'Academie, Bulletin de la Societe Geologique de France, and other publications. But he has collected and republished them as "Etudes Synthetiques de Geologie Experimentale," 8vo, 1879—a storehouse of information. The admirable memoirs of Delèsse in the same journals should also be studied. The transformation of aragonite into calcite has been shown by Favre and Silbermann to give rise to a relatively large disengagement of heat. H. Le Chatelier, Compt. Rend. (1893), p. 390.

[4] Phil. Trans. 1873, p. 187.

may even have been here and there enough for the actual fusion of the rocks by the crushing of which it was produced.

Rise of temperature by intrusion of erupted rock.—The great heat of lava, even when it has flowed out over the surface of the earth, has been already referred to, and some examples have been given of its effects (pp. 385, 393). Where it does not reach the surface, but is injected into subterranean rents and passages, it must effect considerable changes upon the rocks with which it comes in contact. That such intruded igneous rocks have sometimes melted down portions of the crust in their passage can hardly be doubted. But probably still more extensive changes may take place from the exceedingly slow rate of cooling of erupted masses, and the consequently vast period during which their heat is being conveyed through the adjacent rocks. Allusion will be made in later pages to the observed amount of such "contact-metamorphism" (p. 990 *et seq.*).

Expansion.—Rocks are dilated by heat. The extent to which this takes place has been measured with some precision for various kinds of rock, as shown in the subjoined table:

Rock	Linear expansion for every 1° Fahr.	Authority
Black marble, Galway, Ireland	·00000247 = $\frac{1}{404858}$	Adie, Trans. Roy. Soc. Edin. xiii. p. 366
Gray granite, Aberdeen	·00000438 = $\frac{1}{228310}$	Ibid.
Slate, Penrhyn, Wales	·00000576 = $\frac{1}{173611}$	Ibid.
White marble, Sicily	·00000613 = $\frac{1}{163132}$	Ibid.
Red sandstone, Portland, Connecticut	·00000953 = $\frac{1}{104909}$	Totten, Amer. Journ. Sci. xxii. (1832), 136.[5]

According to these data, the expansion of ordinary rocks ranges from about 2·47 to 9·63 millionths for 1° Fahr. Even

[5] For additional results, see Mellard Reade's "Origin of Mountain Ranges" (1886), p. 109.

ordinary daily and seasonal changes of temperature suffice to produce considerable superficial changes in rocks (see p. 559). The much higher temperatures to which rocks are exposed by subsidence within the earth's crust must have far greater effects. Some experiments by Pfaff in heating from an ordinary temperature up to a red heat, or about 1180° C., small columns of granite from the Fichtelgebirge, red porphyry from the Tyrol, and basalt from Auvergne, gave the expansion of the granite as 0·016808, of the porphyry 0·012718, of the basalt 0·01199.[6] The expansion and contraction of rocks by heating and cooling have been already referred to as possible sources of upheaval and depression (p. 494). Mr. Mellard Reade concludes from his experiments that the mean coefficient of expansion for various classes of rocks may be taken as $\frac{1}{190192}$ for each degree Fahr., which would be equivalent to an expansion of 2·77 feet per mile for every 100° Fahr.[7]

Crystallization.—In the experiments of Sir James Hall, pounded chalk, hermetically inclosed in gun-barrels and exposed to the temperature of melting silver, was melted and partially crystallized, but still retained its carbonic acid. Chalk, similarly exposed, with the addition of a little water, was transformed to the state of marble.[8] These experiments have been repeated by G. Rose, who produced by dry heat from lithographic limestone and chalk, fine-grained marble without melting. The distinction of marble is the independent crystalline condition of its component granules of calcite. This structure, therefore, can be superinduced by heat under pressure. In nature, portions of limestone

---

[6] Z. Deutsch. Geol. Ges. xxiv. p. 403.
[7] "Origin of Mountain Ranges," p. 110.
[8] Trans. Roy. Soc. Edin. vi. (1805), pp. 101, 121. See note on page 511.

which have been invaded by intrusive masses of igneous rock have been converted into marble, the gradations from the unaltered into the altered rock being distinctly traceable, as will be shown in subsequent pages (p. 998).

Production of prismatic structure.—The long continued high temperature of iron-furnaces has been observed to have superinduced a prismatic or columnar structure upon the hearth-stones, and on the sand in which these are bedded.[9] This fact is of interest in geology, seeing that sandstones and other rocks in contact with eruptive masses of igneous matter have at various depths below the surface assumed a similar internal arrangement (p. 993).

Dry fusion.—In an interesting series of experiments, the illustrious De Saussure (1779) fused some of the rocks of Switzerland and France, and inferred from them, contrary to the opinion previously expressed by Desmarest,[10] that basalt and lava have not been produced from granite, but from hornstone (pierre de corne), varieties of "schorl," calcareous clays, marls, and micaceous earths, and the cellular varieties from different kinds of slate.[11] He observed, however, that the artificial products obtained by fusion were glassy and enamel-like, and did not always recall volcanic rocks, though some exactly resembled porous lavas. Dolomieu (1788) also contended that as an artificially-fused lava becomes a glass, and not a crystalline mass with crystals of easily fusible minerals, there must be some flux present in the original lava, and he supposed that this might be sulphur.[12]

---

[9] C. Cochrane, Proc. Dudley Geol. Soc. iii. p. 54.
[10] Mem. Acad. Scien. 1771, p. 273.
[11] De Saussure, "Voyages dans les Alpes," edit. 1803, tome i. p. 178.
[12] "Iles Ponces," p. 8 *et seq.* At temperatures between 2000° and 3000° C. various metallic oxides are fused and crystallize. H. Moissan, Compt. Rend. cxv. (1892), p. 1034.

Sir James Hall, about the year 1790, began an important investigation, in which he succeeded in reducing various ancient and modern volcanic rocks to the condition of glass, and in restoring them, by slow cooling, to a stony condition in which distinct crystals (probably pyroxene, olivine, and perhaps enstatite) were recognizable.[13] Gregory Watt afterward obtained similar results by fusing much larger quantities of the rocks. In more recent years, this method of research has been resumed and pursued with the much more effective appliances of modern science, notably by Mitscherlich, G. Rose, C. Sainte-Claire Deville, Delesse, Daubrée, Fouqué, Michel-Lévy, Friedel, and Sarasin. It has been experimentally proved that all rocks undergo molecular changes when exposed to high temperature, that when the heat is sufficiently raised they become fluid, that if the glass thus obtained is rapidly cooled it remains vitreous, and that, if allowed to cool slowly, a more or less distinct crystallization sets in, the glass is devitrified, and a lithoid product is the result.

A glass is an amorphous substance resulting from fusion, perfectly isotropic in its action on transmitted polarized light (*ante*, pp. 203, 212). Its specific gravity is rather lower than that of the same substance in the crystallized condition. By being allowed to cool slowly, or being kept for some hours at a heat which softens it, glass assumes a dull porcelain-like aspect. This devitrification possesses much interest to the geologist, seeing that most volcanic rocks, as has been already described (p. 212), present

[13] Trans. Roy. Soc. Edin. v. p. 43. Hall's actual products have been microscopically examined by Fouqué and Michel-Lévy. Comptes Rend. May, 1881. For repetitions of his fusion of limestone, op. cit. cxv. (1892), pp. 817, 934, 1009, 1296.

the characters of devitrified glasses. It consists in the appearance of minute crystallites, and other imperfect or rudimentary crystalline forms, accompanied with an increase of density and diminution of volume. It must be regarded as an intermediate stage between the perfectly glassy and the crystalline conditions. Rocks exposed to temperatures as high as their melting-points fuse into glass which, in the great majority of cases, is of a bottle-green or black color, the depth of the tint depending mainly on the proportion of iron. In this respect they resemble the natural glasses—pitchstones and obsidians. Microscopic investigation of such artificially-fused rocks shows that, even in what seems to be a tolerably homogeneous glass, there are abundant minute hair-like, feathered, needle-shaped, or irregularly-aggregated bodies diffused through the glassy paste. These crystallites, in some cases colorless, in others opaque, metallic oxides, particularly oxides of iron, resemble the crystallites observed in many volcanic rocks (p. 205). They may be obtained even from the fusion of a granitic or granitoid rock, as in the well-known case of the Mount Sorrel syenite near Leicester, which, being fused and slowly cooled, yielded to Mr. Sorby abundant crystallites, including exquisitely-grouped octahedra of magnetite.[14]

According to the observations of Delesse, volcanic rocks, when reduced to a molten condition, attack briskly the sides of the Hessian crucibles in which they are contained, and even eat them through. This is an interesting fact, for it helps to explain how some intrusive igneous rocks have come to occupy positions previously filled by sedimentary strata, and why, under such circumstances, the composition

---

[14] Zirkel, Mik. Besch. p. 92; Sorby, Address Geol. Sect. Brit. Assoc. 1880. On the microscopic structure of slags, etc., see Vogelsang's "Krystalliten."

of the same mass of rock should be found to vary considerably from place to place.[15]

The most elaborate and successful experiments yet made regarding the fusion of igneous rocks, are those of MM. Fouqué and Michel-Lévy. These observers, by mixing the chemical elements and, in other cases, the mineralogical constituents, of certain minerals and rocks, and fusing these in platinum crucibles in a gas-furnace, have been able to produce both rock-forming minerals, such as several felspars, augite, leucite, nepheline, and garnet, and also rocks possessing the composition and microscopic structure of augite-andesites, leucite-tephrites, and true-basalts. By rapid cooling, they obtained an isotropic glass, often full of bubbles, and varying in color with the nature of the mixture from which it was formed. Where the mixture contains the elements of pyroxene, enstatite, or melilite, it must be cooled very rapidly to prevent these minerals from partially crystallizing out of the glass. Nepheline also crystallizes easily. The felspars, on the other hand, pass much more slowly from the viscous to the crystalline condition. In these experiments, use was made of the law that the fusion-temperature of a crystallized silicate is usually higher than that of the same substance in the glassy state. Hence if such a glass be kept sufficiently long at a temperature slightly higher than that at which it softens, the most favorable con-

---

[15] Bull. Soc. Geol. France, 2d ser. iv. 1382; see also Trans. Edin. Roy. Soc. xxix. p. 492. In the more recent experiments by Doelter and Hussak no change was observed in the porcelain crucibles in which basalt, andesite and phonolite were melted. Neues Jahrb. 1884, p. 19. Bischof has described a series of experiments on the fusion of lavas with different proportions of clay-slate. He found that the lava of Niedermendig, kept an hour in a bellows furnace, was reduced to a black glassy substance without pores, and that a similar product was obtained even after 30 per cent of clay-slate had been added and the whole had been kept for two hours in the furnace. "Chem. und Phys. Geol." supp. (1871), p. 98.

ditions are obtained for the production of molecular arrangements and the formation of those crystalline bodies which can solidify in the midst of a viscous magma. The limits of temperature for the production of a given mineral must thus be comprised within the narrow range between the fusion-point of the mineral and that of its glass. By varying the temperature in the experiments, distinct minerals can be obtained from the same magma. Minerals such as olivine, leucite, and felspar, which solidify at higher temperatures than the others, appear first, and the later forms are molded round them. Thus an artificial basalt, like a natural one, always shows that its olivine has crystallized first. By providing facilities for the crystallization of the minerals in the inverse order of their fusibilities, the characters of naturally formed crystalline rocks can thus be artificially produced by simple igneous fusion.

Certain well-known facts which appear to militate against the principle of these experiments have been successfully explained by MM. Fouqué and Michel-Lévy. Some minerals, very difficult to fuse, contain crystals of others which are easily fusible, as if the latter had crystallized first, as in the case of pyroxene inclosed within leucite. But in reality the pyroxene has slowly crystallized out of inclusions of the surrounding glass which were caught up in the leucite. Where the same silicates are found to have crystallized first in large and subsequently in smaller forms, they may reveal stages in the gradual cooling and consolidation of the mass, one set of crystals, for example, being formed in a lava while still within the vent of a volcano, and another during the more rapid cooling after expulsion from the vent.

The rocks obtained artificially by these observers are thus classed by them: 1. Andesites and andesitic porphyrites—from the fusion of a mixture of four parts of oligoclase and one of augite. 2. Labradorites and labradoric porphyrites—from the fusion of three parts of labrador and one of augite. 3. A microlitic rock formed of pyroxene and anorthite. 4. Basalts and labradoric melaphyres—from the fusion of a mixture of six parts of olivine, two of augite and six of labrador. 5. Nephelinites—from the fusion of a mixture of three parts of nepheline and 1·3 of augite. 6. Leucitites—from the fusion of nine parts of leucite and one of augite. 7. Leucite-tephrite—from the fusion of a mixture of silica, alumina, potash, soda, magnesia, lime, and oxide of iron, representing one part of augite, four of labrador, and eight of leucite. 8. Lherzolite. 9. Meteorites without felspar. 10. Meteorites with felspar. 11. Diabases and dolerites with ophitic structure. In these artificially produced compounds the most complete resemblance to natural rocks was observed, down even to the minutiæ of microscopic structure. The crystals and microlites ranged themselves exactly as in natural rocks, with the same distribution of vitreous base and vitreous inclusions. It is thus demonstrated that a rock like basalt may be produced in nature in the dry way, by a process entirely igneous.[16]

More recently, another series of experiments has been carried on by Messrs. Doelter and Hussak of Gratz, to de-

---

[16] See the work of Messrs. Fouqué and Michel-Lévy, "Synthèse des Mineraux et des Roches," 1882, from which the above digest of their researches is taken. Since this was written I have had the advantage of being shown by M. Michel-Lévy the original slides prepared from the products obtained by him and M. Fouqué, and I can entirely corroborate the results at which these observers have arrived. They have succeeded in imitating all the essential features of such rocks as basalt, down even into minute microscopic details. They have produced rocks, not only showing microlitic forms, but with crystals of the constituent minerals as definitely formed as in any natural lava. Indeed it would be hardly possible to distinguish between one of their artificial products and many true lavas.

termine the effect of immersing various minerals in molten basalt, andesite, or phonolite. Among the results obtained by them are the production of a granular structure in pyroxene and hornblende, especially along the borders, as may be observed in the hornblende of recent eruptive rocks; the conversion of a hornblende crystal, which still retains its form, into an aggregate of augite prisms and magnetite, as observed also in some basalts; the conversion of garnet into various other minerals, such as meionite, melilite, anorthite, lime-olivine, lime-nepheline, specular iron, and spinel, the garnet itself never reappearing in the molten magma.[17]

While experiment has thus shown that certain eruptive rocks of the basic order, such as basalts and augite-andesites, may be produced by mere dry fusion, the acid rocks present difficulties which have as yet proved insuperable in the laboratory. MM. Fouqué and Michel-Lévy have vainly endeavored to reproduce by igneous fusion rocks with quartz, orthoclase, white mica, black mica, and amphibole. We may therefore infer that these rocks have been produced in some other way than by dry igneous fusion. The acid rocks, terminating in granite, form a remarkable series, regarding the origin of which we are still completely ignorant. Some data relating to their production will be given in § 2 (p. 524) in connection with the co-operation of underground water.

Contraction of rocks in passing from a glassy to a stony state.—Reference has been made (pp. 105, 495, 507) to the expansion of rocks by heat and their contraction on cooling; likewise to the difference between their volume in the

---

[17] Neues Jahrb. 1884, pp. 18, 158. Compare also A. Becker's experiments in melting pyroxenes and amphiboles, Zeitsch. Deutsch. Geol. Gesell. xxxvii. (1885), p. 10.

molten and in the solid state. It would appear that the diminution in density, as rocks pass from a crystalline into a vitreous condition, is, on the whole, greater the more silica and alkali are present, and is less as the proportion of iron, lime, and alumina increases. According to Delesse, granites, quartziferous porphyries, and such highly silicated rocks lose from 8 to 11 per cent of their density when they are reduced to the condition of glass, basalts lose from 3 to 5 per cent, and lavas, including the vitreous varieties, from 0 to 4 per cent.[18] More recently, Mallet observed that plate-glass (taken as representative of acid or siliceous rocks) in passing from the liquid condition into solid glass contracts 1·59 per cent, 100 parts of the molten liquid measuring 98·41 when solidified; while iron-slag (having a composition not unlike that of many basic igneous rocks) contracts 6·7 per cent, 100 parts of the molten mass measuring 93·3 when cold.[19] By the contraction due to such changes in the internal condition of subterranean masses of rock, minor oscillations of level of the surface may be accounted for, as already stated (p. 495). Thus the vitreous solidification of a molten mass of siliceous rock 1000 feet thick might cause a subsidence of about 16 feet, while, if the rock were basic, the amount of subsidence might be 67 feet.

Sublimation.—It has long been known that many mineral substances can be obtained in a crystalline form from

[18] Bull. Soc. Geol. France, 1847, p. 1390. Bischof had determined the contraction of granite to be as much as 25 per cent (Leonhard und Bronn, Jahrb. 1841). The correctness of this determination was disputed by D. Forbes (Geol. Mag. 1870, p. 1), who found from his own experiments that the amount of contraction must be much less. The values given by him were still much in excess of those afterward obtained with much care by Mallet. Compare O. Fisher, "Physics of the Earth's Crust," 2d Edit., p. 45, and Barus quoted ante, p. 104.

[19] Phil. Trans. clxiii. pp. 201, 204; clxv.; Proc. Roy. Soc. xxii. p. 328.

the condensation of vapors (pp. 334, 389). This process, called Sublimation, may be the result of the mere cooling and reappearance of bodies which have been vaporized by heat and solidify on cooling, or of the solution of these bodies in other vapors or gases, or of the reaction of different vapors upon each other. These operations, of such common occurrence at volcanic vents, and in the crevices of recently erupted and still hot lava-streams, have been successfully imitated by experiment. In the early researches of Sir James Hall on the effects of heat modified by compression, he obtained by sublimation "transparent and well-defined crystals," lining the unoccupied portion of a hermetically-sealed iron-tube, in which he had placed and exposed to a high temperature some fragments of limestone.[20] Numerous experiments have been made by Delesse, Daubrée, and others in the production of minerals by sublimation. Thus, many of the metallic sulphides found in mineral veins have been produced by exposing to a comparatively low temperature (between that of boiling water and a dull-red heat) tubes containing metallic chlorides and sulphide of hydrogen. By varying the materials employed, corundum, quartz, apatite, and other minerals have been obtained. It is not difficult, therefore, to understand how, in the crevices of lava-streams and volcanic cones, as well as in mineral veins, sulphides and oxides of iron and other minerals may have been formed by the ascent of heated vapors. Superheated steam is endowed with a remarkable power of dissolving that intractable substance, silica; artificially heated to the temperature of the melting-point of cast-iron, it rapidly attacks silica, and deposits the mineral

[20] Trans Roy. Soc. Edin. vi. p. 110.

in snow-white crystals as it cools. Sublimation, however, can hardly be conceived as having operated in the formation of rocks, save here and there in the infilling of open fissures.

§ 2. Influence of Heated Water

In the geological contest fought at the beginning of the century between the Neptunists and the Plutonists, the two great battle-cries were, on the one side, Water, on the other, Fire. The progress of science since that time has shown that each of the parties had some truth on its side, and had seized one aspect of the problems touching the origin of rocks. If subterranean heat has played a large part in the construction of the materials of the earth's crust, water, on the other hand, has performed a hardly less important share of the task. They have often co-operated together, and in such a way that the results must be regarded as their joint achievement, wherein the respective share of each can hardly be exactly apportioned. In Part II. of this Book the chemical operation of infiltrating water, at ordinary temperatures at the surface, and among rocks at limited depths, is described. We are here concerned mainly with the work done by water when within the influence of subterranean heat, and the manner in which this work can be experimentally imitated.

Presence of water in all rocks.—Besides its combinations in hydrous minerals, water may exist in rocks either (1) retained interstitially among minute crevices and pores, or (2) imprisoned within the microscopic cells of crystals.

(1.) By numerous observations it has been proved that all rocks within the accessible portion of the earth's crust contain interstitial water, or, as it is sometimes called, quarry-water (*eau de carrière*). This is not chemically combined with their mineral constituents, but is merely retained in their pores. Most of it evaporates when the stone is taken out of the parent rock, and freely exposed to the atmosphere. The absorbent powers of rocks vary greatly, and chiefly in proportion to their degree of porosity. Gypsum absorbs from about 0·50 to 1·50 per cent of water by weight; granite, about 0·37 per cent; quartz from a vein in granite, 0·08; chalk, about 20·0; plastic clay, from 19·5 to 24·5. These amounts may be increased by exhausting the air from the specimens and then immersing them in water.[21] No mineral substance is strictly impervious to the passage of water. The well-known artificial coloring of agates proves that even mineral substances, apparently the most homogeneous and impervious, can be traversed by liquids. In the series of experiments above referred to (p. 452), Daubrée has illustrated the power possessed by water of penetrating rocks, in virtue of their porosity and capillarity, even against a considerable counter-pressure of vapor; and, without denying the presence of original water, he concludes that the interstitial water of igneous rocks may all have been derived by descent from the surface. The masterly researches of Poiseuille have shown that the rate of flow of liquids through capillaries is augmented by heat. He proved that water at a temperature of 45° C. in such situations moves nearly three times faster than at a temperature of 0° C.[22] At the high temperatures under

---

[21] See an interesting paper by Delesse, Bull. Soc. Geol. France, 2me ser. xix. (1861–62), p. 65.

[22] Comptes Rendus (1840), xi. p. 1048. Pfaff ("Allgemeine Geologie," p. 141) concludes from calculations as to the relations between pressure and tension that water may descend to any depth in fissures and remain in a fluid state even at high temperatures.

which the water must exist at some depth within the crust, its power of penetrating the capillary interstices of rocks must be increased to such a degree as to enable it to become a powerful geological agent.

(2.) Reference has already (p. 196) been made to the presence of minute cavities, containing water and various solutions, in the crystals of many rocks. The water thus imprisoned was obviously inclosed with its gases and saline solutions, at the time when these minerals crystallized out of their parent magma. The quartz of granite is usually full of such water-vesicles. "A thousand millions," says Mr. J. Clifton Ward, "might easily be contained within a cubic inch of quartz, and sometimes the contained water must make up at least 5 per cent of the whole volume of the containing quartz."

.**Solvent power of water among rocks.**—The presence of interstitial water must affect the chemical constitution of rocks. It is now well understood that there is probably no terrestrial substance which, under proper conditions, is not to some extent soluble in water. By an interesting series of experiments, made many years ago by W. B. and H. D. Rogers, it was ascertained that the ordinary mineral constituents of rocks could be dissolved to an appreciable extent even by distilled water, and that the change was accelerated and augmented by the presence of carbonic acid.[23] Water, as pure as it ever occurs in a natural state, can hold in solution appreciable proportions of silica, alkaliferous silicates, and iron oxide, even at ordinary temperatures. The mere presence, therefore, of water within the pores of subterranean rocks cannot but give rise to changes

[23] American Journ. Science (2), v. p. 401.

in the composition of these rocks. Some of the soluble materials must be dissolved, and, as the water evaporates, will be redeposited in a new form.[24]

This power increased by heat.—The chemical action of water is increased by heat, which may be either the earth's original heat or that which arises from internal crushing of the crust. Mere descent from the surface into successive isogeotherms raises the temperature of permeating water until it may greatly exceed the boiling-point. But a high temperature is not necessary for many important mineral rearrangements. Daubrée has proved that very moderate heat, not more than 50° C. (122° Fahr.), has sufficed for the production of zeolites in Roman bricks by the mineral waters of Plombières.[25] He has experimentally demonstrated the vast increase of chemical activity of water with augmentation of its temperature, by exposing a glass tube containing about half its weight of water to a temperature of about 400° C. At the end of a week he found the tube so entirely changed into a white, opaque, powdery mass, as to present not the least resemblance to glass. The remaining water was highly charged with an alkaline silicate containing 63 per cent of soda and 37 per cent of silica, with traces of potash and lime. The white solid substance was ascertained to be composed almost entirely of crystalline materials, partly in the form of minute perfectly limpid bipyramidal crystals of quartz, but chiefly of very small acicular prisms of wollastonite. It was found, moreover, that the portion of the tube which had not been directly in contact with the water was as much altered as the rest, whence it was inferred that, at these high temperatures

---

[24] See further on this subject, postea, pp. 584, 617.

[25] "Geologie Experimentale," p. 462.

and pressures, the vapor of water acts chemically like the water itself.

Co-operation of pressure.—The effect of pressure must be recognized as most important in enabling water, especially when heated, to dissolve and retain in solution a larger quantity of mineral matter than it could otherwise do,[26] and also in preventing chemical changes which take place at once when the pressure is removed.[27] In Daubrée's experiments above cited, the tubes were hermetically sealed and secured against fracture, so that the pressure of the greatly superheated vapor had full effect. By this means, with alkaline water, he not only produced the two minerals above mentioned, but also felspar and diopside. The high pressures under which many crystalline rocks have solidified is indicated by the liquid carbon-dioxide in the vesicles of their crystals. Besides the pressure due to their varying depth from the surface, they must have been subject to the enormous expansion of the superheated water or vapor which filled all their cavities, and sometimes, also, to the compression resulting from the secular contraction of the globe and consequent corrugation of the crust. Mr. Sorby inferred that in many cases the pressure under which granite consolidated must have been equal to that of an overlying mass of rock 50,000 feet, or more than 9 miles in thickness, while De la Vallée Poussin and Renard from other data deduced a pressure equal to 87 atmospheres (p. 199).

---

[26] Sorby has shown that the solubility of all salts which exhibit contraction in solution is remarkably increased by pressure. Proc. Roy. Soc. (1862–63), p. 340.

[27] See Cailletet, Naturforscher, v.; Pfaff, Neues Jahrb. 1871; W. Spring, Bull. Acad. Roy. Belgique, 2d Ser. xlix. (1880), p. 369. Pfaff found that plaster does not absorb water under a pressure of 40 atmospheres.

Aquo-igneous fusion.—As far back as the year 1846, Scheerer observed that there exist in granite various minerals which could not have consolidated save at a comparatively low temperature.[28] He instanced especially gadolinites, orthites, and allanites, which cannot endure a higher temperature than a dull-red heat without altering their physical characters; and he concluded that granite, though it may have possessed a high temperature, cannot have solidified from simple igneous fusion, but must have been a kind of pasty mass containing a considerable proportion of water. It is common now to speak of the "aquo-igneous" origin of some eruptive rocks, and to treat their production as a part of what are termed the "hydro-thermal" operations of geology.

Scheerer, Elie de Beaumont, and Daubrée have shown how the presence of a comparatively small quantity of water in eruptive igneous rocks may have contributed to suspend their solidification, and to promote the crystallization of their silicates at temperatures considerably below the point of fusion and in a succession different from their relative order of fusibility. In this way, the solidification of quartz in granite after the crystallization of the silicates, which would be unintelligible on the supposition of mere dry fusion, becomes explicable. The water may be regarded as a kind of mother-liquor out of which the silicates crystallize without reference to relative fusibility.

The researches of the late Prof. Guthrie on the influence of water in lowering the fusing points of various substances have an important geological bearing. He showed that while the melting-point of nitre by itself is 320° C., an ad-

[28] Bull. Soc. Geol. France, iv. p. 468.

mixture of only 1·14 per cent of water reduced the temperature of fusion by 20°, while by increasing the proportion of water to 29·07 per cent he lowered the melting-point to 97·6°, and he concluded that "the phenomenon of fusion is nothing more than an extreme case of liquefaction by solution." He could see no reason why water should not exist even at the earth's centre, for even granting that it has a "critical temperature," still, "at high pressures it will be compressible as a vapor to a density at least as great as that of liquid water." He concluded that "water at a high temperature may not only play the part of a solvent in the ordinary restricted sense, but that there is in many cases no limit to its solvent faculty; in other words, that it may be mixable with certain rocks in all proportions; that solution and mixture are continuous with one another, in some cases at temperatures not above the temperature of fusion of those bodies *per se*." [29]

Prof. Guthrie was disposed to doubt whether the replenishment of water by capillary descent from the surface was necessary for the production of these phenomena of fusion and volcanic eruption. Prof. Daubrée's experiments, however, enable us to see how the supply of water may be kept up from superficial sources, while from those of Prof. Guthrie we learn that when the descending water reaches masses of highly-heated but still solid rock, it may allow them to pass into a fused condition and to exert a powerful expansive force on the overlying crust.

Artificial production of minerals.—As the result of experiments, both in the dry and moist way, various minerals have been produced in the crystalline form. Among the miner-

---

[29] Phil. Mag. xviii. (1884), p. 117.

als successfully reproduced are quartz, tridymite, olivine, pyroxene, enstatite, wollastonite, zircon, emerald, ruby, melanite, melilite, several felspars, leucite, nepheline, meionite, petalite, several zeolites, dioptase, rutile, brookite, anatase, perowskite, sphene, calcite, aragonite, dolomite, witherite, siderite, cerusite, malachite, corundum, diaspore, spinel, hæmatite, vivianite, apatite, anhydrite, diamond with many metallic ores.[30]

Artificial alteration of internal structures.—Besides showing the solvent power of superheated water and vapor upon glass in illustration of what happens within the crust of the earth, Daubrée's experiments possess a high interest and suggestiveness in regard to the internal rearrangements and new structures which water may superinduce upon rocks. Hermetically sealed glass tubes containing scarcely one-third of their weight of water, and exposed for several days to a temperature below an incipient red heat, showed not only a thorough transformation of structure into a white, porous, kaolin-like substance, incrusted with innumerable bipyramidal crystals of quartz, like those of the drusy cavities of rocks, but had acquired a very distinct fibrous and even an eminently schistose structure. The glass was found to split readily into concentric laminæ arranged in a general way parallel to the original surfaces of the tube, and so thin that ten of them could be counted in a breadth of a single millimetre. Even where the glass, though attacked, retained its vitreous character, these fine zones appeared like the lines of an agate. The whole structure recalled that of some schistose and crystalline rocks. Treated with acid, the altered glass crumbled and permitted the isolation of

---

[30] Fouqué and Michel-Lévy, "Synthèse des Minéraux et des Roches."

certain nearly opaque globules and of some minute transparent infusible acicular crystals or microlites, sometimes grouped in bundles and reacting on polarized light. Reduced to thin slices and examined under the microscope with a magnifying power of 300 diameters, the altered glass presented: 1st, Spherulites, $\frac{5}{10}$ of a millimetre in radius, nearly opaque, yellowish, bristling with points which perhaps belong to a kind of crystallization, and with an internal radiating fibrous structure (these resist the action of concentrated hydrochloric acid, whence they cannot be a zeolite, but may be a substance like chalcedony); 2d, innumerable colorless acicular microlites, with a frequently stellate, more rarely solitary distribution, resisting the action of acid like quartz or an anhydrous silicate; 3d, dark green crystals of pyroxene (diopside). Daubrée satisfied himself that these inclosures did not pre-exist in the glass, but were developed in it during the process of alteration.[81]

But besides the effects from increase of temperature and pressure, we have to take into account the fact that water in a natural state is never chemically pure. Rain, falling through the air, absorbs in particular oxygen and carbon-dioxide, and filtering through the soil, abstracts more of this oxide as well as other results of decomposing organic matter. It is thus enabled to effect numerous decompositions of subterranean rocks, even at ordinary temperatures and pressures. But as it continues its underground journey, and obtains increased solvent power, the very solutions it

[81] "Geol. Experim." p. 158 *et seq.* The production of crystals and microlites in the devitrification of glass at comparatively low temperatures by the action of water is of great interest. The first observer who described the phenomenon appears to have been Brewster, who, in the second decade of this century, studied the effect upon polarized light of glass decomposed by ordinary meteoric action. (Phil. Trans. 1814, Trans. Roy. Soc. Edin. xxii. 1860, p. 670. See, on the weathering of rocks, Part II. Sect. ii. § 1, "Weathering.")

takes up augment its capacity for effecting mineral transformations. The influence of dissolved alkaline carbonates in promoting the decomposition of many minerals was long ago pointed out by Bischof. In 1857 Sterry Hunt showed by experiments that water impregnated with these carbonates would, at a temperature of not more than 212° Fahr., produce chemical reactions among the elements of many sedimentary rocks, dissolving silica and generating various silicates.[32] Daubrée likewise proved that in presence of dissolved alkaline silicates, at temperatures above 700° Fahr., various siliceous minerals, as quartz, felspar, and pyroxene, could be crystallized, and that at this temperature the silicates would combine with kaolin to form felspar.[33]

The presence of fluorine has been proved experimentally to have a remarkable action in facilitating some precipitates, especially tin oxides, as well as in other parts of the mechanism of mineral veins.[34] Further illustrations of the important part probably played by this element in the crystallization of some minerals and rocks have been published by Ste. Claire Deville and Hautefeuille, who by the use of compounds of fluorine have obtained such minerals as rutile, brookite, anatase and corundum in crystalline form.[35] Elie de Beaumont inferred that the mineralizing influence of fluorine had been effective even in the crystallization of granite. He believed that "the volatile compound inclosed in granite, before its consolidation contained not only water, chlorine, and sulphur, like the substance disengaged from

---

[32] Phil. Mag. xv. p. 68. [33] Bull. Soc. Geol. France, xv. (1885), p. 103.
[34] First suggested by Daubrée, Ann. des Mines (1841), 3me ser. xx. p. 65.
[35] Comptes Rendus, xlvi. p. 764 (1858); xlvii. p. 89; lvii. p. 648 (1865). Fouqué and Michel-Lévy, "Synthèse des Minéraux et des Roches."

cooling lavas, but also fluorine, phosphorus and boron, whence it acquired much greater activity and a capacity for acting on many bodies on which the volatile matter contained in the lavas of Etna has but a comparatively insignificant action."[86]

§ 3. Effects of compression, tension, and fracture

Among the geological revolutions to which the crust of the earth has been subjected, its rocks have been in some places powerfully compressed; elsewhere they have undergone enormous tension, and almost everywhere they have been more or less ruptured. Hence internal structures have been developed which were not originally present in the rocks. These structures will be more properly considered in Book IV. We are here concerned mainly with the nature and operation of the agencies by which they have been produced.

The most obvious result of pressure upon rocks is consolidation, as where a mass of loose sand is gradually compacted into a more or less coherent stone, or where, with accompanying chemical changes, a layer of vegetation is compressed into peat, lignite, or coal. The cohesion of a sedimentary rock may be due merely to the pressure of the superincumbent strata, but some cementing material has usually contributed to bind the component particles together. Of these natural cements the most frequent are

---

[86] "Sur les Emanations Volcaniques et Metallifères," Bull. Soc. Geol. France, iv. (1846), p. 1249. This admirable and exhaustive memoir, one of the greatest monuments of Élie de Beaumont's genius, should be consulted by the student. See also De Lapparent (Bull. Soc. Geol. France, xvii. (1889), p. 282) on the part played by mineralizing agents in the formation of eruptive rocks.

peroxide of iron, silica, and carbonate of lime. Moderate pressure equally distributed over a rock presenting everywhere nearly the same amount of resistance will promote consolidation, but may produce no further internal change. Where the component particles are chiefly crystalline, pressure may induce a crystalline structure upon the whole mass, as recent experiments have shown.[37] If, however, the pressure becomes extremely unequal, or if the rock subjected to it can find escape from the strain in one or more directions, it may undergo shear in certain planes, or may be crumpled, or the limit of its rigidity may be passed, and rupture may take place. Some consequences of these movements may be briefly alluded to here in illustration of hypogene action in dynamical geology.

(1.) **Minor Ruptures and Noises.**—Among mountain-valleys, in railway-tunnels through hilly regions, or elsewhere among rocks subjected to much lateral pressure, or where, owing to the removal of material by running water, and the consequent formation of cavities, subsidence is in progress, sounds as of explosions are occasionally heard. In many instances, these noises are the result of relief from great lateral compression, the rocks having for ages been in a state of strain, from which as denudation advances, or as artificial excavations are made, they are relieved. This relief takes place, not always uniformly, but sometimes cumulatively by successive shocks or snaps. Mr. W. H. Niles of Boston has described a number of interesting cases where the effects of such expansion could be seen in quarries; large blocks of rock being rent and crushed into fragments, and smaller pieces being even discharged with explosion into the air.[38]

[37] W. Spring, Bull. Acad. Roy. Belg. 1880, p. 370.
[38] Proc. Boston Soc. Nat. Hist. xviii. p. 272 (1876).

More recently Mr. A. Strahan has called attention to the occurrence of slickensided surfaces in the lead-mines of Derbyshire which on being struck or even scratched with a miner's pick break off with explosive violence, and he suggests that the spars and ores along those surfaces are in "a state of molecular strain, resembling that of the Rupert's Drop or of toughened glass, and that this condition of strain is the result of the earth movements which produced the slickensides." [39]

If such is the state of strain in which some rocks exist even at the surface or at no great distance beneath it, we can realize that at great depths, where escape from strain is for long periods impossible, and the compression of the masses must be enormous, any sudden relief from this strain may well give rise to an earthquake-shock (p. 475). A continued condition of strain must also influence the solvent power of water permeating the rocks (p. 521).

(2.) **Consolidation and Welding.**—That pressure consolidates rocks is familiar knowledge. Loose sedimentary materials may by mere pressure be converted into more or less firm and hard masses. Experiments by W. Spring upon many substances in the state of powder have shown that under high pressure they become welded into solid substances. Under a pressure of 6000 atmospheres, coal-dust becomes a brilliant solid block, taking the mold of the cavity in which it is placed, and thereby giving evidence of plasticity. Peat, in like manner, becomes a brilliant black substance in which all trace of the original structure is gone.[40]

(3.) **Cleavage.**—Over extensive tracts of country a peculiar structure has been superinduced by powerful lateral

[39] Geol. Mag. 1887, p. 400. See also the same volume, pp. 511, 522.
[40] Bull. Acad. Roy. Belg. 1880, p. 325, and ante, p. 249.

pressure, especially upon fine-grained argillaceous rocks, which are then termed slates. They split along a set of planes which, as a rule, are highly inclined or vertical, and independent of the original bedding. Examined more minutely, it is found that their component particles, which in

Fig. 80.—Section of compressed argillaceous rock in which cleavage-structure has been developed. Magnified. (Compare Fig. 256.)

Fig. 81.—Section of similar rock which has not undergone this modification. Magnified.

most cases have a longer and shorter axis, have grouped themselves with their long axes generally in one common direction, and parallel with the planes of fissility. An ordinary shale may present under the microscope such a structure as is shown in Fig. 81. But where it has undergone

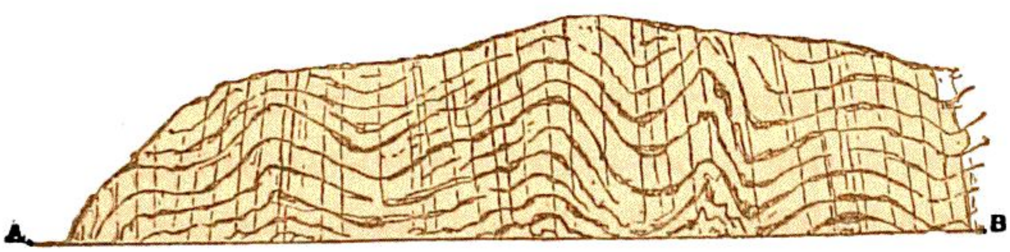


Fig. 82.—Curved quartz-rock traversed by vertical and highly inclined Cleavage. South Stack Lighthouse, Anglesea (*B.*).

the change here referred to, it has acquired the structure represented in Fig. 80. Rocks which, having been thus acted on, have acquired this superinduced fissility, are said to be cleaved, and the fissile structure is termed cleavage. In Fig. 82, for example, where the strata, at first in even parallel beds, have been subjected to great compression from the directions (A) and (B), the original planes of stratification are represented by wavy lines, and the new system of cleavage-planes by fine upright lines. The fineness of the cleavage depends in large measure upon the texture of the original rock. Sandstones, consisting as they do of rounded obdurate quartz-grains, take either a very rude cleavage (or jointing) or none at all. Fine-grained argil-

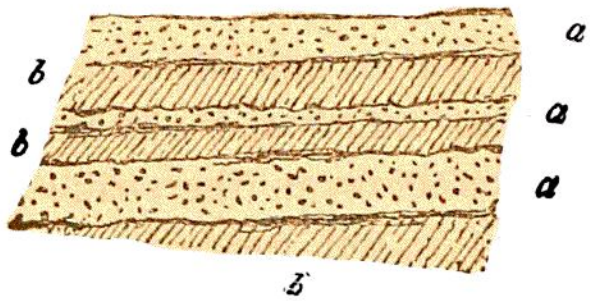


Fig. 83.

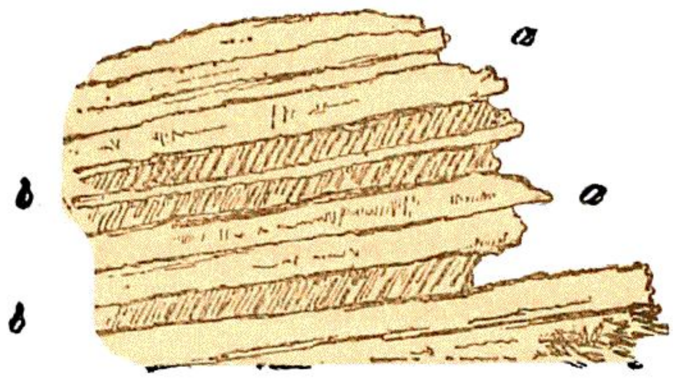


Fig. 84.

Dependence of Cleavage upon the grain of the rock (*B.*).

laceous rocks, consisting of minute particles or flakes, that can adjust their long axes in a new direction, are those in which the structure is best developed. In a series of cleaved rocks, therefore, cleavage may be perfect in argillaceous beds (*b b*, Figs. 83 and 84), and imperfect or absent in interstratified beds of sandstone (*a a*, Fig. 83) or of limestone (as at Clonea Castle, Waterford, *a a*, Fig. 84).

That cleavage may be produced in a mechanical way by lateral pressure has been proved experimentally by Sorby, who effected perfect cleavage in pipe-clay through which scales of oxide of iron had previously been mixed.[41] Tyndall superinduced cleavage on bees-wax and other substances by subjecting them to severe pressure. More recently, Fisher has proposed the view that in nature it is not to the pressure which plicated the rocks that cleavage is to be attributed, but to the shearing movements generated in large masses of rock left in a position too lofty for equilibrium.[42] If such, however, had been the origin of the structure, it is difficult to understand why there should be such a prevalent relation between the strike and the cleavage; for if descent by gravitation were the main cause, we should expect to find the rocks sheared far more irregularly than even the most irregular disposition of cleavage. That in cleavage there has been a true distortion of the rocks is indubitable; and the amount of distortion may be ascertained by the extent of the alteration of shape of fossils (Figs. 85–88). Microscopic study of cleaved rocks shows that their fissility is not always due merely to a rearrangement of original clastic particles, but to the development of new minerals, particularly varieties of mica, along the planes of cleavage. This relation is well seen in the folded and cleaved Devonian and Carboniferous rocks of S. W. Ireland and Cornwall, in the Carboniferous shales of Laval, May-

---

[41] Hopkins, Cambridge Phil. Trans. viii. (1847), p. 456. D. Sharpe, Quart. Journ. Geol. Soc. iii. (1846), p. 74; v. (1848), p. 111. Sorby, Edin. New Phil. Journ. lv. (1853), p. 137. W. King, Roy. Irish Acad. xxv. (1875), p. 605. The student will find recent interesting additions to our knowledge of the microscopic structure and the history of cleaved rocks in Mr. Sorby's address, Q. J. Geol. Soc. xxxvi. p. 72, and in Mr. Harker's very able essay, Brit. Assoc. 1885, Reports, pp. 813–852. See also E. Jannettaz, Bull. Soc. Geol. France, ix. (1881), p. 196; xi. (1884), p. 211. G. F. Becker, Bull. Geol. Soc. Amer. iv. (1893), p. 13.

[42] Geol. Mag. 1884, p. 396.

enne, and in the Jurassic and Eocene shales of the Alps.[43] Just as shales graduate into true cleaved slates, so slates by augmentation of their superinduced mica pass into phyllites, and these into mica-schists. The structure of districts with cleaved rocks is described in Book IV. Part V.

(4.) **Deformation.**—Further evidence of the powerful pressures to which rocks have been exposed is furnished by the way in which contiguous pebbles in a conglomerate have been squeezed into each other, and even sometimes have been elongated in a certain general direction. The coarseness of the grain of such rocks permits the effects of compression or tension to be readily seen. Similar effects may take place in fine-grained rocks and escape observation. Daubrée has imitated experimentally indentations produced by the contiguous portions of conglomerate pebbles.[44]

In discussing the cause of these indentations it must be remembered that imprints of pebbles upon each other, particularly when the material is limestone or other tolerably soluble rock, may have been to some extent produced by solution taking place most actively where pressure was greatest (p. 523). But there are indubitable evidences of crushing and deformation, even in what would be termed solid and brittle rocks. Of these evidences, perhaps the most instructive and valuable are furnished by the remains of plants and animals occurring as fossils, and of which

---

[43] Jannettaz, Renevier and Lory, Bull. Soc. Geol. France, ix. p. 649.

[44] Comptes Rendus, xliv. p. 823; also his "Geologie Experimentale," part i. sect. ii. chap. iii., where a series of important experiments on deformation is given. For various examples and opinions, see Rothpletz, Z. Deutsch. Geol. Ges. xxxi. p. 355. Heim. "Mechanismus der Gebirgsbildung," 1878, vol. ii. p. 31. Hitchcock, "Geology of Vermont," i. p. 28. Proc. Bost. Soc. Nat. Hist. vii. pp. 209, 353; xviii. p. 97; xv. p. 1; xx. p. 313. Amer. Assoc. 1866, p. 83. Amer. Jour. Sci. (2) xxxi. p. 372. Sorby, Rep. Cardiff Nat. Soc. 1873, p. 21. H. H. Reusch, "Fossilien-führender Kryst. Schiefer," p. 25.

the unaltered shapes are well known. Where fossiliferous rocks have undergone a shear, the extent of this movement, as above remarked, can be measured in the resultant

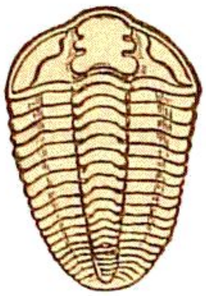


Fig. 85.—A Trilobite (*Calymene Blumenbachii*), natural shape.

Fig. 86.—The same Trilobite, altered by deformation—Lower Silurian, Hendre Wen, near Cerig y Druidion, North Wales (*B.*).

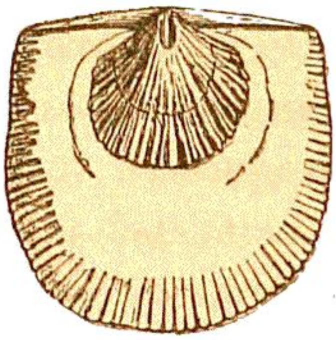


Fig. 87.—A Brachiopod (*Strophomena expansa*), natural shape.

distortion of the fossils. In Figs. 85 and 87 drawings are given of two Lower Silurian fossils in their natural forms. In Fig. 86 a specimen of the same species of trilobite as in Fig. 85 is represented where it has been distorted during

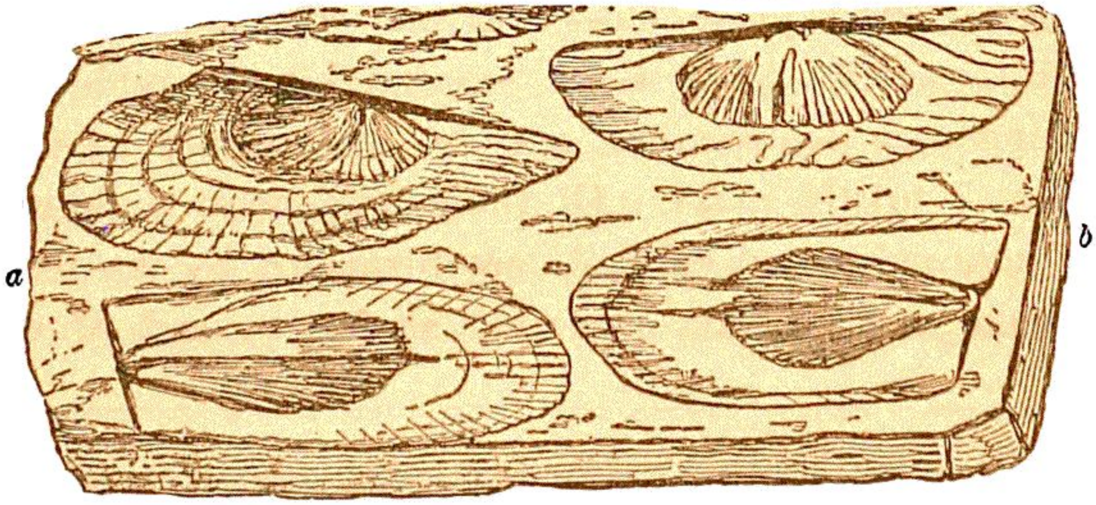


Fig. 88.—*Strophomena expansa*, altered by the deforming influence of Cleavage—Lower Silurian, Cwm Idwal, Caernarvonshire (*B.*).

the shearing of the inclosing rock. In Fig. 88 four examples of the same shell as in Fig. 87 are shown greatly distorted by a strain which has elongated the rock in the direction *a b*.[45] Amorphous crystalline rocks (pegmatite, granite, diorite) have been so crushed as to acquire a schistose structure (see Fig. 256, and Book IV. Part V., Part VIII. § i. § ii.).

Another illustration of the effects of pressure in producing deformation in rocks, is supplied by the so-called "lignilites," "epsomites," or "stylolites." These are cylindrical or columnar bodies varying in length up to more than four inches, and in diameter up to two or more inches. The sides are longitudinally striated or grooved. Each column, usually with a conical or rounded cap of clay, beneath which a shell or other organism may frequently be detected, is placed at right angles to the bedding of the limestones, or calcareous shales through which it passes, and consists of the same material. This structure has been referred by Prof. Marsh to the difference between the resistance offered by the column under the shell, and by the surrounding matrix to superincumbent pressure. The striated surface in this view is a case of "slickensides." The same observer has suggested that the more complex structure known as "cone-in-cone" may be due to the action of pressure upon concretions in the course of formation.[46]

The ingenious experiments of M. Tresca[47] on the flow of solids have thrown considerable light upon the internal deformations of rock-masses. He has proved that, even at ordinary atmospheric temperatures, solid resisting bodies

---

[45] See D. Sharpe, Q. J. Geol. Soc. iii. (1846), p. 75. W. Hopkins, Cambridge Phil. Trans. viii. (1847), p. 466. S. Haughton, Phil. Mag. (1856), xii. p. 409. O. Fisher, Geol. Mag. 1884, p. 399. Harker, Brit. Assoc. 1885, Reports, p. 824.

[46] Proc. American Assoc. Science, 1867. Gümbel, Zeitsch. Deutsch. Geol. Ges. xxxiv. p. 642.

[47] Comptes Rendus, 1864, p. 754; 1867, p. 809. Mem. Sav. Étrangers, xviii. p. 733; xx. p. 75. Inst. Mech. Engineers, June, 1867; June, 1878. See also W. C. Roberts-Austen, Proc. Roy. Institution, xi. (1886), p. 395.

like lead, cast-iron, and ice, may be so compressed as to undergo an internal motion of their parts, closely analogous to that of fluids. Thus, a solid jet of lead has been produced, by placing a piece of the metal in a cavity between the jaws of a powerful compressing machine. Iron, in like manner, has been forced to flow in the solid state into cavities and take their shape. On cutting sections of the metals so compressed, their particles or crystals are found to have ranged themselves in lines of flow which follow the contour of the space into which they have been squeezed. Such experiments are of considerable geological interest. They illustrate how in certain circumstances, under great strain, rocks may not only be made to undergo internal deformation along certain shearing planes, as in cleavage, but may even be subjected to such stresses as to acquire a "shear-structure" resembling the fluxion-structure seen in rocks which have been truly liquid (Fig. 256).[48]

Numerous examples have been found during the last few years in the northwest Highlands of Scotland where rocks have been subjected to such mechanical movements as to have been crushed down and made to flow in certain directions. Massive crystalline pegmatites may there be traced through successive stages until the material becomes a fine compact felsitic substance with thin lines of flow so like the "flow-structure" of a lava that it would deceive even a practiced geologist, and sometimes splitting into thin laminæ like those of shale. Further reference to this subject will be made in Book IV. Part VIII. § ii.

(5.) **Plication.**—On the assumption of a more rapid con-

[48] This remarkable kind of structure has been developed to an enormous extent among the crystalline rocks of the northwest Highlands of Scotland (Book IV. Part VIII. § ii. "Scottish Highlands").

traction of the inner hot nucleus of the globe, and the consequent descent of the cool upper shell, a subsiding area of the curved surface of the earth requires to occupy less horizontal space, and must therefore suffer powerful lateral compression. De la Beche long ago pointed out that if contorted and tilted beds were levelled out, they would require more space than can now be obtained for them without encroaching on other areas.[49] The magnificent example of the Alps brings before the mind the enormous extent to which the crust of the earth has in some places been compressed. According to the measurements and estimates of Prof. Heim of Zurich, the diameter of the northern zone of the central Alps is only about one half of the original horizontal extent of the component strata, which have been corrugated and thrown back upon each other in huge folds reaching from base to summit of lofty mountains, and spreading over many square miles of surface. He computes the horizontal compression of the whole chain at 120,000 metres, that is to say, that two points on the opposite sides of the chain have, by the folding of the crust that produced the Alps, been brought 120,000 metres, or 74 miles, nearer each other than they were before the movement.[50] Though the sight of such colossal foldings of solid sheets of rock impresses us with the magnitude of the compression to which the crust of the earth has been subjected, it perhaps does not convey a more vivid picture of the extent of this compression than is afforded by the fact that even in the minuter and microscopic structure of the rocks intricate puckerings are visible (Fig. 37). So intense has been the pressure, that even the tiny flakes of mica and

[49] "Report, Devon and Cornwall," p. 187.
[50] "Mechanismus der Gebirgsbildung," 1878, vol. ii. p. 213.

other minerals have been forced to arrange themselves in complex, frilled, crimped, and goffered foldings. On an inferior scale, local compression and contortion may be caused by the protrusion of eruptive rocks. The characters of plicated rocks as part of the framework of the terrestrial crust are given in Book IV. Part IV.

As may be supposed, it is difficult to illustrate experimentally the processes by which vast masses of rock have been plicated and crumpled. The early devices of Sir James Hall, however, may be cited from their interest as the first attempts to demonstrate the origin of the contortion of rocks. He placed layers of cloth under a weight, and by compressing them from two sides produced corrugations closely resembling those of the Silurian strata of the Berwickshire coast (Fig. 89). Prof. Favre of Geneva devised an experiment which more closely imitates the conditions in nature. Upon a tightly stretched band of india-rubber he places various layers of clay, making them adhere to it as firmly as possible. By then allowing the band to contract he produces in the overlying strata of clay a series of contortions, inversions, and dislocations which at once recall those of a great mountain-chain.[51] More recently this subject has been illustrated experimentally by Mr. H. M. Cadell, who has obtained results curiously like those exhibited by the crumpled and dislocated rocks of the N.W. Highlands of Scotland.[52]

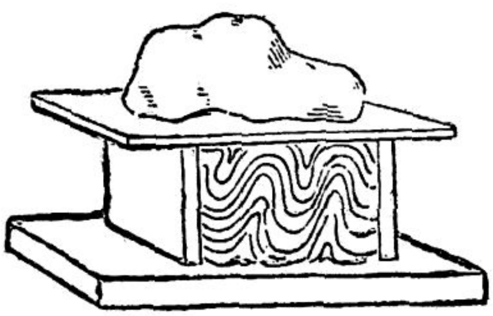


Fig. 89.—Hall's Experiment illustrating contortion.

(6.) **Jointing and Dislocation.**—Almost all rocks are tra-

[51] Nature, xiv. (1878), p. 103.
[52] Trans. Roy. Soc. Edin. xxxvi. (1888), p. 337.

versed by vertical or highly inclined divisional planes termed *joints* (Book IV. Part II.). These have been regarded as due in some way to contraction during consolidation (fissures of retreat); and this is no doubt their origin in innumerable cases. But, on the other hand, their frequent regularity and persistence across materials of very varying texture suggest rather the effects of internal pressure and movement within the crust. In an ingenious series of experiments, Daubrée has imitated joints and fractures by subjecting different substances to undulatory movement by torsion and by simple pressure, and he infers that they have been produced by analogous movements in the terrestrial crust.[53]

But in many cases the rupture of continuity has been attended with relative displacement of the sides, producing what is termed a *fault*. Daubrée also shows experimentally how faults may arise from the same movements as have caused joints, and from bending of the rocks. As the solid crust settles down, the subsidence, where unequal in rate, may cause a rupture between the less stable and more stable areas. When a tract of ground has been elevated, the rocks underlying it get more room by being pushed up, and are placed in a position of more or less instability. As they cannot occupy the additional space by any elastic expansion of their mass, they accommodate themselves to the new position by a series of dislocations.[54] Those segments having a broad base rise more than those with narrow bottoms, or the latter sink relatively to the former. Each broad-bottomed segment is thus bounded by two sides sloping toward the

[53] "Geol. Experim." Part I. sect. ii. chap. ii. See W. King, Roy. Irish Acad. xxv. (1875), p. 605, and the theories of jointing given in Book IV. Part II.
[54] See J. M. Wilson, Geol. Mag. v. p. 206; O. Fisher, op. cit. 1884.

upper part of the block. The plane of dislocation is nearly always inclined from the vertical, and the side to which the inclination rises, and from which it "hades," is the upthrow side. Faults of this kind are termed *normal*, and are by far the most common in nature. In mountainous regions, however, instances frequently occur where one side has been pushed over the other, so that lower are placed above higher beds. Such a fault is said to be *reversed*. It indicates an upward thrust within the crust, and is often to be found associated with lines of plication. Where a sharp fold, of which one limb is pushed forward over the other, gives way along a line of rupture, the result is a reversed fault. The details of these features of geological structure are reserved for Book IV. Part VI.

§ 4. The Metamorphism of Rocks

Metamorphism is a crystalline (usually also a chemical) rearrangement of the constituent materials of a rock.[55] In its production the following conditions have been mainly operative. (1) Temperature, from the lowest at which any change is possible up to that of complete fusion; (2) pressure, the potency of the action of heat being, within certain limits, increased with increase of pressure; (3) mechanical movements, which so often have induced molecular rearrangements in rocks; (4) presence of water, usually containing various mineral solutions, whereby chemical changes would be effected which would not be possible in dry heat; (5) nature of the materials operated upon, some being much more susceptible of change than others.

A metamorphosed rock is one which has suffered such a

---

[55] See A. Harker on the Physics of Metamorphism, Geol. Mag. vi. (1889), p. 15 J. W. Judd, ib. p. 243, and Book IV. Part VIII. of this Text-book.

mineralogical rearrangement of its substance. It may or may not have been a crystalline rock originally. Any rock capable of alteration (and all rocks must be so in some degree) will, when subjected to the required conditions, be metamorphosed. The resulting structure, however, will, save in extreme cases, bear witness to the original character of the mass. In some instances, the change has consisted merely in the rearrangement or crystallization of one mineral originally present, as in limestone converted into marble; in others, there has been a process of paramorphism, as where augite has been changed into hornblende in the alteration of dolerites into epidiorites; in others, the constituents have been forced by mechanical movements to range themselves in parallel laminæ, as where a diorite or pyroxenic rock becomes a hornblende-schist; in others, partial or complete transformation of the original constituents, whether crystalline or clastic, into new crystalline minerals has been accompanied by a complete recrystallization and change of structure in the rock. Quartzite is evidently a compacted sandstone, either hardened by mere pressure, or most frequently by the deposit of silica between its granules, or a slight solution of these granules by permeating water, so that they have become mutually adherent. A clay-slate is a hardened, cleaved, and partially metamorphosed form of muddy sediment, which on the one hand may be found full of organic remains, like any common shale, while on the other, by the appearance and gradual increase of some form of mica and other minerals, it may be traced becoming more and more crystalline, until it passes into phyllite, chiastolite-slate, or some other schistose rock. Yet remains of fossils may be obtained even in the same hand-specimens with crystals of andalusite, garnet, or other minerals. The calcareous matter of corals is sometimes replaced by hornblende, garnet, and axinite, without deformation of the fossils.[56]

Since experiment has proved that in presence of water under pressure, even at comparatively low temperatures, mineral substances are vigorously attacked (p. 521), we may expect to find that as these conditions abundantly exist within the earth's crust, the rocks exposed to them have been more or less altered. A large proportion of the accessible crust consists of sedimentary materials which were laid down on the ocean-bottom, and which were still abundantly soaked with sea-water even after they had been covered over with more recent formations. The gradual growth of submarine accumulations would of course deprive the lower strata of most of their original water, but some proportion of it would probably remain. If, according to Dana, the average amount of interstitial water in stratified rocks, at the earth's surface, such as limestones, sandstones and shales, be assumed to be 2·67 per cent, which is probably less than the truth, "the amount will correspond to two quarts of water for every cubic foot of rock."[57] There is certainly a considerable store of water ready for chemical action when the required conditions of heat and pressure are obtained. We must also remember that the water in which the sedimentary formations of the crust were formed, being mostly that of the ocean, already possessed chlorides, sulphates, and other salts with which to begin its reactions. The inference may therefore be drawn, that rocks possess-

---

[56] Ann. des Mines, 5me ser. xii. p. 318. H. H. Reusch, "Die Fossilien führenden krystallinischen Schiefer von Bergen" (translated by R. Baldauf), Leipzig, 1883.

[57] "Manual," 3d ed. 1880, p. 758

ing not more than 3 per cent of interstitial water cannot be depressed to depths of several thousand feet beneath the level of the earth's surface, and undergo great pressure and crushing, without suffering more or less marked internal change or metamorphism.

A few illustrative examples of metamorphism may be given here; the structure of metamorphic rocks, with the phenomena of "contact" and "regional" metamorphism, will be discussed in Book IV. Part VIII.

Production of marble from limestone.—One of the most obvious cases of alteration—the artificial conversion of limestone into crystalline saccharoid marble—has been already referred to (p. 509).[58] The calcite having undergone complete transformation, its original structure, whether organic or not, has been effaced, and a new structure has been developed, consisting of an aggregate of minute rounded grains, each with an independent crystalline arrangement. The production of a crystalline structure in amorphous calcite may be effected by the action of mere meteoric water at or near the surface (ante, p. 264, and postea, p. 620). But the generation of the peculiar granular structure of marble always demands heat and pressure, and probably usually the presence of water; the details of the process are, however, still involved in obscurity. We know that where a dike of basalt or other intrusive rock has involved limestone, it has sometimes been able to convert it for a short distance into marble. The heat (and perhaps the moisture) of the invading lava have sufficed to produce a granular structure, which even under the microscope is identical with that of marble. The conversion of wide areas of lime-

[58] See also "Marmarosis" in Book IV. Part. VIII.

stone into marble is a regional metamorphism, associated usually with the alteration of other sedimentary masses into schists, etc.

Dolomitization.—Another alteration which, from the labors of Von Buch, received in the early decades of the 19th century much attention from geologists, is the conversion of ordinary limestone into dolomite. Some dolomite appears to be an original chemical precipitate from the saline water of inland lakes and seas (p. 695). But calcareous formations due to organic secretions are often weakly dolomitic at the time of their formation, and may have their proportion of magnesium carbonate increased by the action of permeating water, as is proved by the conversion into dolomite of shells and other organisms, consisting originally of calcite or aragonite, and forming portions of what was no doubt originally a limestone, though now a continuous mass of dolomite. This change may have sometimes consisted in the mere abstraction of carbonate of lime from a limestone already containing carbonate of magnesia, so as to leave the rock in the form of dolomite; or probably more usually in the action of the magnesium salts of sea-water, especially the chloride, upon organically-formed limestone; or sometimes locally in the action of a solution of carbonate of magnesia in carbonated water upon limestone, either magnesian or non-magnesian. Elie de Beaumont calculated that on the assumption that one out of every two equivalents of carbonate of lime was replaced by carbonate of magnesia, the conversion of limestone into dolomite would be attended with a reduction of the volume of the mass to the extent of 12·1 per cent. It is certainly remarkable in this connection that large masses of dolomite, which may be conceived to have once been limestone, have the cavernous, fissured structure which, on this theory of their origin, might have been looked for.

Dolomite has been produced both on a small and on a great scale. In the north of England and elsewhere, the Carboniferous Limestone has been altered for a few feet or yards on either side of its joints into a dull yellow dolomite, locally termed "dunstone." Similar vertical zones of dolomite occur also in the Carboniferous Limestone of Ireland. Harkness pointed out that the dolomite appears in vertical ribs where the rocks are much jointed, and in beds where they have few or no joints.[59] No doubt percolating water has been the agent of change in the vertical zones. The beds, however, which in Ireland and elsewhere constitute important masses in the Carboniferous Limestone, were more probably formed contemporaneously with the rocks among which they lie. They may have been deposited as limestone in shallow lagoons where the magnesian salts of concentrated sea-water would act upon them. Dolomite sometimes forms great ranges of mountains, as in the Eastern Alps, where it has by some writers been regarded as altered ordinary limestone. But these masses may have partly, at least, become dolomite at the beginning by the action of the magnesian salts of the concentrated waters of inland seas upon organic or inorganic calcareous deposits accumulated previous to the concentration, their metamorphism having consisted mainly in the subsequent generation of a crystalline structure analogous to that of the conversion of limestone into marble.[60]

---

[59] Q. J. Geol. Soc. xv. p. 100.

[60] On dolomitization, see L. von Buch, in Leonhard's Mineralog. Taschenbuch, 1824; Naumann's "Geognosie," i. p. 763; Bischof's "Chemical Geology," iii.; Élie de Beaumont, Bull. Soc. Geol. France, viii. 1836, p. 174; Sorby, Brit. Assoc. Rep. 1856, part ii. p. 77, and Address Q. J. Geol. Soc. 1879. A full

Conversion of vegetable substance into coal.—Exposed to the atmosphere, dead vegetation is decomposed into humus, which goes to increase the soil. But sheltered from the atmosphere, exposed to the action of water, especially with an increase of temperature, and under some pressure, it is converted into lignite and coal. An example of this alteration has been observed in the Dorothea mine, Clausthal. Some of the timber in a long-disused level, filled with slate rubbish, and saturated with the mine-water from decomposing pyrites, was found to have a leathery consistence when wet, but, on exposure to the air, hardened to a firm and ordinary brown-coal, with the typical brown color and external fibrous structure, and having the internal fracture of a black glossy pitch-coal.[61] This change must have been produced within less than four centuries—the time since the levels were opened. According to Bischof's determinations the conversion of wood into coal may take place, 1st, by the separation of carbonic acid and carburetted hydrogen; 2d, by the separation of carbonic acid and the formation of water either from oxidation of hydrogen by meteoric oxygen or from the hydrogen and oxygen of the wood; 3d, by the separation of carbonic acid, carburetted hydrogen, and water.[62] The circumstances under which the vegetable matter now forming coal has been accumulated were favorable for this slow transmutation. The carbon-dioxide (choke-damp) of old coal-mines and the carburetted hydrogen (fire-damp, CH_4) given off in such large quantities

---

statement of the literature of this subject will be found in a suggestive memoir by C. Doelter and R. Hoernes, Jahrb. Geol. Reichsanstalt, xxv. The dolomite mountains of the Eastern Alps have been well described by Mojsisovics. See account of Triassic system, postea, Book VI.

[61] Hirschwald, Z. Deutsch. Geol. Ges. xxv. p. 364.

[62] Bischof, "Chem. Geol." i. p. 274.

by coal seams, are products of the alteration which would appear to be accelerated by terrestrial movements, such as those that compress and plicate rocks. During the process these gases escape, and the proportion of carbon progressively increases in the residue, till it reaches the most highly mineralized anthracite (p. 253), or may even pass into nearly pure carbon or graphite. In the coal-basins of Mons and Valenciennes, the same seams which are in the state of bituminous coal (*gras*) at the surface, gradually lose their volatile constituents as they are traced downward till they pass into anthracite. In the Pennsylvanian coal-field the coals become more anthracitic as they are followed into the eastern region, where the rocks have undergone great plication, and where, possibly during the subterranean movements, they were exposed to an elevation of temperature.[63] Daubrée has produced from wood, exposed to the action of superheated water, drop-like globules of anthracite which had evidently been melted in the transformation, and which presented a close resemblance to the anthracite of some mineral veins.[64]

Production of new minerals.—Where metamorphism is well developed the chemical reactions which have been set up have given rise to more or less complete re-combination of the chemical constituents of the rock. New minerals have thus been formed either entirely out of the materials already comprising the rock, or with some addition or replacement of substance introduced from without, by aqueous solution or otherwise. Some of the commonest secondary minerals are micas; andalusite, chiastolite, and

[63] Daubrée, "Geologie Experimentale," p. 463. Part of the framework below a steam-hammer has been found after twenty years to be converted into lignite. F. Seeland, Verh. Geol. Reichs. 1883, p. 192.

[64] Op. cit. p. 177.

garnet are also of frequent occurrence. (See Book IV. Part VIII.)

Production of the schistose structure.—All rocks are not equally permeable by water, nor is the same rock equally permeable in all directions. Among the stratified rocks especially, which form so large a proportion of the visible terrestrial crust, there are great differences in the facility with which water can travel, the planes of sedimentation, or those of cleavage or shearing where these have been developed, being naturally those along which water passes most easily. It is along these planes that differences of mineral structure and composition are ranged. Alternate layers of siliceous, argillaceous, and calcareous material vary in porosity and capability of being changed by permeating water. We may, therefore, expect that unless the original stratified structure has been effaced or rendered inoperative by any other superinduced structure, it will guide the metamorphic action of underground water, and will remain more or less distinctly traceable even after very considerable mineralogical transformations have taken place. Even without this guiding influence, superheated water can, to a certain extent, produce a schistose structure, parallel to its bounding surfaces, as Daubrée's experiments upon glass, above cited, have proved.

The stratified formations consist largely of silica, silicates of alumina, lime, magnesia, soda and potash, and iron oxides. These mineral substances exist there as original ingredients, partly in recognizable worn crystals, partly in a granular or amorphous condition, ready to be acted on by permeating water under the requisite conditions of temperature and pressure. We can understand that any re-combination and re-crystallization of the silicates will probably follow the laminæ of deposit or of cleavage, and that in this way a crystalline foliated structure may be developed. Round masses of granite erupted among Palæozoic rocks, instructive sections may be observed where a transition can be traced from ordinary unaltered sedimentary strata, such as sandstones, graywackes and shales containing fossils, into foliated crystalline rocks, to which the names of mica-schist and even gneiss may be applied. (Book IV. Part VIII.) Not only can the gradual change into a crystalline foliated structure be readily followed with the naked eye, but with the aid of the microscope the finer details of the alteration can be traced. Minute plates of some micaceous mineral and small concretions of andalusite, garnet, quartz, etc., may be observed to have crystallized out of the surrounding amorphous sediment. These, especially the mica, can be seen gradually to increase in size and number toward the granite, until the rock assumes a thoroughly foliated structure and passes into a true schist. Yet even in such a schist, traces of the original and durable water-worn quartz-granules may be detected.[65] Foliation is a crystalline segregation of the mineral matter of a rock in certain dominant planes which may be those of original stratification, of joints, of cleavage, of shearing, or of fracture.[66] Mr. Sorby has recognized foliation in three sets of planes even among the same rocks.[67]

Scrope many years ago called attention to the analogy between the foliation of schists and the ribboned or streaked structure of trachyte, obsidian, and other lavas.[68]

---

[65] Sorby, Q. J. Geol. Soc. xxxvi. p. 82.

[66] Darwin, "Geological Observations," p. 162. Ramsay, "Geology of North Wales," in Memoirs of Geol. Survey, vol. iii. p. 182.

[67] Op. cit. p. 84.

[68] "Volcanoes," pp. 140, 300.

This analogy has even been regarded as an identity of structure, and the idea has found supporters that the schistose rocks have been in a condition similar to or identical with that of many volcanic masses, and have acquired their peculiar fissility by differential movements within the viscous or pasty magma, the solidified minerals being drawn out into layers in the direction of shearing. Daubrée, availing himself of the researches of Tresca on the flow of solids (p. 537), has endeavored to imitate artificially some of the phenomena of foliation by exposing clay and other substances to great but unequal pressure.[69] That some of the lenticular wavy laminæ of different minerals in gneiss and other foliated rocks may be due to original segregation or flow in still unconsolidated igneous rock seems to be rendered highly probable by the curious analogies to this structure to be observed in the deeper parts of large intrusive bosses of rock, such as granite, diabase, and gabbro. These layers may thus be the remains of the oldest structure now retained by the gneiss. But subsequent pressure and deformation have frequently produced a foliation cutting obliquely across this original lamination and even entirely effacing it.

That the schistose structure has been largely induced by mechanical movements cannot be doubted. The evidence in the field and under the microscope has now rendered it certain that many rocks have been subjected to enormous mechanical stresses within the earth's crust; that they have yielded to the pressure both by disruption and by molecular shearing, that in some cases they have been crushed into minute fragments or dust, and have then been made to flow and to simulate the flow-structure of lava, while, in other

---

69 "Geologie Experimentale," p. 410.

cases, the crushed particles have crystallized into a granulitic structure, or the recrystallization has taken place along the flow-planes and has given rise to a perfect foliation. The action that produced cleavage, if further developed, might be accompanied with sufficient augmentation of temperature to permit of extensive mineralogical transformation along the cleavage-planes. But probably a rise of temperature was not essential. The conversion of pyroxene into hornblende, which has been observed in regions of crystalline schists, points indeed to a lower temperature than that required for the crystallization of the original mineral.[70] A schistose structure of almost any degree of coarseness might conceivably be produced. A mixed rock, such as granite, has been converted into a foliated gneiss. Diorite, diabase, or gabbro has likewise by mechanical movement, with accompanying chemical and crystallographic transformation, been made to assume a schistose structure and pass into amphibolite-schist.

The study of metamorphism and metamorphic rocks leads us from unaltered mechanical sediments at the one end, into thoroughly crystalline masses at the other. We are presented with a cycle of change wherein the same particles of mineral matter pass from crystalline rocks into sedimentary deposits, then by increasing stages of alteration back into crystalline masses, whence, after being reduced to detritus and redeposited in sedimentary formations, they may be once more launched on a similar series of transformations. The phenomena of metamorphism appear to be linked together with those of igneous action as connected manifestations of hypogene change.

---

[70] See G. H. Williams, Amer. Journ. Sci. 3d ser. xxviii. (1884), p. 259.

PART II. EPIGENE OR SURFACE ACTION

An Inquiry into the Geological Changes in Progress upon the Earth's Surface

On the surface of the globe and by the operation of agents working there, the chief amount of visible geological change is now effected. This branch of inquiry is not involved in the preliminary difficulty, regarding the very nature of the agents, which attends the investigation of plutonic action. On the contrary, the surface agents are carrying on their work under our eyes. We can watch it in all its stages, measure its progress, and mark in many ways how well it represents similar changes which for long ages previously must have been effected by similar means. But in the systematic treatment of this subject, a difficulty of another kind presents itself. While the operations to be discussed are numerous and often complex, they are so interwoven into one great network that any separation of them under different subdivisions is sure to be more or less artificial, and is apt to convey an erroneous impression. While, therefore, under the unavoidable necessity of making use of such a classification of subjects, we must bear always in mind that it is employed merely for convenience, and that in nature, superficial geological action must be viewed as a whole, since the work of each agent has close relations with that of the others and is not properly intelligible unless this connection be kept in view.

The movements of the air; the evaporation from land and sea; the fall of rain, hail, and snow; the flow of rivers and glaciers; the tides, currents, and waves of the ocean; the growth and decay of organized existence, alike on land and in the depths of the sea—in short, the whole circle of movement, which is continually in progress upon the surface of our planet, are the subjects now to be examined. It would be desirable to adopt some general term to embrace the whole of this range of inquiry. For this end the word epigene may be suggested as a convenient term, and antithetical to hypogene, or subterranean action.

The simplest arrangement of this part of Geological Dynamics will be into three sections:

I. Air.—The influence of the atmosphere in destroying and forming rocks.

II. Water.—The geological functions of the circulation of water through the air and between sea and land, and the action of the sea.

III. Life.—The part taken by plants and animals in preserving, destroying, or originating geological formations.

The words destructive, reproductive, and conservative, employed in describing the operations of the epigene agents, do not necessarily imply that anything useful to man is destroyed, reproduced, or preserved. On the contrary, the destructive action of the atmosphere may cover bare rock with rich soil, while its reproductive effects may bury fertile soil under sterile desert. Again, the conservative influence of vegetation has sometimes for centuries retained as barren morass what might otherwise have become rich meadow or luxuriant woodland. The terms, therefore, are used in a strictly geological sense, to denote the removal and redeposition of material, and its agency in preserving what lies beneath it.

Section i. Air

The geological action of the atmosphere arises partly from its chemical composition and partly from its movements. The composition of the atmospheric envelope has been already discussed (p. 63), and further information will be found under the head of Rain. The movements of the atmosphere are due to variations in the distribution of pressure or density, the law being that air always moves spirally from where the pressure is high to where it is low. Atmospheric pressure is understood to be determined by two causes, temperature and aqueous vapor. Since warm air, being less dense than cold air, ascends, while the latter flows in to take its place, the unequal heating of the earth's surface, by causing upward currents from the warmed portions, produces horizontal currents from the surrounding cooler regions inward to the central ascending mass of heated air. The familiar land and sea breezes offer a good example of this action. Again, the density of the air lessens with increase of water-vapor. Hence moist air tends to rise as warmed air does, with a corresponding inflow of the drier and consequently heavier air from the surrounding tracts. Moist air, ascending and diminishing atmospheric pressure, as indicated by the fall of the barometer, rises into higher regions of the atmosphere, where it expands, cools, condenses into visible cloud and into showers that descend again to the earth.

Unequal and rapid heating of the air, or accumulation of aqueous vapor in the air, and possibly some other influences not yet properly understood, give rise to extreme disturbances of pressure, and consequently to storms and hurricanes. For instance, the barometer sometimes indicates in tropical storms a fall of an inch and a half in an hour, showing that somewhere about a twentieth part of the whole mass of atmosphere has, in that short space of time, been displaced over a certain area of the earth's surface. No such sudden change can occur without the most destructive tempest or tornado. In Britain the tenth of an inch of barometric fall in an hour is regarded as a large amount, such as only accompanies great storms.[1] The rate of movement of the air depends on the difference of barometric pressure between the regions from and to which the wind blows. Since much of the potency of the air as a geological agent depends on its rate of motion, it is of interest to note the ascertained velocity and pressure of wind as expressed in the subjoined table:[2]

	Velocity in Miles per hour	Pressure in Pounds per square foot
Calm	0	0
Light breeze	14	1
Strong breeze	42	9
Strong gale	70	25
Hurricane	84	36

While the paramount importance of the atmosphere as the vehicle for the circulation of moisture over the globe, and consequently as powerfully influencing the distribution of climate and the growth of plants and animals, must be fully recognized by the geologist, he is specially called upon to consider the influence of the air in directly producing geological changes upon the surface of the land, and in augmenting the geological work done by water.

§ 1. Geological work of the atmosphere on land

Viewed in a broad way, the air is engaged in the twofold task of promoting the disintegration of superficial rocks and in removing and redistributing the finer detritus. These two operations, however, are so intimately bound up with

[1] Buchan's "Meteorology," p. 266.

[2] For another statement see Czerny, Peterman. Mitt. 1876, Ergänzungsheft.

each other that they cannot be adequately understood unless considered in their mutual relations.

1. Destructive action.—Still dry air, not subject to much range of temperature, has probably little or no effect on minerals and rocks. The chemical action of the atmosphere takes place almost entirely through dissolved moisture. This subject is discussed in the section devoted to Rain. But sunlight produces remarkable changes on a few minerals. Some lose their colors (celestine, rose-quartz), others change it, as cerargyrite does from colorless to black, and realgar from red to orange-yellow. Some of these alterations may be explained by chemical modifications induced by such causes as the loss of organic matter and oxidation.

Effects of lightning.—Hibbert has given an account of the disruption by lightning of a solid mass of rock 105 feet long, 10 feet broad, and in some places more than 4 feet high, in Fetlar, one of the Shetland Islands, about the middle of the 18th century. The dislodged mass was in an instant torn from its bed and broken into three large and several lesser fragments. "One of these, 28 feet long, 7 feet broad, and 5 feet in thickness, was hurled across a high point of rock to a distance of 50 yards. Another broken mass, about 40 feet long, was thrown still further, but in the same direction and quite into the sea. There were also many lesser fragments scattered up and down." [3]

The more usual effect of lightning, however, is to produce in loose sand or more compact rock patches of vitreous drops or bubbles coating the surface, also tubes termed *fulgurites*, which range up to 2½ inches in diameter. These tubes descend vertically, but sometimes obliquely, from

[3] Hibbert's "Shetland Islands," p. 389, quoting from the MS. of Rev. George Low.

the surface, occasionally branch, and rapidly lessen in dimensions till they disappear. They are formed by the actual fusion of the particles of the soil or rock surrounding the pathway of the electric spark. They have been most frequently found in loose sand. Abich has observed examples of such tubular perforations with vitreous walls in the porous reddish-white andesite at the summit of Little Ararat.[4] A piece of the rock about a foot long may be obtained perforated all over with irregular tubes having an average diameter of 3 centimetres. Each of these is lined with a blackish-green glass. As the whole summit of the mountain, owing to its frequent storms, is drilled in this manner, it is evident that the action of lightning may considerably modify the structure of the superficial portions of any mass of rock exposed on lofty eminences to frequent thunderstorms. Humboldt collected fulgurites from a trachyte peak in Mexico, and in two of his specimens the fused mass of the walls has actually overflowed from the tubes on the surrounding surface.[5]

Effects of changes of temperature.—Of far wider geological importance are the effects that arise among rocks and soils from the alternate expansion and contraction caused by daily or seasonal changes of temperature. In countries with a great annual range of temperature, considerable difficulty is sometimes experienced in selecting building-materials liable to be little affected by rapid or extreme

---

[4] Sitzb. Akad. Wiss. Wien, lx. (1870), p. 155.

[5] G. Rose, Zeitsch. Deutsch. Geol. Ges. xxv. p. 112; Gümbel, op. cit. xxxiv. (1882), p. 647; A. Wichmann, op. cit. xxxv. (1883), p. 849. Fusion by lightning was observed by De Saussure in hornblende-schist on the summit of Mont Blanc (see also F. Rutley, Quart. Journ. Geol. Soc. 1885, p. 152); by Ramond in mica-schist and limestone on a peak of the Pyrenees; by J. S. Diller on the basalt of Mount Thielson, Oregon, and on the top of Mount Shasta, California, Amer. Journ. Sci. Oct. 1884; by J. Eccles in glaucophane schist on Monte Viso, F. Rutley, Quart. Journ. Geol. Soc. xlv. (1889), p. 60.

variations in temperature, which induce an alternate expansion and contraction that prevents the joints of masonry from remaining close and tight.[6] If the daily thermometric variations are large, the effects are frequently striking. In Western America, where the climate is remarkably dry and clear, the thermometer often gives a range of more than 80° in the twenty-four hours. Thus in the Yellowstone district, at a height of 9000 feet above the sea, the author found the temperature of rocks exposed to the sun at noon to be more than 90° Fahr., and the thermometer at night to sink below 20°. In the Sahara and other African regions, as well as in Central Asia, the daily range is considerably greater. This rapid nocturnal contraction produces such a superficial strain as to disintegrate rocks into sand, or cause them to crack or peel off in skins or irregular pieces. Dr. Livingstone found in Africa (12° S. lat., 34° E. long.) that surfaces of rock which during the day were heated up to 137° Fahr., cooled so rapidly by radiation at night that, unable to sustain the strain of contraction, they split and threw off sharp angular fragments from a few ounces to 100 or 200 lbs. in weight.[7] In the plateau region of North America, though the climate is too dry to afford much scope for the operation of frost, this daily vicissitude of temperature produces results that quite rival those usually associated with the work of frost.

---

[6] In the United States, with an annual thermometric range of more than 90° Fahr., this difficulty led to some experiments on the amount of expansion and contraction in different kinds of building-stones, caused by variations of temperature. It was found that in fine-grained granite the rate of expansion was ·000004825 for every degree Fahr. of increment of heat; in white crystalline marble it was ·000005668; and in red sandstone ·000009532, or about twice as much as in granite. Totten, in Silliman's Amer. Journ. xxii. p. 136. See ante, pp. 495, 508.

[7] Livingstone's "Zambesi," pp. 492, 516. According to Stanley, cold rain falling on these sun-heated African rocks causes them to split open and peel off. Proc. Roy. Geog. Soc. xx. (1876), p. 142.

Cliffs are slowly disintegrated, the surface of arid plains is loosened, and the fine débris is blown away by the wind.

Effects of wind.—The geological work directly due to the air itself is mainly performed by wind.[8] A dried surface of rock or soil, when exposed to wind, has the finer disintegrated particles blown away as dust or sand. This process, which takes place familiarly before our eyes on every street and roadway, over cultivated ground, as well as on surfaces with which man has not interfered, is most marked in dry climates. Aridity indeed is its main cause. Mr. Flinders Petrie, the able Egyptian archeologist and explorer, has brought forward evidence of the abrading influence of the wind upon mud-brick walls and other buildings, and he estimates that in some parts of the Nile delta about eight feet of soil has been swept away by the wind during the last 2600 years, or nearly four inches in a century.[9] Many old fortifications in Northern China have been laid bare to the very foundations by the removal of the surrounding soil through long-continued action of wind.[10] In the dry plateaus of North America, too, though no human memorials serve there as measures, extensive denudation from the same cause is in progress.

It is not merely that the wind blows away what has already been loosened and pulverized. The grains of dust and sand are themselves employed to rub down the surfaces over which they are driven. The nature and potency of the erosion done by sand-grains in rapid motion is well illustrated by the artificial sand-blast, in which a spray of fine

---

[8] The general geological effects of wind are discussed by F. Czerny, Petermann's Mittheil. Ergänzungsheft, No. 48. Nature, xv. p. 231.

[9] Proc. Roy. Geograph. Soc. 1889, p. 648.

[10] Richthofen's "China," Berlin, 1877, i. p. 97.

siliceous sand, driven with great velocity, is made to etch or engrave glass.[11] The abrading and polishing effects of wind-blown sand have long been noticed on Egyptian monuments exposed to sand-drift from the Libyan desert.[12] Similar effects have been observed on dry volcanic plains of barren sand and ashes, as on the island of Volcano.[13] On the sandy plains of Wyoming, Utah, and the adjacent territories, surfaces even of such hard materials as chalcedony are etched into furrows and wrinkles, acquiring at the same time a peculiar and characteristic polish. There, also, large blocks of sandstone or limestone which have fallen from an adjacent cliff are attacked, chiefly at their base, by the stratum of drifting sand, until by degrees they seem to stand on narrow pedestals. As these supports are reduced in diameter the blocks eventually tumble over, and a new basal erosion leads to a renewal of the same stages of waste.[14] Hollows on rock-surfaces may also be noticed where grains of sand, or small pebbles kept in gyration by the wind, gradually erode the shallow cavities in which they lie.

As the result of the protracted action of wind upon an area exposed at once to great drought and to rapid vicissitudes of temperature, a continuous lowering of the general level takes place. The great sandy deserts thus produced

[11] The student will find much valuable information on this subject in the experimental results obtained by Thoulet, Comptes Rend. civ. p. 381. Ann. des Mines, 1887; and in the essay by Walther cited below

[12] An excellent account of the denudation phenomena of the Egyptian deserts will be found in an essay by J. Walther in vol. xvi. (1891) of the Abhand. Königl. Sächsisch. Gesellsch. d. Wissensch. The polishing of rocks by the sand of the Sahara is described by M. Choisy in his report "Documents relatifs à la mission dirigee au Sud de l'Algerie," 1890, p. 327.

[13] Kayser, Z. Deutsch. Geol. Ges. xxvii. p. 966.

[14] See Gilbert in Wheeler's Report of U. S. Geograph. Surv. W. of 100th Meridian, iii. p. 82. W. P. Blake, Union Pacific Railroad Report, v. pp. 92, 230. Amer. Journ. Sci. xx. (1885), p. 178. Naumann, Neues Jahrb. 1874, p. 337. Cazalis de Fondouce, Assoc. Française, 1879, p. 646. Many good illustrations are given by Walther in the essay above cited.

represent, however, only a portion of the disintegration. Vast quantities of the finer dust are borne away by the wind into other regions, where, as will be immediately pointed out, they tend to raise the general level. Again, a considerable amount of fine dust and sand, blown into the neighboring rivers, is carried down in their waters. In inland areas of drainage, indeed, like that of Central Asia, this transport does not finally remove the river-borne sediment from the basin of evaporation, but tends to fill up the lakes. Where, however, as in North America, rivers cross from the desert areas to the sea, there must be a permanent removal of wind-swept detritus by these streams. In the arid plateaus drained by the Colorado and its tributaries, so great has been the subaerial denudation that a thickness of thousands of feet of horizontal strata has been removed from the surface of level plains thousands of square miles in extent. This denudation, the extent of which is attested by the remaining cliffs and "buttes," or outliers, of the strata, appears to be in great measure due to the causes here discussed, augmented in some districts by the effects of occasional heavy storms of rain.

One further effect produced by air in violent motion may be seen in the destruction caused by cyclones. Not only are houses demolished, with much damage to other property and loss of life, but permanent changes of more or less importance are produced upon the surface of a country. Loose rocks on the face of cliffs are hurled down, and blocks of stone and loose gravel are swept away. But the most obvious effects are those in wooded districts, where the trees are prostrated far and near in the path of the storm. On the 18th and 19th of May, 1883, a succession of hurricanes passed over the States of Illinois and Wisconsin, with such fury that the brick chimney of a factory was carried to a distance of three-quarters of a mile, an entire house was lifted into the air and blown to pieces, and an oak two feet in diameter was dashed through a house. When such a storm passes over forest-ground in temperate latitudes, the surface-drainage may be so obstructed by the fallen stems, that marsh-plants spring up, and eventually the site of a forest may be occupied by a peat-moss (see Book III. Part II. Sect. iii. § 3).

2. **Reproductive action.**—Growth of Dust. The fine dust and sand resulting from the general superficial disintegration of rocks would, if left undisturbed, accumulate *in situ* as a layer that would serve to protect the still undecayed portions underneath. Such a layer, indeed, partially remains, but, being liable to continual attack and removal, may be taken to represent, where it occurs, the excess of disintegration over removal. In the vast majority of cases, however, the superficial coating of loose material is not due merely to the direct action of the sun's rays and of the air, but in far greater degree to the work of rain, aided by the co-operation of plants and animals. To the layer thus variously produced, the name of Soil is given. Its formation is described at p. 597.

That wind plays an effective part in the redistribution of superficial detritus is demonstrated by every cloud of dust blown from desiccated ground. We only need to take into account the multiplying power of time, to realize how extensively the soil of a district may be lowered, or, in other cases, may be replenished and heightened by the dust-storms of centuries. Dust and sand, intercepted by the leaves of plants, gradually descend into the soil, whither they are washed down by rain, so that even a permanently grassy surface may be slowly and imperceptibly heightened in this way, and a soil may be formed differing considerably in chemical composition from what would result merely from the decay of the subsoil.[15]

On the sites of ancient monuments and cities, this reproductive action of the atmosphere can be most impressively seen and most easily measured. In Europe, on sites still inhabited by an abundant population, the deep accumulations beneath which ancient ruins often lie are doubtless mainly to be assigned to the successive destructions and rebuildings of generation after generation of occupants. But at Nineveh, Babylon, and many other Eastern sites, mounds which have been practically untouched by man for many centuries consist of fine dust and sand gradually drifted by the wind round and over abandoned cities, and protected and augmented by the growth of vegetation.[16] In those arid lands, the air is often laden with fine detritus, which drifts like snow round conspicuous objects and tends to bury them up in a dust-drift. In Central Asia, even when there is no wind, the air is often thick with fine dust, and a yellow sediment settles from it over everything. In Khotan an exceedingly fine dust sometimes so obscures the sun that even at midday one cannot read large print without a lamp. This dust, deposited on the soil, heightens and fertilizes it, and is regarded by the inhabitants as a kind of manure, without which the ground would be barren.[17]

---

[15] C. Reid, Geol. Mag. 1884, p. 165.

[16] The rubbish which, in the course of many centuries, has accumulated above the foundations of the Assyrian buildings at Kouyunjik was found by Layard to be in some places twenty feet deep. It consisted partly of ruins, but mostly of fine sand and dust blown from off the plains and mixed with decayed vegetable matter. Layard, "Nineveh and its Remains," 3d edit. ii. p. 120. See also Richthofen's "China," i. p. 97.

[17] Johnson's "Journey to Hohi, the capital of Khotan," Journ. Geog. Soc. xxxvii. 1867, p. 1. H. B. Guppy, Nature, xxiv. (1881), p. 126.

Loess.—This name has been given to a remarkable deposit, first described in the valley of the Rhine, but which has been found to cover vast areas both in the Old World and in the New.[18] It is usually a yellowish homogeneous clay or loam, unstratified, and presenting a singular uniformity of composition and structure. When carefully examined, its quartz-grains are found to be remarkably angular, and its mica-flakes, instead of being deposited horizontally, as they are by water, occur dispersedly in every possible position and with no definite order.[19] The chief constituent of loess is always hydrated silicate of alumina, in which the scattered grains of quartz and flakes of mica are distributed. It is in some measure calcareous, the lime being here and there segregated into curious concretionary forms (Lössmänchen, Lösspuppen, p. 855) by the action of infiltrating water. Though a firm unstratified mass, it is traversed by innumerable tubes, formed by the descent of roots and mostly crusted with carbonate of lime. These have generally a vertical position, and ramify downward. Where the surface is covered with vegetation, they may be seen occupied by rootlets to a depth of a foot or a few feet from the surface. By means of these pipes a tendency is given to a vertical jointing of the mass. With these characters, the loess unites a remarkable peculiarity in respect of its organic remains, which consist chiefly of land-shells, sometimes in immense numbers, likewise of the bones of various herbivorous and carnivorous mammals, which are either identical with or closely allied to living

---

[18] The calcareous clays of the arid regions of North America have been largely used for the manufacture of sun-dried bricks called in Spanish "adobe"—a term which has been proposed as a geological designation for these deposits. I. C. Russell, Geol. Mag. 1889, p. 291.

[19] See Mr. Russell's paper cited in the previous note, p. 294.

species that abound on steppes and grassy plains. Fresh-water shells are usually rare, and marine forms do not occur. Loess is found at all elevations, up to 5000 feet among the Carpathians, 8000 feet in Shansi, China, and probably to still higher altitudes further west. In hilly regions it fills up the valleys, shading off on either side up the slopes into the angular débris of the adjoining rock. Elsewhere, it spreads over the surface so as completely to conceal the original inequalities of the ground. In Northern China, Richthofen found it to have a thickness of 1500 or possibly over 2000 feet, and to be cut into deep valleys and precipitous ravines, with cliffs 500 feet high, which are excavated into tiers of chambers and passages by a teeming population.[20] In the arid tracts of North America the loess or "adobe" is estimated to be sometimes 2000 or 3000 feet thick.[21]

Various theories have been proposed in explanation of this singular deposit. By some it has been referred to the operation of the sea; by others to the work of lakes or of rivers. But its wide extent, its independence of the altitude or contours of the ground, its uniform and unstratified character, the unworn condition of its component particles, and the nature of its organic remains, show that it cannot be assigned to the action of large bodies of water. Richthofen propounded in 1870 the opinion that the loess is mainly due to the long-continued drifting and deposit of fine dust by wind over areas more or less covered with grassy vegetation, aided by the washing influence of rain, and this view has been widely accepted. Where rain is

---

[20] See Richthofen's description, Geol. Mag. 1882, p. 293, and his "China," above cited.

[21] Russell, Geol. Mag. 1889, p. 292.

distributed somewhat equally throughout the year little dust is formed; but where dry and wet seasons alternate, as in Central Asia, vast quantities of dust may be moved during the months of dry weather. When the dust falls on bare ground, it is eventually swept away by the wind; but where it settles down on ground covered with vegetation it is in great measure protected from further transport, and thus heightens the soil.[22]

For atmospheric accumulations of this nature, Trautschold has proposed the name *eluvium.* They originate *in situ*, or at least only by wind-drift, whereas *alluvium* requires the operation of water, and consists of materials brought from a greater or less distance.[23] For wind-formed deposits the term "æolian" is sometimes used.

Sandhills or Dunes.—Winds blowing continuously upon sand drive it onward, and pile it into irregular heaps and ridges, called "dunes." This takes place more especially on windward coasts either of the sea or of large inland lakes, where sandy shores are exposed to the drying influence of solar heat and wind; but similar effects may be seen even in the heart of a continent, as in the sandy deserts of the Sahara,[24] Arabia, and in the arid lands of Utah, Arizona, etc. The dunes travel in parallel, irregular,

---

[22] Richthofen, Geol. Mag. 1882, p. 297. For some of the more important contributions to this subject, see Richthofen's "China," vols. i. and ii.; also Verh. Geol. Reichs. 1878, p. 289; E. Tietze, Verh. Geol. Reichs. 1878, p. 113; 1881, p. 37; Jahrb. Geol. Reichs. 1881, p. 80; 1882, p. 11; 1883, p. 279; R. Pumpelly, Amer. Journ. Sci. xvii. (1879); E. W. Hilgard, op. cit. xviii. (1879), p. 106 (p. 427); I. C. Russell, Geol. Mag. 1889, pp. 288, 342; F. Wahnschaffe, Z. Deutsch. Geol. Ges. 1886. Jahrb. Preuss. Landesanst. 1889, p. 328. A. Sauer, Zeitsch. für Naturwissensch. lxii. (1889); and postea, Book VI. Part V. Sect. i. On the loess of Alsace, see E. Schumacher, Commiss. Landesuntersuch. Elsass-Lothringen, vol. ii. Part I. (1889), p. 79; on the loess of the Pampas, S. Roth, Zeitsch. Deutsch. Geol. Gesell. xl. (1888), p. 422.

[23] Z. Deutsch. Geol. Ges. xxxi. p. 578.

[24] For an account of the sand-dunes of the Sahara see "Documents relatifs à la Mission dirigee au Sud de l'Algerie," A. Choisy, 1890, p. 323.

and often confluent ridges, their general direction being transverse to the prevalent course of the wind. Local wind-eddies cause many irregularities of form. In humid climates, rain-water or the drainage of small brooks is sometimes arrested between the ridges to form pools (*étangs* of the French coasts), where formations of peat occasionally take place. On the coast of Gascony, the sea for 100 miles is so barred by sand-dunes that in all that distance only two outlets exist for the discharge of the drainage of the interior. As fast as one ridge is driven away from a beach another forms in its place, so that a series of huge sandy billows, as it were, is continually on the move from the sea-margin toward the interior. A stream or river may temporarily arrest their progress, but eventually they push the obstacle aside or in front of them. In this way the river Adour, on the west coast of France, has had its mouth shifted two or three miles. Occasionally, as at the mouths of estuaries, the sand is blown across, so as gradually to exclude the sea, and thus to aid the fluviatile deposits in adding to the breadth of the land. In Fig. 90 a stream (*e e*) is represented as crossing a plain (*a*) at the margin of the sea or of a large inland sheet of water, bounded by a range of sand-dunes (*b b*) extending between the two lines of cliff (*c g*). The stream has been turned to its right bank by the advance of the dunes driven by a prevalent wind blowing in the direction of the arrows. A brook (*f*) has been ar-

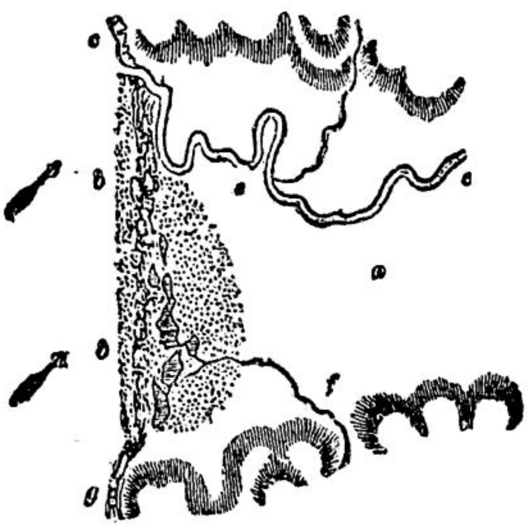


Fig. 90.—Sand-dunes affecting land-drainage (*B.*).

rested among the sandy wastes, whence, after forming a few pools, it finds egress by soaking through the sandy barrier.

The nature of the grains of sand depends on the character of the rocks from the destruction of which they are derived, and their form and size are largely regulated by the force of the wind and the relative share taken by subaerial and subaqueous action in their production. Quartz is the most frequent constituent, but the other minerals of rocks also occur, especially those which are most capable of resisting mechanical trituration. In some cases, organic remains, such as particles of shells, nullipores, etc., form the main mass of the sand (see p. 572).[25] The sand-grains liberated by

Fig. 91.—Diagram of Ripples in blown Sand. The ridges b^1, b^2, b^3, impelled in the direction of W W, successively come to occupy the hollows a^1, a^2, a^3 (*B.*).

inland subaerial disintegration are apt to be more angular than those brought within the influence of the wind along a shore-line.[26]

Perfect "ripple-marks" (p. 848) may often be observed on blown sand. The sand-grains, pushed along by the wind, travel up the long slopes and fall over the steep slopes. Not only do the particles travel, but the ridges also more slowly follow each other, as in Fig. 91.[27]

The western sea-board of Europe, exposed to prevalent westerly and southwesterly winds, affords many instructive

---

[25] Mr. Russell (Geol. Mag. 1889) refers to some parts of the sands of the arid lands of North America as being composed mainly of the cases of cyprids, blown away from the beds of dried-up lakes.

[26] Engravings of some of the sand-grains from the Egyptian deserts are given by Walther in the essay already cited.

[27] On the origin of ripple-mark, see Book IV. Part I. p. 850.

examples of these æolian or wind-formed deposits. The coast of Norfolk is occasionally fringed with sand-hills 50 to 60 feet high. On parts of the coast of Cornwall,[28] the sand consists mainly of fragments of shells and corallines, and, through the action of rain upon these calcareous particles, becomes sometimes cemented by carbonate of lime (or oxide of iron) into a stone so compact as to be fit for building purposes. Long tracts of blown sand are likewise found on the Scottish and Irish[29] coast-lines. Sand-dunes extend for many leagues along the French coast, and thence, by Flanders and Holland, round to the shores of Courland and Pomerania. On the coast of Holland they are sometimes, though rarely, 260 feet high—a common average height being 50 to 60 feet.[30]

The breadth of this maritime belt of sand varies considerably. On the east coast of Scotland it ranges from a few yards to 3 miles; on the opposite side of the North Sea it attains on the Dutch coast sometimes to as much as 5 miles. The rate of progress of the dunes toward the interior depends upon the wind, the direction of the coast, and the nature of the ground over which they have to move. On the low and exposed shores of the Bay of Biscay, when not fixed by vegetation, they travel inland at a rate of about 16½ feet per annum, in Denmark at from 3 to 24 feet. In the course of their march they envelop houses and fields; even whole parishes and districts once populous have been overwhelmed by them.[31]

Along the margins of large lakes and inland seas many of the phenomena of an exposed sea-coast are repeated on a scarcely inferior scale. Among these must be included sand-dunes, such as those which, reaching heights of 100 to 200 feet on the southeastern shores of Lake Michigan, have entombed forests, the tops of the trees being still visi-

---

[28] Ussher, Geol. Mag. (2), vi. p. 307, and authorities there cited. The upper parts of the blown sand are sometimes crowded with land-shells, the decay of which furnishes the cementing material (see Fig. 76).

[29] See Kinahan, Geol. Mag. viii. p. 155.

[30] On the growth of Holland through the operation of the wind and the sea, see Élie de Beaumont, "Leçons de Geologie pratique," i. A detailed description of the dunes of Holland is given by J. Lorié, Arch. Musee Teyler, ser. ii. vol. iii. Part V. (1890), p. 375. For an account of the sand-dunes of Western Europe, see W. Topley, Pop. Science Rev xiv. (1875), p. 133.

[31] This destruction has more recently been averted to a great extent by the planting of pine forests, the turpentine of which has become the source of a large revenue.

ble above the drifting sand. Large dunes occur also on the eastern borders of the Caspian Sea, where the sand spreads over the desert region between that sea and the Sea of Aral, into which latter sheet of water the spread of the sand has driven the course of the Oxus, once a tributary of the Caspian.

In the interior of continents, the existence of vast arid wastes of loose sand, situated far inland and remote from any sheet of fresh water, suggest curious problems in physical geography. In some instances, these tracts have been at a comparatively recent geological period covered by the sea. Yet the disintegration of rock in torrid and rainless regions is so great (ante, p. 559), that the existing sand is doubtless mainly, if not entirely, of subaerial origin. The sandy deserts of the high plateaus of Western North America, which have never been under the sea for a long series of geological ages, show, as we have already found (p. 560), the mode and progress of their formation from atmospheric disintegration alone. In Asia lie the vast deserts of Gobi, where in some places ancient cities have been buried under the sand.[32] In Rajputana, wide tracts of sandy desert present a succession of nearly parallel ridges or waves of sand, varying up to 180 feet from trough to crest, and presenting long gentle slopes toward southwest, whence the prevalent winds blow, but with northeastern fronts as steep as the sand will lie.[33] To the east of the Red Sea stretch the great sand-wastes of Arabia; and to the west those of Libya. The sandy wastes of the Sahara have in recent years been partially explored, especially by French observers from the Algerian frontier. According to M. Rolland, the sand is entirely due to the action of the wind, and though there is a transport of sand and fine dust, the position of the large dunes, sometimes 70 metres in height, remains on the whole unchanged.[34] In the southeast of Europe, over the steppes of southern Russia and the adjacent territories, wide areas of sandy desert occur. Captain Sturt found vast deserts of sand in the interior of Australia, with long bands of

---

[32] For important information regarding the Central Asiatic wastes, see Richthofen's "China," i. Also Tchihatchef, Brit. Assoc. 1882, p. 356. T. D. Forsyth, Journ. Roy. Geog. Soc. xlvii. (1878), p. 1.

[33] Major C. Strahan in "Report of Survey of India," 1882–83.

[34] G. Rolland, Bull. Soc. Geol. France, 3d ser. x. p. 30. See also A Parran, op. cit. xviii. (1890), p. 245.

dunes 200 feet high, united at the base and stretching in straight lines as far as the eye could reach.[35]

Some of the most remarkable æolian formations are in course of accumulation at Bermuda and other coral-islands. The finer coral-sand, with remains of shells, echinoderms, calcareous algæ, and other organisms, is driven by the wind into dunes, the surface of which by the action of rain-water soon becomes cemented into coherence, while by degrees the whole mass of calcareous débris is converted into a hard compact rock which rings under the hammer. The highest point of Bermuda is 245 feet above the sea, and the whole land up to that height is composed of these hardened calcareous æolian deposits.[36]

Dust-showers, Blood-rain.—Besides the universal transport and deposit of dust and sand already described, a phenomenon of a more aggravated nature is observed in tropical countries, where great droughts are succeeded by violent hurricanes. The dust or sand of deserts and of dried lakes or river-beds is then sometimes borne away into the upper regions of the atmosphere, where, meeting with strong aerial currents which may transport it for many hundreds of miles, it descends again to the surface, in the form of "red fog," "sea-dust," or "sirocco-dust." This transported material, usually of a brick-dust or cinnamon color, is occasionally so abundant as to darken the air and

---

[35] For accounts of sand-dunes, their extent, progress, structure, and the means employed to arrest their progress, the student may consult Andersen's "Klitformationen," 1 vol. 8vo, Copenhagen, 1861; Laval in Annales des Ponts-et-Chaussees, 1847, 2me sem. Marsh's "Man and Nature," 1864, and the works cited by him. Forchhammer, Edin. New Phil. Journ. xxxi. (1841), p. 61. Élie de Beaumont, "Leçons de Geologie pratique," vol. i. p. 183. Winkler, Cong. Internat. Geol. 1878, p. 181. Information regarding the sands of the interior of continents will be found in Palgrave's "Travels in Arabia"; Blake, in Union Pacific Railroad Report, v.; Tristram, "The Great Sahara," 1860; Desor, "Le Sahara, ses differents types de deserts," Bull. Soc. Sci. Nat. Neufchâtel, 1864; E. Fuchs, Petermann's Mittheil. 1879; A. Pomel, Assoc. Française, 1877, p. 428; G. Rolland, Bull. Soc. Geol. France, 3me ser. x., La Nature, 1882, Soc. de Geog. 1890; Richthofen's "China," i.; I. C. Russell on the subaerial deposits of North America, Geol. Mag. 1889, p. 289.

[36] Nelson, Q. J. Geol. Soc. ix. p. 226. Wyville Thomson's "Atlantic," vol. i., and ante, p. 226.

obscure the sun, and to cover the decks, sails, and rigging of vessels which may even be hundreds of miles from land. Rain falling through such a dust-cloud mixes with it, and descends, either on sea or land, as what is popularly called "blood-rain." Occasionally the dust is brought down to the surface of the ground by snow.

This phenomenon is frequent on the northwest of Africa, about the Cape Verd Islands, in the Mediterranean, and over the bordering countries. A microscopic examination of this dust by Ehrenberg led him to the belief that it contains numerous diatoms of South American species; and he inferred that a dust-cloud must be swimming in the atmosphere, carried forward by continuous currents of air in the region of the trade-winds and anti-trades, but suffering partial and periodical deviations. But much of the dust seems to come from the sandy plains and desiccated pools of the north of Africa. Daubrée recognized in 1865 some of the Sahara sand which fell in the Canary Islands. On the coast of Italy, a film of sandy clay, identical with that from parts of the Libyan desert, is occasionally found on windows after rain. In the middle of the 18th century an area of northern Italy, estimated at about 200 square leagues, was covered with a layer of dust which in some places reached a depth of one inch. In 1846 the Sahara dust reached Lyons, and it is said to have been since detected as far as Boulogne-sur-Mer. Should the travelling dust encounter a cooler temperature, it may be brought to the ground by snow, as has happened in the north of Italy, and more notably in the east and southeast of Russia, where the snows are sometimes rendered dirty by the dust raised by winds on the Caspian steppes.[37] It is easy to see how widespread deposits of dust may arise, mingled with the soil of the land, and with the silt and sand of lakes, rivers, or the sea; and how the minuter organisms of tropical regions may thus come to be preserved in the same formations with the terrestrial or marine organisms of temperate latitudes.[38]

---

[37] Consult an interesting paper by C. von Camerlander on snow with dust which fell in Silesia, Moravia and Hungary in February, 1888, Jahrb. Geol. Reichsanst. xxxviii. (1888), p. 281.

[38] See Humboldt on dust whirlwinds of Orinoco, "Aspects of Nature"; also

The transport of volcanic dust by wind, already referred to (p. 369), may be again cited here, as another example of the geological work of the atmosphere. Thus, from the Icelandic eruptions of 1874–75, vast showers of fine ashes not only fell on Iceland to a depth of six inches, destroying the pastures, but were borne over the sea and across Scandinavia to the east coast of Sweden.[39] The remarkable sunsets of Europe during the winter and spring of 1883–84 are ascribed to the diffusion of the fine dust from the great Krakatoa eruption of August, 1883 (p. 365). Considerable deposits of volcanic material may thus be formed in the course of time even far remote from any active volcano.

Transportation of Plants and Animals.—Besides the transport of dust for distances of perhaps thousands of miles, wind may also transport living seeds or spores, which, finally reaching a congenial climate and soil, may survive and spread. We are yet, however, very ignorant as to the extent to which this cause has actually operated in the establishment of any given local flora. With regard to the minute forms of vegetable life, indeed, there can be no doubt as to the efficacy of the wind to transport them across vast distances on the surface of the globe. Upward of 300 species of diatoms have been found in the deposits left by dust-showers. Among the millions of organisms thus transported it is hardly conceivable that some should not fall still alive into a fitting locality for their continued existence and the perpetuation of their species. Animal forms of life are likewise diffused through the agency of winds. Insects and birds are often met with at sea, many miles distant from the land from which they have been blown. Such organisms are in this way intro-

Maury, "Phys. Geog. of Sea," chap. vi.; Ehrenberg's "Passat-Staub und Blut-Regen," Berlin Akad. 1847. A. von Lasaulx on so-called "cosmic dust," Tschermak's Mineral. Mittheil. 1880, p. 517.

[39] Nordenskiöld, Geol. Mag. (2), iii. p. 292. F. Zirkel, Neues Jahrb. 1879, p. 399. G. vom Rath, ibid. p. 506, and ante, p. 370.

duced into oceanic islands, as is well shown in the case of Bermuda. Hurricanes, by which large quantities of water are sucked up from lakes and rivers over which they pass, may also transport part of the fauna of these waters to other localities.

Efflorescence products.—Among the formations due in large measure to atmospheric action must be included the saline efflorescences which form upon the ground in the dry interior basins of continents. The steppes of Southern Russia, and the plains round the Great Salt Lake of Utah, may be taken as illustrative examples. Water, rising by capillary attraction through the soil to the surface, is there evaporated, leaving behind a white crust, by which the upper portion of the soil is covered and permeated. The incrustations consist of sodium-chloride, sodium- and calcium-carbonates, calcium- sodium- and potassium-sulphates in various proportions, these being the salts present also in the salt lakes of the same regions (p. 688).[40]

§ 2. Influence of the Air on Water

The results of the action of the air upon water will be more fitly noticed in the section devoted to Water. It will be enough to notice here—

1. Ocean currents.—These are mainly dependent for their existence and direction on the circulation of the atmosphere. The in-streaming of air from cooler latitudes toward the equator causes a drift of the sea-water in the same direction. As, owing to the rotation of the earth, these

---

[40] On efflorescence of Great Salt Lake region, see Exploration of 40th Parallel, i. sect. v. Consult also E. Tietze, "Entstehung der Salzsteppen," Jahrb. Geol. Reichsanst. 1877, and H. le Chatelier on the salt-crusts of Algeria, Comptes Rend, lxxxiv. p. 396.

aerial currents tend to take a more and more westerly trend in approaching the equator, they communicate this trend to the marine currents, which, likewise moving into regions with a greater velocity of rotation than their own, are all the more impelled in the same westerly direction. Hence the dominant equatorial current which flows westward across the great ocean. Owing, however, to the position of the continents across its path, this great current cannot move uninterruptedly round the earth. It is split into branches which turn to right and left, and, bathing the shores of the land, carry some of the warmth of the tropics into more temperate latitudes. Return currents are thus generated from cooler latitudes toward the equator (p. 730).

2. Waves.—The impulse of the wind upon a surface of water throws that surface into pulsations which range in size from mere ripples to huge billows. Long-continued gales from the seaward upon an exposed coast indirectly effect much destruction, by the formidable battery of billows which they bring to bear upon the land (p. 746). Wave-action is likewise seen in a marked manner when wind blows strongly across a broad inland sheet of water, such as Lake Superior (p. 686).

3. Alteration of the Water-level.—Wind blowing freshly across a lake or narrow sea drives the water before it, and keeps it temporarily at a higher level on the further or windward side. In a tidal sea, such as that which surrounds Great Britain, and which sends abundant long arms into the land, a high tide and a gale are sometimes synchronous. This conjunction makes the high tide rise to a greater height than elsewhere in those bays or firths which look windward, occasionally causing considerable damage to property by the flooding of warehouses and

stores, with even a sensible destruction of cliffs and sweeping away of loose materials. On the other hand, a wind from the opposite quarter coincident with an ebb tide, by driving the water out of the inlet, makes the water-level lower than it would otherwise be. In inland seas where tides are small or imperceptible, considerable oscillations of water-level may arise from the action of the wind. At Naples, for example, a long-continued southwest wind raises the level of the water several inches. Similar results attend prolonged gales on large fresh-water lakes (p. 683).

Rapid and great diminution of atmospheric pressure may also cause a rise in the level of the sea and produce great destruction (p. 437).

Section ii. Water

Of all the terrestrial agents by which the surface of the earth is geologically modified, by far the most important is water. We have already seen, when following hypogene changes, how large a share is taken by water in the phenomena of volcanoes and in other subterranean processes. Returning to the surface of the earth and watching the operations of the atmosphere, we soon learn how important a part of these is sustained by the aqueous vapor by which the atmosphere is pervaded.

The substance which we term water exists on the earth in three well-known forms—(1) gaseous, as invisible vapor; (2) liquid, as water; and (3) solid, as ice. The gaseous form has already been noticed as one of the characteristic ingredients of the atmosphere (p. 64). Vast quantities of vapor are continually rising from the surface of the seas, rivers, lakes, snow-fields, and glaciers of the world. This vapor remains invisible until the air containing it is cooled down below its dew-point, or point of saturation—a result which follows upon the union or collision of two aerial currents of different temperatures, or the rise of the air into the upper cold regions of the atmosphere, where it is chilled by expansion, by radiation, or by contact with cold mountains. According to recent researches, condensation appears only to take place on free surfaces, and the formation of cloud and mist is explained by condensation upon the fine microscopic dust of which the atmosphere is full.[41] At first minute particles of water-vapor appear, which either remain in the liquid condition, or, if the temperature is sufficiently low, are frozen into ice. As these changes take place over considerable spaces of the sky, they give rise to the phenomena of clouds. Further condensation augments the size of the cloud-particles, and at last they fall to the surface of the earth, if still liquid, as rain; if solid, as snow or hail; and if partly solid and partly liquid, as sleet. As the vapor is largely raised from the ocean-surface, so in great measure it falls back again directly into the ocean. A considerable proportion, however, descends upon the land, and it is this part of the condensed vapor which we have now to follow. Upon the higher elevations it falls as snow, and gathers there into snow-fields, which, by means of glaciers, send their drainage toward the valleys and plains. Elsewhere it falls chiefly as rain, some of which sinks underground to gush forth again in springs, while the rest pours down the slopes of the land, feeding brooks and torrents, which, swollen further by springs, gather into broader and yet broader rivers that bear the accumulated drainage of the land out to sea.

[41] Coulier and Mascart. Naturforscher, 1875, p. 400. Aitken, Proc. Roy. Soc. Edin. Dec. 1880.

Thence once more the vapor rises, condensing into clouds and rain to feed the innumerable water-channels by which the land is furrowed from mountain-top to sea-shore.[42]

In this vast system of circulation, ceaselessly renewed, there is not a drop of water that is not busy with its allotted task of changing the face of the earth. When the vapor ascends into the air it is, comparatively speaking, chemically pure. But when, after being condensed into visible form, and working its way over or under the surface of the land, it once more enters the sea, it is no longer pure, but more or less loaded with material taken by it out of the air, rocks, or soils through which it has travelled. Day by day the process is advancing. So far as we can tell, it has never ceased since the first shower of rain fell upon the earth. We may well believe, therefore, that it must have worked marvels upon the surface of our planet in past time, and that it may effect vast transformations in the future. As a foundation for such a belief let us now inquire what it can be proved to be doing at the present time.

§ 1. Rain

Rain effects two kinds of changes upon the surface of the land. (1) It acts *chemically* upon soils and stones, and, sinking under ground, continues, as we shall find, a great series of similar reactions there. (2) It acts *mechanically*, by washing away loose materials, and thus powerfully affecting the contours of the land.

1. Chemical Action.—This depends mainly upon the nature and proportion of the substances abstracted by rain from the air in its descent to the earth. Rain absorbs a

[42] For estimates of the distribution of rain over the globe, see Murray, Scottish Geol. Mag. 1887.

little air, which always contains carbonic acid as well as other ingredients, in addition to its nitrogen and oxygen (p. 64). Rain thus washes the air and takes impurities out of it, by means of which it is enabled to work many chemical changes that it could not accomplish were it to reach the ground as pure water.

Composition of Rain-water.—Numerous analyses of rain-water show that it contains in solution about 25 cubic centimetres of gases per litre.[43] An average proportional percentage is by measure—nitrogen, 64·47; oxygen, 33·76; carbonic acid, 1·77. Carbonic acid, being more soluble than the other gases, is contained in rain-water in proportions between 30 and 40 times greater than in the atmosphere. Oxygen too is more soluble than nitrogen. These differences acquire a considerable importance in the chemical operations of rain. Other substances are present in smaller quantities. In England there is an average of 3·95 parts of solid impurity in 100,000 parts of rain.[44] Nitric acid sometimes occurs in marked proportions: at Basel it was found to reach a maximum of 13·6 parts in a million, with 20·1 parts of nitrate of ammonia. Sulphuric acid likewise occurs, especially in the rain of towns and manufacturing districts.[45] Sulphates of the alkalies and alkaline earths have been detected in rain. But the most abundant salt is chloride of sodium, which appears in marked propor-

---

[43] Baumert, Ann. Chem. Pharm. lxxxviii. p. 17. The proportion of carbonic acid found by Peligot was 2·4. See also Bunsen, op. cit. xciii. p. 20. Roth, "Chem. Geol." i. p. 44. Angus Smith, "Air and Rain," 1872, p. 225.

[44] Rivers Pollution Commission, 6th Rep. p. 29.

[45] The occurrence of sulphuric and nitric acids in the air, especially noticeable in large towns, leads to considerable corrosion of metallic surfaces, as well as of stones and lime. The mortar of walls may often be observed to be slowly swelling out and dropping off, owing to the conversion of the lime into sulphate. Great injury is likewise done, from a similar cause, to marble monuments in exposed graveyards. See Angus Smith, "Air and Rain," p. 444. Geikie, Proc. Roy. Soc. Edin. 1879–80, p. 518.

tions on coasts, as well as in the rain of towns and industrial districts. Rain taken at the Land's End in Cornwall during a strong southwest wind was found to contain 2·180 of chlorine, or 3·591 parts of common salt, in every 10,000 of rain. The mean proportion of chlorine over England is about 0·022 in every 10,000 parts of rain; at Ootacamund 0·003 to 0·004.[46]

In washing the air, rain carries down also inorganic particles or motes floating there; likewise organic dust and living germs.[47] As the result of this process the soil comes to be not merely watered but fertilized by the rain. Angus Smith cites the experience of J. J. Pierre, who found by analysis that in the neighborhood of Caen, in France, a hectare of land receives annually from the atmosphere by means of rain:[48]

Chloride of	sodium	37·5	kilogrammes
"	potassium	8·2	"
"	magnesium	2·5	"
"	calcium	1·8	"
Sulphate of	soda	8·4	kilogrammes
"	potash	8·0	"
"	lime	6·2	"
"	magnesia	5·9	"

[46] Angus Smith, "Air and Rain." Rivers Pollution Commission, 6th Rep. 1874, p. 425. During a westerly gale on the Atlantic coasts of Britain, when the sea is white with foam, the air, elsewhere clear, may be seen to be quite misty alongshore from the clouds of fine spray swept by the wind from the crests of the breakers. This salt-water dust is borne far inland. From the investigations carried on at the Agricultural Laboratory, Rothamsted, it appears that the average proportion of chlorine is 2·01 per million parts of rain, which in a rainfall of 31·65 inches is equal to a discharge of 24 pounds of pure sodium chloride per acre. At Cirencester, where the rainfall is 33·31 inches, the proportion of chlorine is 3·25 per million, which is equivalent to 40·3 pounds of sodium chloride per acre. R. Warington, Journ. Chem. Soc. 1887, p. 502.

[47] Among the inorganic contents of rain and snow, fine terrestrial dust and spherules of iron, probably in part of cosmic origin, have been specially noted. See authorities cited ante, p. 125; A. von Lasaulx, as cited on p. 575. The organic matter of rain is revealed by the putrid smell which long-kept rain-water gives out.

[48] Angus Smith, "Air and Rain," p. 233.

Not only rain, but also dew and hoar-frost abstract impurities from the atmosphere. The analyses performed by the Rivers Pollution Commission show that dew and hoar-frost, condensing from the lower and more impure layers of the air, are even more contaminated than rain, as they contain on an average in England 4·87 parts of solid impurity in 100,000 parts, with 0·198 of ammonia.[49]

It is manifest that rain reaches the surface by no means chemically pure water, but having absorbed from the air various ingredients which enable it to accomplish a series of chemical changes in rocks and soils. So far as we know at present, the three ingredients which are chiefly effective in these operations are oxygen, carbonic acid, and organic matter. As soon as it touches the earth, however, rain-water begins to absorb additional impurities, notably increasing its proportion of carbonic acid and of organic matter, from decomposing animals and plants. Among the organic products most efficacious in promoting the corrosion of minerals and rocks are the so-called ulmic or humous substances that form with alkalies and alkaline earths soluble compounds, which are eventually converted into carbonates.[50] Hence as rain-water, already armed with gases absorbed from the atmosphere, proceeds to take up these organic acids from the soil, it is endowed with considerable chemical activity even at the very beginning of its geological career.

Chemical and mineralogical changes due to rain-water.—In previous pages, it was pointed out

---

[49] Rivers Pollution Commission, 6th Rep. p. 32.

[50] Senft, Z. Deutsch. Geol. Ges. xxiii. p. 665, xxvi. p. 954. This subject has been well treated in a paper by A. A. Julien "On the Geological Action of the Humous Acids" (Proc. Amer. Assoc. xxviii. 1879, p. 311), to which further reference is made in later pages. See also his excellent paper on the decomposition of pyrites, Ann. New York Acad. Sci. vol. iv. (1888).

that all rocks and minerals are, in varying degrees, porous and permeable by water, that probably no known substance can, under all conditions, resist solution in water, and that the subsequent solvent power of water is greatly increased by the solutions which it effects and carries with it in its progress through rocks (pp. 519–521). The chemical work done by rain may be conveniently considered under the five heads of Oxidation, Deoxidation, Solution, Formation of Carbonates, and Hydration.

1. *Oxidation.*—The prominence of oxygen in rain-water, and its readiness to unite with any substance that can contain more of it, render oxidation a marked feature of the passage of rain over rocks. A thin oxidized pellicle is formed on the surface, and this, if not at once washed off, is thickened from inside until a crust is formed over the stone, while at the same time the common dark green or black color of the original rock changes into a yellowish, brownish, or reddish hue. This process is simply a rusting of those ingredients which, like metallic iron, have no oxygen, or have not their full complement of it. The ferrous and manganous oxides so frequently found as constituents of minerals are specially liable to this change. In hornblende and augite, for example, one cause of weathering is the absorption of oxygen by the iron and the hydration of the resultant peroxide. Hence the yellow and brown sand into which rocks abounding in these minerals are apt to weather. Sulphides of the metals give rise to sulphates, and sometimes to the liberation of free sulphuric acid. Iron disulphide, for example, becomes copperas, which, on oxidation of the iron, gives a precipitate of limonite, with the escape of free sulphuric acid.

2. *Deoxidation.*—Rain becomes a reducing agent by ab-

sorbing from the atmosphere and soil organic matter which, having an affinity for oxygen, decomposes peroxides and reduces them to protoxides. This change is especially noticeable among iron-oxides, as in the familiar white spots and veinings so common among red sandstones. These rocks are stained red by ferric oxide (hæmatite), which, reduced by decaying organic matter to ferrous oxide, is usually removed in solution as an organic salt or a carbonate. When the deoxidation takes place round a fragment of plant or animal, it usually extends as a circular spot; where water containing the organic matter permeates along a joint or other divisional plane, the decoloration follows that line. Another common effect of the presence of organic matter is the reduction of sulphates to the state of sulphides. Gypsum is thus decomposed into sulphide of calcium, which in water readily gives calcium carbonate and sulphuretted hydrogen, and the latter by oxidation leaves a deposit of sulphur. Hence from original beds of gypsum, layers of limestone and sulphur have been formed, as in Sicily and elsewhere (p. 124).[51]

3. *Solution.*—A few minerals (halite, for example) are readily soluble in water without chemical change, and without the aid of any intermediate element; hence the copious brine-springs of salt regions. In the great majority of cases, however, solution is effected through the medium of carbonic acid or other reagent. Limestone is soluble to the extent of about 1 part in 1000 of water saturated with carbonic acid. The solution and removal of lime from the mortar of a bridge or vault, and the deposit of the material so removed in stalactites and stalagmites (p. 620), likewise

[51] The reducing action of organic acids is further described in Section iii.

the rapid effacement of marble epitaphs in our churchyards, are instances of this solution. It has been shown that in the atmosphere of a large town, with abundant coal-smoke and rain, exposed inscriptions on marble become illegible in half a century. Pfaff determined that a slab of Solenhofen limestone, 2520 square millimetres in superficies, lost in two years, by the solvent action of rain, 0·180 gramme in weight, in three years 0·548, the original polish being replaced by a dull earthy surface on which fine cracks and incipient exfoliation began to appear. Taking the specific gravity of the stone at 2·6, the yearly loss of surface amounts to $\frac{1}{72 \cdot 8}$ millimetre, so that a crag of such limestone would be lowered 1 metre in 72,800 years by the solvent action of rain.[52] J. G. Goodchild, from observations of dressed surfaces of Carboniferous limestone in the north of England, has inferred that these surfaces have been lowered at rates varying from one inch in 240 years to the same amount in 500 years.[53] Dolomite is much more feebly soluble than limestone. As rain-water attacks the carbonate of lime more readily than the carbonate of magnesia, the rock is apt to acquire a somewhat porous or carious texture, with a corresponding increase in the proportion of its magnesian carbonate. Eventually the latter carbonate is dissolved and redeposited in the pores of the rock, which then assumes a characteristic crystalline aspect. Among the sulphates, gypsum is the most important example of solution. It is dissolved in the proportion of about 1 part in 400 parts of water.

---

[52] Pfaff, Z. Deutsch. Geol. Ges. xxiv. p. 405; and "Allgemeine Geologie als exacte Wissenschaft," p. 317. Roth, "Allgemeine und Chem. Geol." i. p. 70. Geikie, Proc. Roy. Soc. Edin. x. 1879–80, p. 518.

[53] Geol. Mag. 1890, p. 466.

4. *Formation of Carbonates.*—Silicates of lime, potash, and soda, with the ferrous and manganous silicates which exist so abundantly in rocks, are attacked by rain-water containing carbonic acid, with the formation of carbonates of these bases and the liberation of silica. The felspars are thus decomposed. Their crystals lose their lustre and color, becoming dull and earthy on the outside, and the change advances inward until the whole substance is converted into a soft pulverulent clay. In this decomposition the whole of the alkali, together with about two-thirds of the silica, is removed, leaving a hydrous aluminous silicate or kaolin behind. But the rapidity and completeness of the process vary greatly, especially in proportion to the abundance of carbonic acid. Where it advances with sufficient slowness, most of the silica, after the abstraction of the alkali, may be left behind. In the case of magnesian minerals (augite, hornblende, olivine, etc.) the silicates of magnesia and alumina, being less soluble, may remain as a dark brown or yellow clay, colored by the oxidation of the iron, while the lime and alkalies are removed.[54] Evidence of the progress of these changes may be obtained even for some distance from the surface in many massive rocks. Diabase, basalt, diorite, and other crystalline rocks, which may appear to be quite fresh, will often reveal, by the effervescence produced when acid is dropped on their newly broken and seemingly undecomposed surfaces, that their silicates have been attacked by meteoric water and have been partially converted into carbonates.

5. *Hydration.*—Some anhydrous minerals, when exposed to the action of the atmosphere, absorb water (become hy-

[54] Roth, op. cit. i. p. 112.

drous), and may then be more prone to further change. Anhydrite becomes, by addition of water, gypsum, the change being accompanied by an increase of bulk to the extent of about 33 per cent. Local uplifts of the ground and crumpling or fracture of rocks may sometimes be caused by the hydration of subterranean beds of anhydrite (p. 506). Many substances on oxidizing likewise become hydrous. The oxidation of ferrous oxide in damp air gives rise to hydrous ferric oxide, with its characteristic yellow and brown colors on weathered surfaces.

Weathering.—This term expresses the general result of all kinds of meteoric action upon the superficial parts of rocks. As these changes almost invariably lead to disintegration of the surface, the word weathering has come to be naturally associated in the mind with a loosened crumbling condition of stone. But the influence of the atmospheric agents is not invariably to destroy the coherence of the integral particles of rocks. In some cases, stones harden on exposure. Certain sandy rocks, for example, like the "gray-weathers" and scattered Tertiary blocks in the Ardennes, become under meteoric influence a kind of lustrous quartzite. In other cases, there may be more complex molecular rearrangements, such as those remarkable transformations to which Brewster first called attention in the case of artificial glass.[55] He showed that in thin films of decomposed glass, obtained from Nineveh and other ancient sites, concentric agate-like rings of devitrification are formed round isolated points, closely analogous to those above described as artificially produced by the action of heated alkaline waters (p. 526), and that groups of crystals or crystal-

[55] Trans. Roy. Soc. Edin. xxii. 607; xxiii. 193. See ante, p. 527.

lites, "probably of silex," are developed from many independent points in the decomposing layer. Colored films indicative of incipient decomposition have been observed on surfaces of glass exposed only to the air of the atmosphere for twenty or thirty years. Brilliantly iridescent films have been produced on the glass of windows exposed for not more than twenty years to the air and ammoniacal vapors of a stable.[56] That similar transformations take place in the natural silicates of rocks seems in the highest degree probable. They may form the earliest stages of the change to the usual opaque earthy decomposing crust, in which, of course, all trace of any structure developed in the preliminary weathering is lost.[57]

In humid and temperate climates, weathering is mainly due to the combined influence of rain and sunshine. Saturated with rain-water, which dissolves more or less of any soluble constituents that may be present, and thereafter exposed to the desiccating and expanding influence of the warm rays of the sun, rock-surfaces are disintegrated, breaking up into angular fragments or crumbling into dust.[58] In high mountainous situations, as well as in lower regions where the temperature falls below the freezing-point in winter, weathering is in large measure caused by the action of frost (p. 698); in arid lands subject to great and rapid alternations of temperature, it may be mainly due to the strain of alternate expansion and contraction (p. 559) and the mechan-

[56] This fact has been observed by my friend M. P. Dudgeon, of Cargen, in an ill-ventilated cow-house, and I have seen the plates of glass removed from the windows. The process of decay in glass has been treated of in great detail by Mr. James Fowler, Trans. Soc. Antiquaries, xlvi. (1879), pp. 65–162.

[57] Reference may be made here to the liquid inclusions already alluded to as developed in felspar during the decomposition of gneiss, ante, p. 200.

[58] This action can be instructively imitated by boiling and drying shales in the manner described in Book V. Sect. vii.

ical action of the wind (p. 561 *et seq.*). As the name denotes, weathering is dependent on meteorological conditions, and varies, even in the same rock, as these conditions change, but is likewise almost infinitely diversified according to the structure, texture, and composition of rocks.

Mere hardness or softness forms no sure index to the comparative power of a rock to resist weathering. Many granites, for instance, weather to clay, deep into their mass, while much softer limestones retain smooth, hard surfaces. Nor is the depth of the weathered surface any better guide to the relative rapidity of waste. A tolerably pure limestone may weather with little or no crust, and yet may be continually losing an appreciable portion of its surface by solution, while an igneous rock, like a diorite or basalt, may be incased in a thick decomposed crust and weather with extreme slowness. In the former case, the substance of the rock being removed in solution, few or no insoluble portions are left to mark the progress of decay, while in the igneous rock, the removal of but a comparatively small proportion causes disintegration, and the remaining insoluble parts are found as a crumbling crust. Impure limestone, however, yields a weathered crust of more or less insoluble particles. Hence, as we have already seen (p. 148), the relative purity of limestones may be roughly determined from their weathered surfaces, where, if they contain much sand, the grains will be seen projecting from the calcareous matrix; should they be very ferruginous, the yellow hydrous peroxide, or ochre, will be found as a powdery crust; or if they be fossiliferous, they will commonly present the fossils standing out in relief. An experienced fossil-collector will always carefully search weathered surfaces of limestone, for he often finds there, delicately picked out by the weather, minute and frail fossils, which are wholly invisible on the freshly broken stone. This difference arises from the crystalline calcite of the organic remains being less soluble than the more granular calcite in which these are imbedded. Limestones frequently assume a remarkable channelled rugose surface, with projecting knobs, ridges, and pinnacles especially developed in high bare tracts of ground (Karrenfelder).[59]

Rocks liable to little chemical change are best fitted to resist weathering, provided their particles have sufficient

Fig. 92.—Weathered sandstone cliffs showing irregular honeycombing and weathering along planes of stratification (*B.*).

cohesion to withstand the mechanical processes of disintegration.[60] Siliceous sandstones offer excellent examples of this permanence. Consisting mainly of the durable mineral quartz, they are sometimes able so to withstand decay that buildings made of them still retain, after the lapse of centuries, the chisel-marks of the builders. Many sand-

[59] Heim, Jahrb. Schweiz. Alpenclubs, xiii. (1878).

[60] On weathering of building-stones, see Proc. Roy. Soc. Edin. 1879–80, p. 518. Julien, Trans. New York Acad. Sci. Jan. 1883. W. Wallace, Proc. Phil. Soc. Glas. xiv. (1882–83), p. 22.

stones, however, contain argillaceous, calcareous, or ferruginous concretions which weather more rapidly than the surrounding rock, and cause it to assume a honeycombed surface; others are full of a diffused cement (clay, lime, iron) the decay of which makes the rock crumble down into sand. In sandstones, as indeed in most stratified rocks, there is a tendency toward more rapid weathering along the planes of stratification, so that the stratified structure is brought out very clearly on natural cliffs (Fig. 92). In many ferruginous sandstones and clay ironstones, successive yellow or brown zones or shells may be traced inward from the surface, frequently due to changes of the ferrous carbonate into limonite, the interior remaining still fresh. In many prismatic massive rocks (basalt, diorite, etc.) segments of the prisms weather into spheroids, in which successive weathered rings form crusts like the concentric coats of an onion (Figs. 93, 94). Where one of these rocks has been intruded as a dike, it sometimes decomposes to a considerable depth into a mass of brown ferruginous balls in a surrounding sandy matrix—the whole having at first a resemblance to a conglomerate made of rolled and transported fragments (Fig. 95).

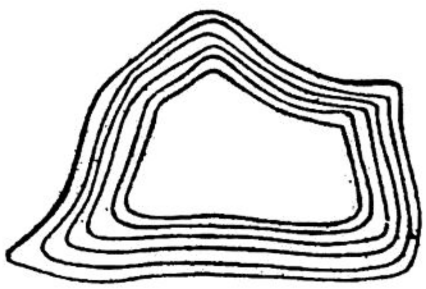


Fig. 93.—Rings of Weathering.

No rock presents greater variety of weathering than granite. Some remarkably durable kinds only yield slowly at the edges of the joints, the separated masses gradually assuming the form of rounded blocks like water-worn bowlders. Other kinds decompose to a depth of 50 feet or more, and can be dug out with a spade. In Cornwall and Devon, the kaolin from the rotted granite, largely extracted for pottery purposes, is found down to a depth of occasionally 600 feet. That what appears to be mere loose sand and clay is really rock decomposed *in situ*, is proved by the quartz-veins and bands of schorl-rock which ascend from the solid rock (*a*, Fig. 96) into the friable part (*b*), and by the entire agreement in structure between the two portions. Here and

Fig. 94.—Spheroidal Weathering of Dolerite, North Queensferry.

there, kernels of still undecomposed granite may be seen (as at *c c* in Fig. 97), surrounded by thoroughly decayed material, and, like the solid cores of basalt above mentioned, presenting a deceptive resemblance to accumulations of transported materials. There can be no doubt that the granite bowlders, so abundantly transported by the ice-sheets and glaciers of the Ice Age, originated in great measure in this way. Owing to its numerous joints, granite occasionally weathers into forms that resemble ruined walls. Large slabs, each defined by joint planes, weather out one above another like tiers of masonry (Fig. 98), until, loosened by disintegration, they slip off and expose lower parts of the rock to the same influences. Here and there, a separate block becomes so poised that it may be readily moved to and fro by the hand, as in the so-called "rocking-stones" of granite districts. As the disintegration varies with local differences in durability, some portions weather into cavities, others into

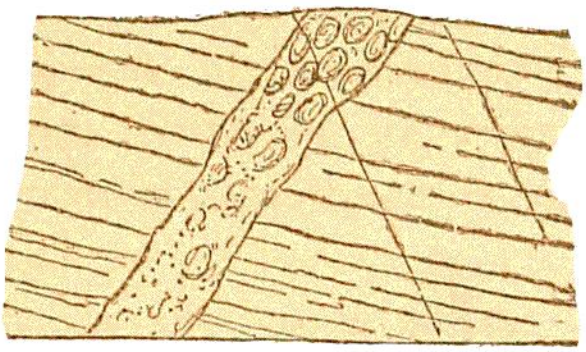


Fig. 95.—Felsite Dike weathering into spheroids, Cornwall (*B*.).

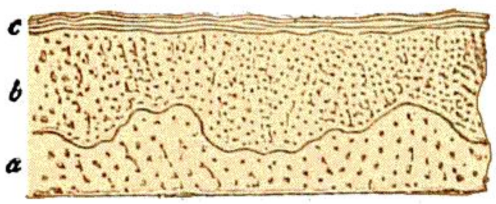


Fig. 96.—Decomposition of Granite. *a*, Solid granite; *b*, decomposed granite; *c*, vegetable soil.

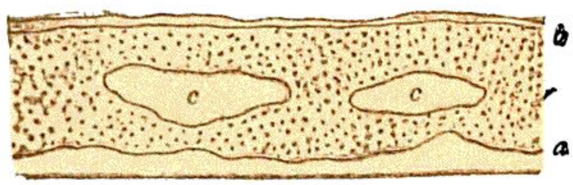


Fig. 97.—Decomposition of Granite. *a*, Solid granite; *b*, decomposed granite; *c*, *c*, kernels of still undecomposed granite.

prominences, often with a singularly artificial appearance, as in the "rock basins" (Fig. 99) and "tors" (Fig. 98) of the southwest of England. The ruin-like weathering of dolomite gives rise in the Cevennes to some singularly picturesque scenery.

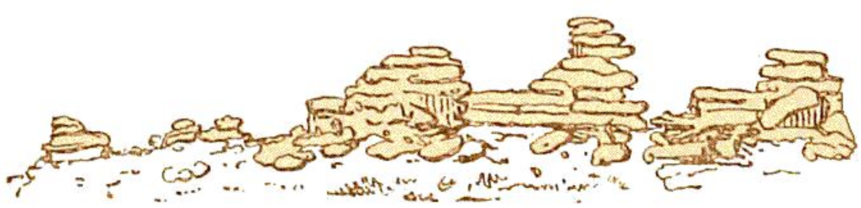


Fig. 98.—Weathering of Granite along its joints (*B*.).

To the influence of weathering, many of the most familiar minor contours of the land may be traced. So characteristic are these forms for particular kinds of rock, that they serve as a means of recognizing them even from a distance. (Book VII.)

In countries which have not been under water for a vast lapse of time, and where consequently the superficial rocks have been continuously exposed to subaerial disintegration, thick accumulations of "rotted rock" are found on the surface. The extent of this change is sometimes impressively marked in areas of calcareous rocks. Limestone being

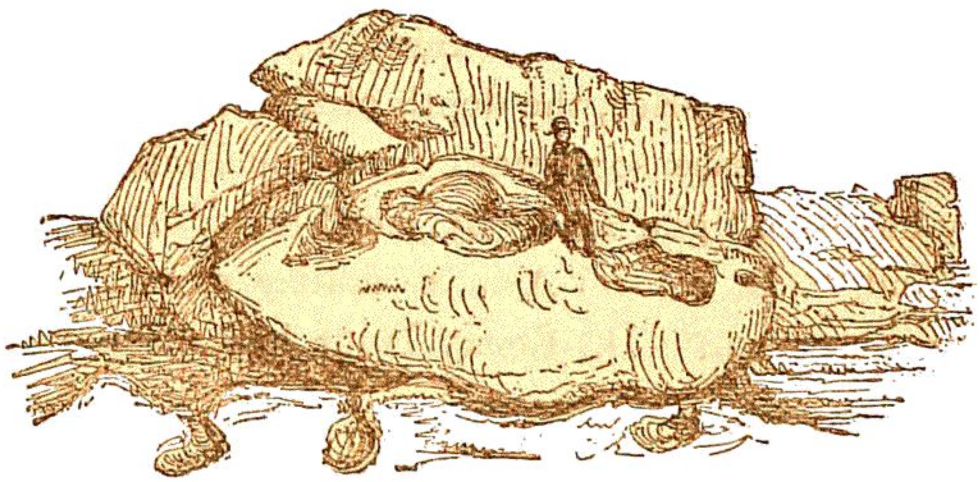


Fig. 99.—The "Kettle and Pans," St. Mary, Scilly: cavities weathered out of Granite (*B.*).

mostly soluble, its surface is continually dissolved by rain, while the insoluble portions remain behind as a slowly increasing deposit. In regions which, possessing the necessary conditions of climate, have been for a long period unsubmerged, tracts of limestone, unprotected by glacial or other accumulations, are found to be covered with a red loam or earth. This characteristic layer occurs on a limited scale over the chalk of the southeast of England, where, with its abundant flints, it lies as the undissolved ferruginous residue of the chalk that has been removed to a depth of many yards. It occurs likewise in swallow-holes and other passages dissolved out of calcareous masses, and forms the well-known red earth of bone caves. In southeastern Europe it plays an important part among superficial deposits, being extensively developed over the limestone districts, especially in Istria and Dalmatia, where it is known as the ferruginous red earth or *terra rossa.*[61]

Other remarkable examples of similar subaerial waste have been specially noticed among crystalline schists and eruptive rocks. In Brazil, it has been remarked with astonishment that the crystalline rocks are sometimes decayed to a depth of more than 300 feet.[62] In Massachusetts, Pennsylvania, and generally in the middle and southern Atlantic States of North America, the depth of disintegration appears gradually to increase southward from the limits where the country has been "glaciated" by ice-sheets during the Glacial Period.[63] In central Asia, a similar superficial decay has been observed.[64] Dr. Sterry Hunt has specially drawn

---

[61] On the origin of "Terra Rossa," see M. Neumayr, Verhandl. Geol. Reichsanst. 1875, p. 50; Th. Fuchs, op. cit. p. 194; E. von Mojsisovics, Jahrb. Geol. Reichsanst. xxx. (1880), p. 210; E. Tietze, op. cit. xxx. (1880), p. 729; Lorenz, Verh. Geol. Reichs. 1881, p. 81; C. de Georgi, Boll. Com. Geol. Ital. vii. p. 294. It is included among the ferruginous deposits by Stoppani ("Corso di Geologia," iii. p. 534). Neumayr shows that it is of various ages; in the Karst it incloses Miocene mammals.

[62] Liais, "Geologie du Bresil," p. 2. Ann. des Mines, 7me ser. viii. p. 698. T. Belt, "Naturalist in Nicaragua" (1874), p. 86. T. Sterry Hunt, Amer. Journ. Sci. 3d ser. vii. p. 60; xxvi. (1883), p. 196; Geol. Mag. 1883, p. 310; American Naturalist, ix. (1875), p. 471. This writer dwells especially on the great geological antiquity of the weathered crust. On the secular rock-weathering of the Swedish mountains see Nathorst, Geol. Fören. Stockholm. Förhand. 1879, iv. No. 13.

[63] I. C. Russell, Bull. U. S. Geol. Survey, No. 52 (1889), p. 12 *et seq.* There is a useful bibliography of papers on the subaerial decay of rocks appended to this essay. See also W. O. Crosby, Proc. Nat. Hist. Soc. Boston, xxiii. p. 219.

[64] On a smaller scale it is also to be noted in the granite and killas (phyllite) of Cornwall and Devon, which, not having suffered from the abrading action of the ice of the Glacial Period, show a deep cover of rotted rock, and afford some indication of what may have been elsewhere the condition of Britain before the period of glaciation. The sea-cliffs along the north coast of Cornwall expose instructive sections of the deep upper decomposed, and of the lower blue solid killas, with the remarkably uneven boundary along which they pass into each other.

attention to the geological importance of this prolonged disintegration *in situ*. Mr. Pumpelly points out that, as masses of decomposed rock may be observed to a depth of over 100 feet, the surface of the still solid rock underneath presents ridges and hollows, succeeding each other according to varying durability under the influence of percolating carbonated water. In this kind of weathering, where erosion does not come into play, it is evident that the resulting topography must, in some important respects, differ from that of an ordinary surface of superficial denudation. In particular, rock-basins may be gradually eaten out of the solid rock. These will remain full of the decomposed material, but any subsequent action, such as that of glacier-ice, which could scoop out the detritus, would leave the basins and their intervening ridges exposed.[65]

Formation of Soil.—On level surfaces of rock the weathered crust may remain with comparatively little re-arrangement until plants take root on it, and by their decay supply organic matter to the decomposed layer, which eventually becomes what we term "vegetable soil." Animals also furnish a smaller proportion of organic ingredients. Though the character of soil depends primarily on the nature of the rock out of which it has been formed, its fertility largely depends on the commingling of decayed animal and vegetable matter with decomposed rock.

A gradation may be traced from the soil downward into what is termed the "subsoil," and thence into the solid rock underneath (Fig. 100). Between soil and subsoil a marked difference in color is often observable, the former being yellow or brown, when the latter is blue, gray, red, or

[65] Pumpelly, Amer. Journ. Sci. 3d ser. xviii. 136; L. S. Burbank, Proc. Bost. Nat. Hist. Soc. xvi. (1874), part 2, p. 150.

other color of the rock beneath.[66] This contrast, evidently due to oxidation and hydration, especially of the iron, extends downward as far as the subsoil is opened up by rootlets and fibres to the ready descent of rain-water. The yellowing of the subsoil may even occasionally be noticed around some stray rootlet which has struck down further than the rest, below the general lower limit of the soil (postea, p. 793).

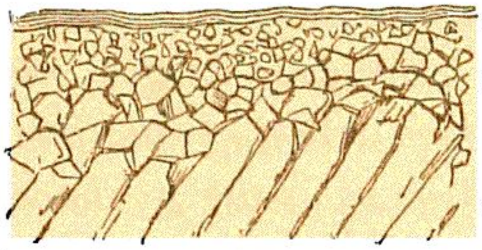


Fig. 100.—Section showing the upward passage of Rock (*a*) into Subsoil (*b*), and thence into Vegetable Soil (*c*).

Mr. Darwin observed many years ago that a layer of soil, three inches in depth, had grown above a layer of burnt marl spread over the land fifteen years previously; also that in another example, a similar layer had, as it were, sunk beneath the soil, to a depth of twelve or thirteen inches in eighty years. He connected these facts with the work of the common earth-worm, and concluded that the fine loam which had grown above these original superficial layers had been carried up to the surface, and had been voided there in the familiar form of worm-castings.[67] This action of the earth-worm is doubtless highly important, but, as Richthofen has pointed out, we have to take also into account the gradual augmentation of level due to the daily deposit of dust (ante, p. 564, and postea, p. 794).

Soil being composed mainly of inorganic, and to a slight extent of organic materials, the proportion between these two elements is a question of high economic impor-

---

[66] Deceptive appearances of a break between the soil or subsoil and what lies beneath are sometimes produced by this means. See W. Whitaker, Q. J. Geol. Soc. xxxiii. p. 122. E. Van den Broeck, Mem. Couronn. Acad. Brussels, 1881.

[67] Geol. Trans. v. 1840, p. 505; and his more recent researches in his volume on "Vegetable Mould." See also C. Reid, Geol. Mag. 1884, p. 165.

tance. With regard to the organic matter, it is the experience of practical agriculturists in Britain that oats and rye will grow upon a soil with $1\frac{1}{2}$ per cent of organic matter, but that wheat requires from 4 to 8 per cent.[68] To a geologist, this organic matter has much interest, as the source of most of the carbonic acid with which so wide a series of changes is worked by subterranean water. The inorganic portion of soil, or still undissolved residue of the original surface-rock, varies from a loose open substance with 90 per cent or more of sand, to a stiff, cold, retentive material with more than 90 per cent of clay. When this sand and clay are more equally mixed they form a "loam."[69]

Reference has just been made to the thick accumulation of rock decomposed *in situ* observable in certain regions which, having been above the sea for a lengthened period, have been long exposed to the action of weathering. Where this action has been supplemented by that of rain, widespread formations of loam and earth have been gathered together. These are well illustrated by the "brick-earth," "head," and "rain-wash" of the south of England—earthy deposits, with angular stones, derived from the subaerial waste of the rocks of the neighborhood.[70]

2. **Mechanical Action.**—Besides chemically corroding

---

[68] Johnston's "Elements of Agricultural Chemistry," p. 80.

[69] For measurements of the permeability of soils, see Hondaille and Semichow, Compt. Rend. cxv. (1892), p. 1015.

[70] Godwin-Austen, Q. J. Geol. Soc. vi. p. 94, vii. p. 121; Foster and Topley, op. cit. xxi. p. 446. The vast extent of some superficial formations, like the "loess" above referred to (p. 566), has often suggested submergence below the sea. But when, instead of marine organisms, only terrestrial, fluviatile, or lacustrine remains occur in them, as in the brick earths and loess, the idea of marine submergence cannot be entertained. The remarkable "tundras" or steppes of Siberia, and the "black earth" of Russia, are examples of such extensive formations, which are certainly not of marine origin, but point to long-continued emergence above the sea. See Murchison, Keyserling and De Verneuil's "Geology of Russia." Belt, Q. J. Geol. Soc. xxx. p. 490.

rocks and thereby loosening the cohesion of their particles, rain acts mechanically by washing off these particles, which are held in suspension in the little rain-runnels or are pushed by them along the surface. The amount and rapidity of this action do not depend merely on the annual quantity of rain. A comparatively large rainfall may be so equably distributed through a year or season as to produce less change than may be caused by a few heavy rainstorms which, though inferior in total amount of precipitated moisture, descend rapidly in great volume. Such copious rains, by deluging the surface of a country and rapidly flooding its water-courses, may transport in a few hours an enormous amount of sand and mud to lower levels. Another feature to be kept in view is the angle of declivity: the same amount of rain will perform vastly more mechanical work if it can swiftly descend a steep slope, than if it has to move tardily over a gentle one.

Removal and Renewal of Soil.—Elie de Beaumont drew attention to what appeared to be proofs of the permanence or long duration of the layer of vegetable soil.[71] But the cases cited by him are not inconsistent with a belief that the doctrine of the persistence of the soil is true rather of the layer as a whole, than of its individual particles.[72] Were there no provision for its renewal, soil would comparatively soon be exhausted, and would cease to support the same vegetation. This result, indeed, occurs partially, especially on flat lands, but would be far more widespread were it not that rain, gradually washing off the upper part of the soil, exposes what lies beneath to further disintegration. This removal takes place even on grass-covered sur-

---

71 "Leçons de Geologie pratique," i. p. 140.
72 Geikie, Trans. Geol. Soc. Glasgow, iii. p. 170.

faces, through the agency of earth-worms, by which fine particles of loam are brought up and exposed to the air, to be dried and blown away by wind, or washed down by rain. The lower limit of the layer of soil is thus made to travel downward into the subsoil, which in turn advances into the underlying rock. As Hutton long ago insisted, the superficial covering of soil is constantly, though slowly, travelling to the sea.[73] In this ceaseless transport, rain acts as the great carrying agent. The particles of rock and of soil are, step by step, moved downward over the face of the land, till they reach the nearest brook or river, whence their seaward progress may be rapid. A heavy rain discolors the water-courses of a country, because it loads them with the fine débris which it removes from the general surface of the land. In this way, rain serves as the means whereby the work of other disintegrating forces is made conducive to the general degradation of the land. The decomposed crust produced by weathering, which would otherwise accumulate over the solid rock, and in some measure protect it from decay, is removed by rain, and a fresh surface is thereby laid bare to further decomposition.

Movement of Soil-cap.—In some countries, where the ground is covered with a thick spongy mass of vegetation exposed to considerable variation of temperature and moisture, appearances have been observed of an extensive slipping of the layer of soil to lower levels, bearing with it whatever may be growing or lying upon it. Such are the so-called "stone-rivers" of the Falkland Islands, and the superficial débris of certain parts of the west coast of Patagonia.[74] In Western Europe, slight indications of a

[73] "Theory of the Earth," Part II. chaps. v. vi.

[74] Wyville Thomson's "Atlantic," vol. ii. p. 245. R. W. Coppinger, Q. J. Geol. Soc. 1881, p. 348. See postea, under "Landslips," p. 628.

similar movement may often be noticed on the sides of hills or valleys.

Unequal Erosive Action of Rain.—While the result of rain action is the general lowering of the level of the land, this process necessarily advances very unequally in different places. On flat ground, the waste may be quite inappreciable, except after long intervals and

Fig. 101.—Rain-eroded pillars of Old Red Conglomerate, Fochabers.

by the most accurate measurements, or it may even give place to deposition, the fine detritus washed off the slopes being spread out, so as actually to heighten the alluvial surface. In numerous localities, great variations in the rate of erosion by rain may be observed. Thus, from the pitted, channelled ground lying immediately under the drip of the eaves of a house, fragments of stone and gravel stand up prominently, because the earth around and above them has been washed away by the falling drops, and because, being hard, they resist the erosive action and screen the earth below them. On a larger scale the same kind of operation may be noticed in districts of conglomerate, where the larger blocks, serving as a protection to the rock underneath, come to form, as it were, the capitals of slowly deepening columns of rock (Fig. 101). In certain valleys of the Alps a stony clay is cut by the rain into pillars,

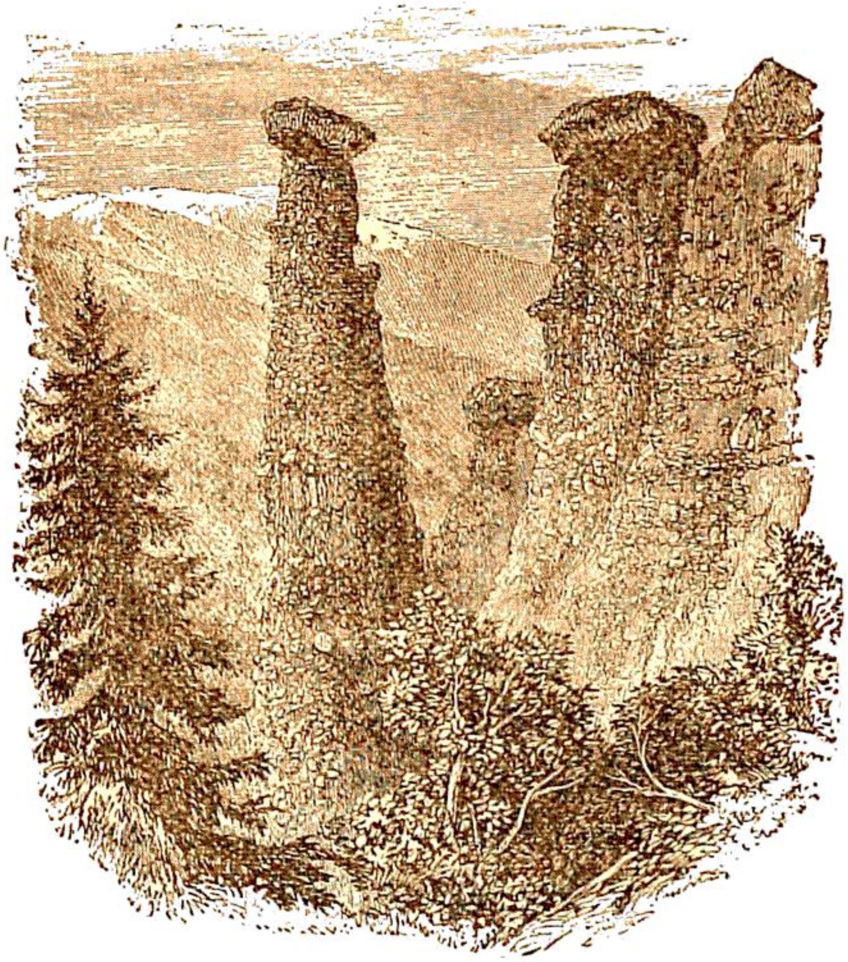


Fig. 102.—Earth-pillars left by the weathering of moraine-stuff, Tyrol.

each of which is protected by, and indeed owes its existence to, a large block of stone which lay originally in the heart of the mass (Fig. 102). These columns, or "earth-pillars," are of all heights, according to the original positions of the stones. More colossal examples have been described by Hayden from the conglomerates of Colorado.

There are instances, however, where the disintegration has been so complete that only a few scattered fragments remain of a once extensive stratum, and where it may not be easy to realize that these fragments are not transported bowlders. In Dorsetshire and Wiltshire, for example, the surface of the country is in some parts so thickly strewn with fragments of sandstone and conglomerate "that a person may almost leap from one stone to another without touching the ground. The stones are frequently of considerable size, many being four or five yards across, and about four feet thick."[75] They are found lying abundantly on the Chalk, suggestive at first of some former agent of transport by which they were brought from a distance. They are now, however, generally admitted to be simply fragments of some of the sandy Tertiary strata which once covered the districts where they occur. While the softer portions of these strata have been carried away, the harder parts (their hardness perhaps increasing by exposure) have remained behind as "Gray Wethers," and have subsequently suffered from the inevitable splitting and crumbling action of the weather. Similar blocks of quartzite and conglomerate, referable to the disintegration of Lower Tertiary beds *in situ*, are traceable in the northeast of France up into the Ardennes, showing that the Tertiary deposits of the Paris basin once had a much wider extension than they now possess.[76] On a far grander scale, the apparent caprice of general subaerial dis-

---

[75] They have been used for the huge blocks of which Stonehenge and other of the so-called Druidical circles have been constructed, hence they have been termed Druid Stones. Other names are Sarsen Stones (supposed to indicate that their accumulation has been popularly ascribed to the Saracens), and Gray Wethers, from their resemblance in the distance to flocks of (wether) sheep. See "Descriptive Catalogue of Rock Specimens in Jermyn Street Museum," 3d ed.; Prestwich, Q. J. Geol. Soc. x. p. 123; Whitaker, Geological Survey Memoir on parts of Middlesex, etc., p. 71.

[76] Barrois, Ann. Soc. Geol. du Nord, vi. p. 366.

integration is exhibited among the "buttes" and "bad lands" of Wyoming and the neighboring territories of North America. Colossal pyramids, barred horizontally by level lines of stratification, rise up one after another far out into the plains, which were once covered by a continuous sheet of the formations whereof these detached outliers are only fragments.

As a consequence of this inequality in the rate of waste, depending on so many conditions, notably upon declivity, amount and heaviness of rain, lithological texture and composition, and geological structure, great varieties of contour are worked out upon the land. A survey of this department of geological activity shows, indeed, that the unequal wasting by rain has in large measure produced the details of relief on the present surface of the continents, those tracts where the destruction has been greatest forming hollows and valleys, others, where it has been less, rising into ridges and hills. Even the minuter features of crag and pinnacle may be referred to a similar origin. (Book VII.)

§ 2. Underground Water

A great part of the rain that falls on land, sinks into the ground and apparently disappears; the rest, flowing off into runnels, brooks, and rivers, moves downward to the sea. It is most convenient to follow first the course of the subterranean water.

All rocks being more or less porous, and traversed by abundant joints and cracks (p. 521), it results that from the bed of the ocean, from the bottoms of lakes and rivers, as well as from the general surface of the land, water is continually filtering downward into the rocks beneath. To what depth this descent of surface-water may go is not known. As stated in a former section, it may reach as far as the intensely heated interior of the planet, for, as the already quoted researches of Daubrée have shown, capillary water can penetrate rocks even against a high counter-pressure of vapor (ante, p. 520). Probably the depth to which the water descends varies indefinitely according to the varying nature of the rocky crust. Some shallow mines are practically quite dry, others of great depth require large pumping engines to keep them from being flooded by the water that pours into them from the surrounding rocks. Yet, as a rule, the upper layers of rock in the earth's crust are fuller of moisture than those deeper down.

Underground Circulation and Ascent of Springs.—The water which sinks below ground is not permanently removed from the surface, though there must be a slight loss due to absorption and chemical alteration of

Fig. 103.—Simple or Surface Springs.

rocks. Finding its way through joints, fissures, or other divisional planes, it issues once more at the surface in springs. This may happen either by continuous descent to the point of outflow, or by hydrostatic pressure. In the former case, rain-water, sinking underneath, flows along a subterranean channel until, when that channel is cut by a valley or other depression of the ground, the water emerges again to daylight. Thus, in a district having a simple geological structure (as in Fig. 103), a sandy porous stratum (*d*), through which water readily finds its way, may rest on a less easily permeable clay (*e*), followed underneath by a second sandy pervious bed (*c*), resting as before upon comparatively impervious"[77] strata (*a*). Rain falling upon the upper sandy stratum (*d*), will sink through it to the surface of the clay (*e*), along which it will flow until it issues either as springs, or in a general line of wetness along the side of the valley (*b*). The second sandy bed (*c*) will serve as a reservoir of subterranean water so long as it remains below the surface, but any valley cutting down below its base will drain it.

Except, however, in districts of gently inclined and unbroken strata, springs are more usually of the second class, where the water has descended to a greater or less distance, and has risen again to the surface in fissures, as in so many siphons. Lines of joint and fault afford ready channels for subterranean drainage (Fig. 104). Powerful faults which

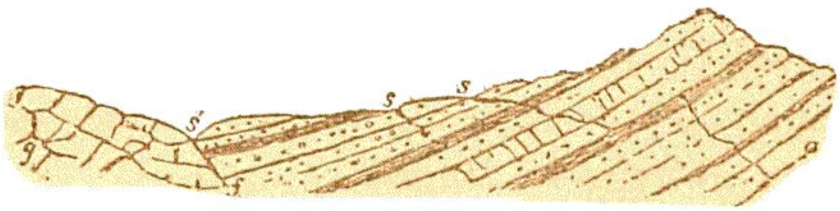


Fig. 104.—Deep-seated Springs (*s*, *s'*) rising through joints and a fault (*f*).

bring different kinds of rock against each other (as *a* and *g* are by the fault *f* in Fig. 104) are frequently marked at the surface by copious springs. So complex is the network of divisional planes by which rocks are traversed, that water may often follow a most labyrinthine course before it completes its underground circulation (Fig. 105). In countries with a sufficient rainfall, rocks are saturated with water below a certain limit termed the *water-level*. Owing to varying structure, and relative capacity for water among rocks,

[77] This term *impervious* must evidently be used in a relative and not in an absolute sense. A stiff clay is practically impervious to the trickle of underground water; hence its employment as a material for puddling (that is, making watertight) canals and reservoirs. But it contains abundant interstitial water, on which, indeed, its characteristic plasticity depends.

this line is not strictly horizontal, like that of the surface of a lake. Moreover, it is liable to rise and fall according as the seasons are wet or dry. In some places it lies quite near, in others far below, the surface. A well is an artificial hole dug down below the water-level, so that the water may

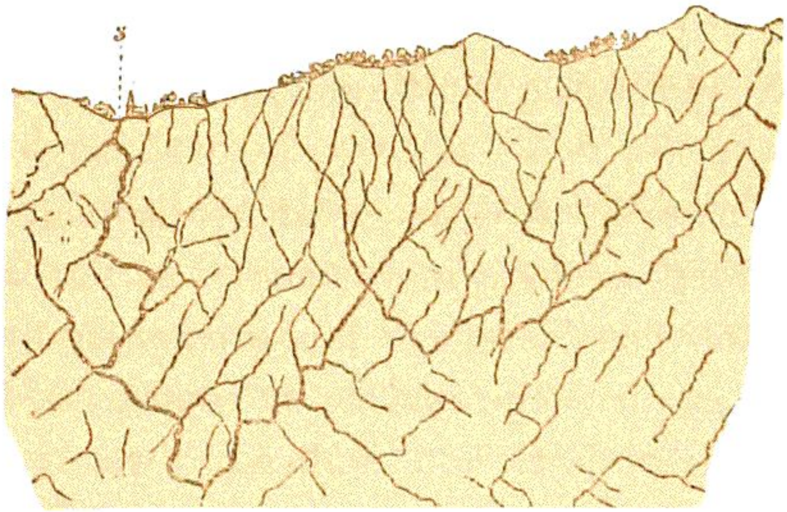


Fig. 105.—Intricate subterranean course of percolating water.

percolate into it. Hence, when the water-level happens to be at a small depth, wells are shallow; when at a greater depth, they require to be deeper.

Since rocks vary greatly in porosity, some contain far more water than others. It often happens that, percolating along some porous bed, subterranean water finds its way

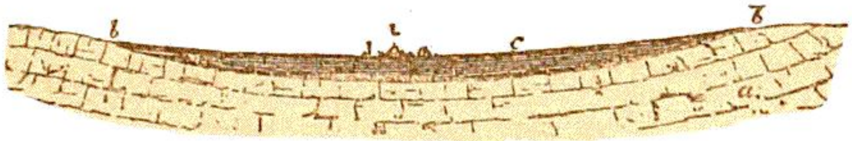


Fig. 106.—Diagram illustrative of the theory of Artesian Wells.
a, *b*, Lower water-bearing rocks, covered by an impervious series (*c*), through which, at L, and elsewhere, borings are made to the water-level beneath.

downward until it passes under some more impervious rock. Hindered in its progress, it accumulates in the porous bed, from which it may be able to find its way up to the surface again only by a tedious circuitous passage. If, however, a bore-hole be sunk through the upper impervious bed down to the water-charged stratum below, the water will avail itself of this artificial channel of escape, and will rise in the hole, or even gush out as a *jet d'eau* above ground. Wells of this kind are now largely employed. They bear the name of *Artesian*, from the old province of Artois in France, where they have long been in use[78] (Fig. 106).

That the water really circulates underground, and passes not merely through the pores of the rocks, but in crevices and tunnels, which it has no doubt to a large extent opened for itself along natural joints and fissures, is proved by the occasional rise of leaves, twigs and even live fish, in the shaft of an artesian well. Such testimony is particularly striking when found in districts without surface-waters, and even perhaps with little or no rain. It has been met with, for instance, in sinking wells in some of the sandy deserts on the southern borders of Algeria.[79] In these and similar cases, it is clear that the water may, and sometimes does, travel for many leagues underground, away from the district where it fell as rain or snow, or where it leaked from the bed of a river or lake.

The temperature of springs affords a convenient, but not always quite reliable, indication of the relative depth from which they have risen. Some springs are just one degree or less above the temperature of ice (C. 0°, Fahr. 32°). Others, in volcanic districts, issue with the temperature of boiling water (C. 100°, Fahr. 212°). Between these two extremes every degree may be registered. Very

---

[78] See Prestwich Q. J. Geol. Soc. xxviii. p. lvii., and the references there given. One of the best recent essays on the subject of Artesian Wells is that by Prof. T. C. Chamberlin in the 5th Annual Report of the U. S. Geol. Survey (1883–84), p. 131.

[79] Desor, Bull. Soc. Sci. Nat. Neufchâtel, 1864. On the hydrology of the Sahara consult G. Rolland, Assoc. Française, 1880, p. 547. Tchihatchef, Brit. Assoc. 1882, p. 356. Choisy, "Documents relatifs à la Mission dirigee au Sud de l'Algerie." Paris, 1890.

cold springs may be regarded as probably deriving their supply from cold or snow-covered mountains. Certain exceptional cases, however, occur, where, owing to the subsidence of the cold winter air into caverns (*glacières*), ice is formed which is not wholly melted even though the summer temperature of the caves may be above freezing-point. Water issuing from these ice-caves is of course cold.[80] On the other hand, springs whose temperature is higher than the mean temperature of the places at which they emerge must have been warmed by the internal heat of the earth. These are termed *Thermal Springs*.[81] The hottest springs are found in volcanic districts (see p. 402). But even at a great distance from any active volcano, springs rise with a temperature of 120° Fahr. (which is that of the Bath springs) or even more. These have probably ascended from a great depth. If we could assume a progressive increase of 1° Fahr. of subterranean heat for every 60 feet of descent, the water at 120°, issuing at a locality whose ordinary temperature is 50°, should have been down at least 4200 feet below the surface. But from what has been already stated (p. 95) regarding the irregular stratification of temperature within the earth's crust, such estimates of the probable depth of the sources of springs are not quite reliable. The source

---

80 A remarkable example of a glacière is that of Dobschau, in Hungary, of which an account, with a series of interesting drawings, was published in 1874 by Dr. J. A. Krenner, keeper of the national museum in Buda-Pesth. See also Murchison, Keyserling and De Verneuil, "Geology of Russia." Thury, Biblioth. Univ. Geneva, 1861. Browne, "Ice-Caves in France and Switzerland," 1865. Fifty-six of these caves are known in the Alps, some in the Jura, and many elsewhere.

81 Studer points out that some springs which are thermal in high latitudes or at great elevations would be termed cold springs near the equator, and, consequently, that springs having a lower temperature than that of the inter-tropical zone, that is from C. 0° to 30° (Fahr. 32°–84°), should be called "relative," those which surpass that limit (C. 30°–100°) "absolute," and he gives a series illustrative of each group: "Physikalische Geographie," ii. (1847), p. 49. For volcanic thermal springs see ante, p. 402, and postea, p. 617.

of heat in these cases may be some crushing of the crust or ascent of heated matter from underneath, which does not, however, produce volcanic phenomena.

1. **Chemical Action.**—Every spring, even the clearest and most sparkling, contains dissolved gases, also solid matter abstracted from the soils and rocks which it has traversed. The gases include those absorbed by rain from the atmosphere (p. 581), also carbon-dioxide supplied by decomposing organic matter in the soil, sulphuretted hydrogen, and marsh-gas or other hydrocarbon derived from decompositions within the crust. The solid constituents consist partly of organic, but chiefly of mineral matter. Where spring-water has been derived from an area covered with ordinary humus, organic matter is always present in it. Organic acids are abstracted from the soil by descending water, and these, before they are oxidized into carbonic acid, are effective in decomposing minerals and forming soluble salts (p. 584). The mineral matter of spring-water consists principally of carbonates of calcium, magnesium, and sodium, sulphates of calcium and sodium, and chloride of sodium, with minute traces of silica, phosphates, nitrates, etc. The nature and amount of mineral impregnation depend, on the one hand, upon the chemical energy of the water, and on the other, upon the composition of the rocks.

Various sources of augmentation of its chemical energy are available for subterranean water. (1) The abundant organic matter in the soil partially abstracts oxygen from the water, but supplies organic acids, especially carbonic acid. In so far as the water carries down from the soil any oxidizable organic substance, its action must be to reduce oxides (p. 584). Ordinary vegetable soil possesses the power of removing from permeating water potash, silica, phosphoric acid, ammonia, and organic matter, elements which had been already in great measure abstracted from it by living vegetation, and which are again ready to be taken up by the same organic agents. (2) Carbon-dioxide is here and there largely evolved within the earth's crust, especially in regions of extinct or dormant volcanoes. Subterranean water coming in the way of this gas dissolves it, and thereby obtains increased solvent power. (3) The capacity of water for dissolving mineral substances is augmented by increase of temperature (ante, p. 522). It is conceivable that cold springs, containing a large percentage of mineral solutions, may have acquired this impregnation at a great depth and at a higher temperature. As a rule, however, thermal water, as it cools, deposits its dissolved minerals on the walls of the fissures up which it ascends. Hence, no doubt, the successive layers in mineral veins. (4) Pressure likewise raises the solvent power of water (p. 521). (5) Some of the solutions, due to decompositions effected by the water, increase its ability to accomplish further decompositions (p. 527). Thus the alkaline carbonates, which are among the earliest products, enable it to dissolve silica and decompose silicates. These carbonates likewise promote the decomposition of some sulphates and chlorides. Calcium-carbonate, which is found in the water of most springs, is the result of decomposition, and by its presence leads to the further disintegration of various minerals. "Carbonic acid, bicarbonate of lime, and the alkaline carbonates bring about most of the decompositions and changes in the mineral kingdom. It is a matter of great importance to find that the same substances which give rise to so many decompositions in the mineral kingdom are the chief ingredients in the waters."[69]

[69] Bischof, "Chem. Geol." i. p. 17.

The nature of the changes effected by the percolation of water through subterranean rocks will be best understood from an examination of the composition of spring-water. Springs may be conveniently, though not very scientifically, grouped into two classes: 1st, common springs, such as are fit for ordinary domestic purposes, and, 2d, mineral springs, in which the proportions of dissolved mineral matter are so much higher as to remove the water from the usual potable kinds.

1. Common Springs possess a temperature not higher but frequently lower than that of the localities at which they rise, and ordinarily contain, besides atmospheric air and its gases, calcium-carbonate and sulphate, common salt, with chlorides of calcium and magnesium, and sometimes organic matter. The amount of dissolved mineral contents in ordinary drinking water does not exceed 0·5, or at most 1·0 gramme per litre; the best waters contain less. The amount of organic matter should not exceed from 0·005 to 0·01 gramme per litre in wholesome drinking water.[83] Spring-water containing a very minute percentage of mineral matter, or in which this matter, even if in more considerable quantity, consists chiefly of alkaline salts, dissolves common soap readily, and is known in domestic economy as "soft" water. Where, on the other hand, the salts in solution are calcic or magnesic carbonates, sulphates, or chlorides, they decompose soap, forming with its fatty acids insoluble compounds which appear in the familiar white curdy precipitate. Such water is termed "hard." Where the hardness is due to the presence of bicarbonates it disappears on boiling, owing to the loss of carbonic acid and the consequent precipitation of the insoluble carbonate, while in the case of sulphates and chlorides no such change takes place.

The extensive investigations carried on by the Rivers Pollution Commission in Britain have thrown much light on the relation between the amount of mineral matter in solution in springs and wells, and the character of the under-

[83] Dr. B. H. Paul in Watts' "Dict. Chem." v. p. 1022.

lying rock. The following table of analyses of waters from different kinds of rocks gives a summary of results obtained:

	No. of Analyses	Mean amount of Solid Contents in 10,000 Parts of Water
1. Fluviomarine, Drift and Gravel	10	6·132
2. Chalk	30	2·984
3. Hastings Sand and Greensands	19	3·005
4. Oolites	35	3·033
5. Lias	7	3·641
6. New Red Sandstone	15	2·869
7. Magnesian Limestone	1	6·652
8. Coal-Measures	14	2·430
9. Yoredale Beds and Millstone-Grit	8	1·773
10. Mountain Limestone	13	3·206
11. Devonian and Old Red Sandstone	32	2·506
12. Silurian	15	1·233
13. Granite and Gneiss	8	0·594

From this table it is evident how greatly the proportion of dissolved mineral substance augments in those waters which rise in calcareous tracts, and how it correspondingly sinks in those where the rocks are mainly siliceous. The maximum percentage in group No. 13 was less than 1 part in every 10,000 of water, the minimum being 0·140 from granite. In No. 1, on the contrary, the maximum was 22·524, in No. 6 it was 7·426, and in No. 10 it was 9·850.[84]

2. Mineral Springs are in some instances cold, in others warm, or even boiling. Thermal springs are more usually mineral waters than cold springs, but there does not appear to be any necessary relation between temperature and chemical composition. Mineral springs may be roughly classified for geological purposes according to the prevailing mineral substance contained in them, which may range in amount from 1 to 300 grammes per litre.[85]

Calcareous Springs contain calcium-carbonate in such quantity as to be deposited in the form of a white crust round objects over which the water flows. Calcium-carbonate, according to Fresenius, is dissolved by 10,600 of cold and by 8834 parts of warm water.[86] But in nature, the pro-

[84] Rivers Pollution Commission, 6th Report, 1874, pp. 107–131. See also Reports of Brit. Assoc. Committee on underground circulation of water, beginning in 1876, and R. Warington's Report on experiments at the Rothamsted Laboratory, Journ. Chem. Soc. 1887.

[85] Paul, Watts' "Dict. Chem." v. p. 1016.

[86] Roth, "Chem. Geol." i. p. 48. "One litre of water, either cold or boiling, dissolves about 18 milligrammes." Roscoe and Schorlemmer, "Chemistry," ii. p. 208.

portion of this carbonate present in springs depends mainly on the proportion of free carbonic acid, which retains the lime in solution. On the loss of carbonic acid by exposure and evaporation, the carbonate is thrown down as a white precipitate. This deposition is frequently brought about by the action of living plants. (Book III. Part II. Sect. iii. § 3.) Water saturated with carbonic acid will at the freezing-point dissolve 0·70 gramme and at 10° C. 0·88 gramme of calcium-carbonate per litre. Calcareous springs occur abundantly in limestone districts, and indeed may be looked for wherever the rocks are of a markedly calcareous character. In some regions, they have brought up such enormous quantities of lime as to form considerable hills (see, p. 622).

Ferruginous or Chalybeate Springs contain a large proportion of ferrous sulphate (iron-vitriol, copperas) in the total mineral ingredients, and are known by their inky taste, and the yellow, brown, or red ochry deposit along their channel. They may be frequently observed in districts where beds or veins of pyritous ironstone occur, or where the rocks contain much iron-disulphide in combination, particularly in the waters of old mines. By the weathering of this sulphide (marcasite), so abundantly contained among stratified rocks, ferrous sulphate is produced and brought to the surface, but in presence of carbonates, particularly of the ubiquitous carbonate of lime, is decomposed, the acid being taken up by the alkaline earth or alkali, and the iron becoming a ferrous carbonate, which rapidly oxidizes and falls as the familiar yellow or brown crust of hydrous peroxide. The rapidity with which ferrous-carbonate is thus oxidized and precipitated was well shown by Fresenius in the case of the Langenschwalbach chalybeate spring. In its fresh state the water contains in 1000 parts 0·37696 of protoxide of iron. After standing twenty-four hours it was found to contain only 87·7 per cent of the original amount of iron; after sixty hours 62·9 per cent, and after eighty-four hours 53·2 per cent.[87]

Brine-Springs (Soolquellen) bring to the surface a solution in which sodium chloride greatly predominates. Springs of this kind appear where beds of solid rock-salt exist underneath, or where the rocks are impregnated with that min-

---

[87] Journal für Prakt. Chem. lxiv. 368, quoted by Roth, op. cit. i. p. 565. The river in the Vale of Avoca, Ireland, formerly contained so much ferrous sulphate, carried into it by mine-waters, that its bed and banks for several miles down to the sea were covered with an ochreous deposit.

eral. Most of the brines worked as sources of salt are derived from artificial borings into saliferous rocks. Those of Cheshire in England, the Salzkammergut in Austria, Bex in Switzerland, etc., have long been well known. That of Clemenshall, Würtemberg, yields upward of 26 per cent of salts, of which almost the whole is chloride of sodium. The other substances contained in solution in the water of brine-springs are chlorides of potassium, magnesium, and calcium; sulphates of calcium, and less frequently of sodium, potassium, magnesium, barium, strontium, or aluminium; silica; compounds of iodine and fluorine; with phosphates, arseniates, borates, nitrates, organic matter, carbon-dioxide, sulphuretted hydrogen, marsh-gas, and nitrogen.[88]

Medicinal Springs, a vague term applied to mineral springs which have or are believed to have curative effects in different diseases. Medical men recognize various qualities, distinguished by the particular substance most conspicuous in each variety of water: *Alkaline Waters*, containing lime or soda and carbonic acid—Vichy, Saratoga; *Bitter Waters*, with sulphate of magnesia and soda—Sedlitz, Kissingen; *Salt* or *Muriated Waters*, with common salt as the leading mineral constituent—Wiesbaden, Cheltenham; *Earthy Waters*, lime, either a sulphate or carbonate being the most marked ingredient—Bath, Lucca; *Sulphurous Waters*, with sulphur as sulphuretted hydrogen and in sulphides—Aix-la-Chapelle, Harrogate. Some of these medicinal springs are thermal waters. Even where no longer warm, the water may have acquired its peculiar medicinal characters at a great depth, and therefore under the influence of increased temperature and pressure. Sulphur springs are sometimes warm, but also occur abundantly cold, where the water rises through rocks containing decomposing sulphides and organic matter. Sulphates are there first formed, which by the reducing effect of the organic matter are decomposed, with the resultant formation of sulphuretted hydrogen (p. 124). Sulphuretted hydrogen and sulphurous acid are sometimes oxidized into sulphuric acid, which remains free in the water.[89]

---

[88] Roth, "Chem. Geol." i. p. 442. Bischof, "Chem. Geol." ii. Many subterranean waters, though not deserving the name of brines, contain considerable proportions of chlorides. On the alkaline chlorides of the Coal-measures see R. Malherbe, Bull. Acad. Roy. Belgique, 1875, p. 16; also R. Laloy, Ann. Soc. Geol. Nord, 1875, p. 195.

[89] Roth, op. cit. i. pp. 444, 452.

Hot Springs, Geysers.—The thermal waters of volcanic districts usually contain a marked percentage of dissolved mineral matter, notably silica, with sulphates, carbonates, chlorides, bromides, and other combinations. Perhaps the most detailed examination yet made of any such group of springs is the series of analyses performed by the Geological Survey of the United States on the waters of forty-three hot springs in the Yellowstone National Park. The temperatures of these waters ranged up to 93° C., and the total amount of dissolved mineral matter up to 2·8733 grammes in every kilogramme. The silica sometimes amounted to 0·6070 gramme, the sulphuric acid to 1·9330, the carbonic acid to 1·2490, the chlorine to 1·0442, the calcium to 0·3076, the magnesium to 0·0797, the potassium to 0·1603, the sodium to 0·4407, and there were minute quantities of numerous other constituents.[90]

Oil Springs.—Petroleum is sometimes brought up in drops floating in spring-water (St. Catherine's, near Edinburgh). In many countries it comes up by itself or mingled with inflammable gases. Reference has already been made (pp. 254, 401) to the abundance of this product in North America. In western Pennsylvania, some oil-wells have yielded as much as 2000 to 3000 barrels of oil per day. That the oil, which is specially confined to particular layers of rock in the Carboniferous and Devonian systems, arises from the alteration of organic substances imbedded in the rocks of the crust, appears to be probable, but no satisfactory explanation has been given of the nature and distribution of the organisms which yielded the oil.[91]

Results of the Chemical Action of Underground Water.—Three remarkable results of the chemical operations of underground water are: 1st, The internal composition and minute structure of rocks are altered. 2d, Enormous quantities of mineral matter are carried up to the surface, where they are partly deposited in visible form, and partly conveyed by brooks and rivers to the sea. 3d, As a consequence of this transport, subterranean

[90] F. A. Gooch and J. E. Whitfield, Bull. U. S. Geol. Survey, No. 47, 1888.
[91] See the authorities cited ante, p. 402.

tunnels, passages, caverns, grottoes, and other cavities of many varied shapes and dimensions are formed.

(1) *Alteration of Rocks.*—The processes of oxidation, deoxidation, solution, hydration, and the formation of carbonates, described (pp. 584, 586) as carried on above ground by rain, are likewise in progress on a great scale underneath. Since the permeability of subterranean rocks permits water to find its way through their pores as well as along their divisional planes, chemical changes, of a kind like those in ordinary weathering, take place in them, and at some depth may be intensified by internal terrestrial heat and pressure. This subterranean alteration of rocks may consist in the mere addition of substances introduced in chemical solution; in the simple solution and removal of some one or more constituents; or in a complex process of removal and replacement, wherein the original substance of a rock is molecule by molecule removed, while new ingredients are simultaneously or afterward substituted. In tracing these alterations of rocks, the study of pseudomorphs becomes important, for we thereby learn what was the original composition of the mineral or rock. The mere existence of a pseudomorph points to the removal and substitution of mineral matter by permeating water.[92]

The extent to which such mineral replacement has been carried among rocks of the most varied structure and composition is probably best shown by the abundant petrified organic forms in formations of all geological ages. The

[92] It is not needful to take account here of such exceptional cases as the artificial conversion of aragonite into calcite by exposure to a high temperature. In such paramorphs the change is a molecular or crystalline rather than a chemical one, though how it takes place is still unknown. Pseudomorphs may be artificially formed. Crystals of atacamite ($Cu_4O_3Cl_2+4H_2O$) placed in a solution of bicarbonate of soda are completely changed into malachite in four years. Tschermak's Min. Mitth. 1877, p. 97.

minutest structures of plants and animals have been, particle by particle, removed and replaced by mineral matter introduced in solution, and this so imperceptibly, and yet thoroughly, that even minutiæ of organization, requiring a high power of the microscope for their investigation, have been preserved without distortion or disarrangement. From this perfect condition of preservation, gradations may be traced until the organic structure is gradually lost amid the crystalline or amorphous infiltrated substance (Fig. 107). The most important petrifying media in nature are calcium-carbonate, silica, and iron-disulphide (marcasite more usually than pyrite). (See Book V.)

Another proof of the alteration which rocks have suffered from permeating water is supplied by the abundance of veins of calcite and quartz by which they are traversed, these minerals having been introduced in solution and often from the decomposition of the inclosing rock. As Bischof pointed out, a drop of acid seldom fails to give effervescence on pieces of rock, composed of silicates, which have been taken even at some little depth from the surface, thus indicating the decomposition and deposit caused by permeating water. As already stated, one of the most remarkable results of the application of the microscope to geological inquiry is the extent to which it has revealed these all-pervading alterations, even in what might be supposed to be perfectly fresh rocks. Among the silicates, the most varied and complex interchanges have been effected. Besides the production of calcium-carbonate by the decomposition of such minerals as the lime-felspars, the series of hydrous green ferruginous silicates (delessite, saponite, chlorite, serpentine, etc.), so commonly met with in crystalline rocks, are usually witnesses of the influence of infiltrating water. The changes visible in olivine (p. 300) offer instructive lessons on the progress of transformation. One further example may be cited as supplied by the zeolites, so common in cavities and veins among many ancient volcanic and other crystalline rocks. These have commonly resulted from the decomposition of felspars or allied minerals. Their mode of formation is indicated by the observation already cited (p. 522), that Roman masonry at the

Fig. 107.—Fossil wood from tuff, Burntisland, showing parts perfectly preserved and parts destroyed by crystallization of calcite. Magnified 10 diameters.

Fig. 108.—Section of a part of a Stalactite. Magnified 10 diameters.

baths of Plombieres has in the course of centuries been so decomposed by the slow percolation of alkaline water at a temperature not exceeding 50° C. (122° Fahr.) under ordinary atmospheric pressure, that various zeolitic silicates have been developed in the brick.[93]

(2) *Chemical Deposits.*—Of these by far the most abundant is calcium-carbonate. The way in which this substance is removed and redeposited by permeating water can be instructively studied in the formation of the familiar *stalactites* and *stalagmites* beneath damp arches and in limestone caves (p. 262). As each drop gathers on the roof and begins

[93] Daubrée, "Geologie Experimentale," p. 179 *et seq.*

to evaporate and lose carbonic acid, the excess of carbonate which it can no longer retain is deposited round its edges as a ring (Fig. 108). Drop succeeding drop, the original ring grows into a long pendent tube, which, by subsequent deposit inside, becomes a solid stalk, and on reaching the floor may thicken into a massive pillar. At first the calcareous substance is soft and, when dry, pulverulent, but by prolonged saturation and the internal deposit of calcite it becomes by degrees crystalline. Each stalactite is found to possess an internal radiating fibrous structure, the fibres (prisms) passing across the concentric zones of growth. The stalactite remains saturated with calcareous water, and the divergent prisms are developed and continued as radii from the centre of the stalk. This process may be completed within a short period. At the North Bridge, Edinburgh, for example, which was erected in 1772, stalactites were obtained in 1874, some of which measure an inch and a half in diameter and possess the characteristic radiating structure.[94] It is doubtless by an analogous process that limestones, originally composed of the débris of calcareous organisms and interstratified among perfectly unaltered shales and sandstones, have acquired a crystalline structure (p. 216).[95]

Some calcareous springs deposit abundantly a precipitate of carbonate of lime upon mosses, twigs, leaves, stones, and other objects. The precipitate takes place when from any cause the water parts with carbonic acid. This may arise

---

[94] The rate of deposit in the Ingleborough Cave is stated to be ·2946 inch per annum, or about 2½ feet in a century (Boyd Dawkins, Brit. Assoc. 1880, Sects. p. 573). This is probably an exceptionally rapid growth.

[95] Sorby, Address to Geological Society, Q. J. Geol. Soc. 1879, p. 42 *et seq.* The finely fibrous structure seen in chalcedony under the microscope with polarized light passes in a similar way through the bands of growth of pebbles.

from mere evaporation, but is frequently due to the action of bog-mosses and water-plants, which, decomposing the carbonic acid, cause a crust of carbonate of lime to be deposited round their stems and branches (postea, p. 482). Hence calcareous springs are popularly called "petrifying," though they merely incrust organic bodies, and do not convert them into stone. Calc-sinter or travertine, as this precipitate is called, may be found in course of formation in most limestone districts, sometimes in masses large enough to form hills, and compact enough to furnish excellent building-stone. The travertine of Tuscany is deposited at the Baths of San Vignone at the rate of six inches a year, at San Filippo one foot in four months. At the latter locality it has been piled up to a depth of at least 250 feet, forming a hill a mile and a quarter long and a third of a mile broad.[96]

Chalybeate springs give rise to a deposit of hydrous peroxide of iron. This has already been referred to as a yellow and reddish-brown deposit along the channels of the water. Some acidulous springs, like those of the Laacher See, deposit large quantities of ochre. In undrained districts of temperate latitudes in Northern Europe and America, much iron is also deposited beneath soil which rests on a retentive subsoil. When the descending water is arrested on this subsoil, the iron, in solution as organic salts that oxidize into ferrous carbonate, is gradually converted into the insoluble hydrous ferric oxide, which is precipitated and

---

[96] Lyell, "Principles," i. p. 402. At Narni, the greater the velocity of flow, the greater the deposit of lime, very little being deposited in stagnant water. The amount thrown down increases with temperature and distance from source, exposure to the air being necessary for deposition. B. Fabri, Proc. Inst. Civ. Engineers, xli. 1876, p. 246. The student will find much detail regarding the abstraction and deposit of carbonate of lime by subterranean water in a paper by Senft, "Die Wanderungen und Wandelungen des kohlensäuren Kalkes," Z. Deutsch. Geol. Ges. xiii. p. 263.

forms a dark ferruginous layer, known to Scottish farmers as "moorband pan." So effectually does this layer interrupt the drainage that the soil remains permanently damp and infertile. But when the "pan" is broken up and spread over the surface it quickly disintegrates, and improves the soil, which can then be properly drained (postea, p. **811**).

Siliceous springs form important masses of sinter round the point of outflow. The basins and funnels of geysers have already been described (p. 402). One of the sinter-beds in the Iceland geyser region is said to be two leagues long, a quarter of a league wide, and a hundred feet thick. Enormous beds of similar material have been formed in the Yellowstone geyser region. Such accumulations usually point to proximity to former volcanic centres, and are formed during one of the latest phases of volcanic action.

(3) *Formation of subterranean channels and caverns.*—Measurement of the yearly amount of mineral matter brought up to the surface by a spring, furnishes an approximate idea of the extent to which underground rocks undergo continual loss of substance. The warm springs of Bath, for example, with a mean temperature of 120° Fahr., are impregnated with sulphates of lime and soda, and chlorides of sodium and magnesium. Sir A. C. Ramsay estimated their annual discharge of mineral matter to be equal to a square column 9 feet in diameter and 140 feet in height. Again, the St. Lawrence spring at Louèche (Leuk) discharges every year 1620 cubic metres (2127 cubic yards) of dissolved sulphate of lime, equivalent to the lowering of a bed of gypsum one square kilometre (0·3861 square mile) in extent, more than 16 decimetres (upward of five feet) in a century.[97]

[97] E. Reclus, "La Terre," i. p. 340.

By prolonged abstraction of this nature, subterranean tunnels, channels, and caverns have been formed. In regions abounding in rock-salt deposits, the result of the solution and removal of these by underground water is visible in local sinkings of the ground and the consequent formation of pools and lakes. The landslips and meres of Cheshire are illustrations of this process. In that county, owing to the pumping out of the brine in the manufacture of salt, tracts of ground sometimes more than 100 acres in extent have sunk down and become the sites of lakes of varying depth,

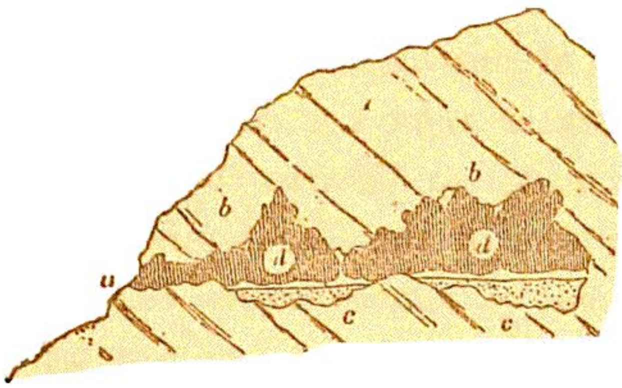


Fig. 109.—Section of a Limestone Cavern (*B.*).

l l, A limestone hill, perforated by a cavern (*b b*) which communicates with the valley (*v*) by an opening (*a*). The bottom of the cavern is covered with ossiferous loam, above which lies a layer of stalagmite (*d d*), while stalactites hang from the roof, and by joining the floor separate the cavern into two chambers.

some being 45 feet deep.[98] In calcareous districts, still more striking effects are observable. The ground may there be found drilled with vertical cavities (*swallow-holes*, *sinks*, *dolinas*), by the solution of the rock along lines of joint or of faults that serve as channels for descending rain-water. The line of outcrop of a limestone-band, among non-calcareous strata, may often be traced, even under a covering of superficial deposits, by its row of swallow-holes. Surface-drainage, thus intercepted, passes at once underground, where, in course of time, an elaborate system of spacious

[98] T. Ward, "History and Cause of the subsidences at Northwich," etc., 1887, Geol. Mag. 1887, p. 517.

tunnels and chambers may be dissolved out of the solid rock (Fig. 111). Such has been the origin of the Peak caverns of Derbyshire, the intricate grottoes of Antiparos and Adelsberg, and the vast labyrinths of the Mammoth Cave of Kentucky.[99] In the course of time, the underground rivers open out new courses, and leave their old ones dry, as the Poik has done at Adelsberg. By the falling in of the roofs of caverns, a communication is established with the surface, and land-shells and land-animals fall into the holes, or the caverns are used as dens by beasts of prey, so that the remains of terrestrial animals are preserved under

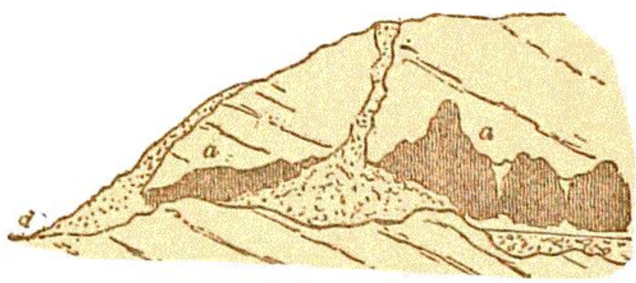


Fig. 110.—Section of a Limestone Cavern with fallen-in roof and concealed entrance (*B.*).

the stalagmite. Not infrequently caverns, once open and freely used as haunts of carnivora, have had their entrances closed by the fall of débris, as at *d* in Fig. 110, where also the partial filling-up of a cavern (*a a*) from the same cause is seen. Where the collapse of a cavern roof takes place below a water-course, the stream is engulfed. In this way, brooks and rivers suddenly disappear from the surface, and after a long subterranean course, issue again in a totally different surface-area of river-drainage from that in which they took their rise, and sometimes with volume enough to be navi-

[99] For accounts of the remarkable honeycombed region of Carniola, etc., see Mojsisovics, "Geologie von Bosnien-Hercegovina," pp. 44–60; Zeitsch. Deutsch. Alpenvereins, 1880. E. Tietze, Jahrb. Geol. Reichsanst. xxx., 1880, p. 729, and papers cited by him. Dr. J. H. Kloos and Dr. Max Müller, description and photographs of the Hermann's Cave of Rübeland in Brunswick (Weimar, 1889).

gable almost up to their outflow. In such circumstances, lakes, either temporary, like the Lake Zirknitz in Carniola, or perennial, may be formed over the sites of the broken-in caverns; and valleys may thus be deepened, or gorges may be formed.[100] Mud, sand, and gravel, with the remains of plants and animals, are swept below ground, and sometimes

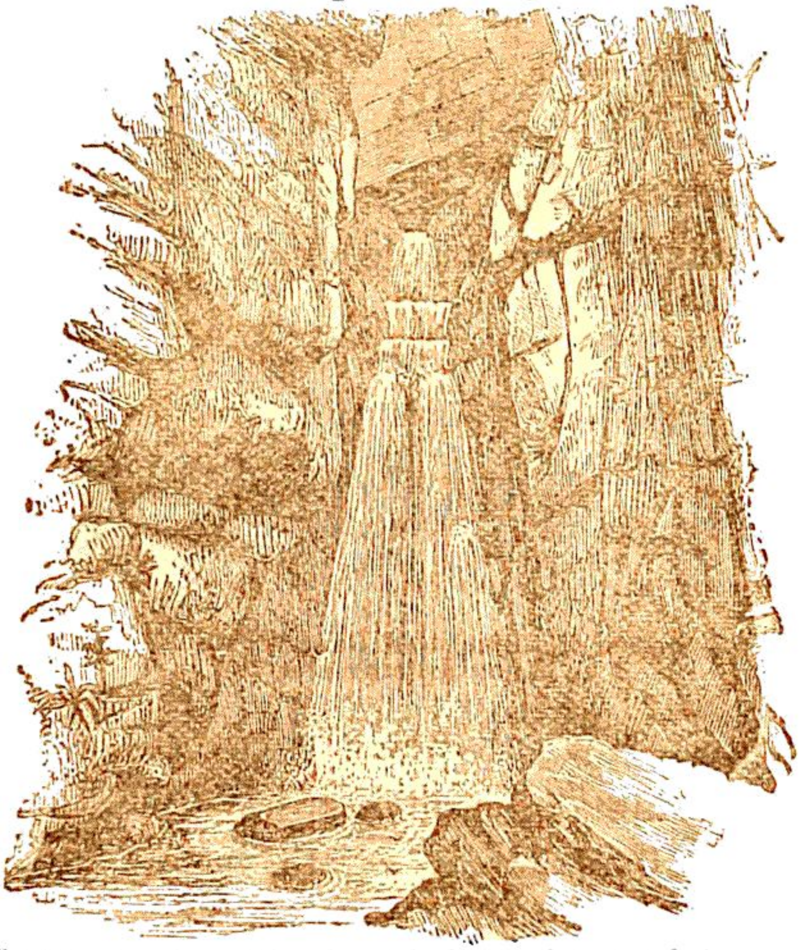


Fig. 111.—Section of the channel of an underground stream.

accumulate in deposits of loam and breccia, such as are so often found in ossiferous caverns (Figs. 109, 110).

As from time to time the roofs of underground chambers, weakened by the constant abstraction of mineral matter, collapse, or large portions are detached from them and fall on the floors below, sudden shocks are generated which are

[100] See interesting accounts by M. Martel of the subterranean channels of the Causses or Jurassic limestone plateaus of Gard and Lozère in the South of France, and of the formation of cañons there. Compt. Rend. 1888. Bull. Soc. Geol. France, xvii. 1889, p. 610.

felt above ground as earthquakes. In subsiding to fill up hollows from which the rock has been removed in solution, the overlying strata may be greatly contorted and fractured, those underneath remaining undisturbed.

2. **Mechanical Action.**—In its passage along fissures and channels, underground water not merely dissolves and removes materials in solution, it likewise loosens finer particles and carries them along in mechanical suspension. This removal of material sometimes produces remarkable surface-changes along the sides of steep slopes or cliffs. A thin porous layer, such as loose sand or ill-compacted sandstone, lying between more impervious rocks, such as masses of clay or limestone, and sloping down from higher ground, so as to come out to the surface near the base of a line of abrupt cliff, serves as a channel for underground water which issues in springs or in a more general oozing at the foot of the declivity. Under these circumstances the support of the overlying mass of rock is apt to be loosened; for the water not only removes piecemeal the sandy layer on which that overlying mass rests, but, as it were, lubricates the rock underneath. Consequently, at intervals, portions of the upper rock break off and slide down into the valley or plain below. Such dislocations are known as *landslips.*[101] The movement may be gradual, as in the case of the Bec

[101] Baltzer, in his work "Ueber Bergstürze in den Alpen" (Zürich, 1875), classifies Swiss landslips into four categories, viz., 1st, Rock-falls (Felsstürze); 2d, Earth-slips (Erdschliffe); 3d, Mud-streams (Schlammströme), where soft strata saturated with water are crushed by the weight of overlying rock and move down in mass, like lava; 4th, Mixed falls (gemischte Stürze), where, as in most instances, rock, earth and mud are launched down the declivities. More recently he has offered another classification of landslips, according to the dimensions of the mass moved and the solid or muddy condition of the material, Neues Jahrb. 1880 (ii.), p. 198. See A. Rothpletz, Zeitsch. Deutsch. Geol. Ges. 1881, p. 540; also op. cit. 1882, pp. 430, 435. E. Buss and A. Heim, "Der Bergsturz von Elms," Zurich, 1881.

Rouge in the Tarentaise, where the side of the mountain is slowly overwhelming the village of Miroir,[102] or it may be sudden and disastrous.

Along sea-coasts and river valleys, at the base of cliffs subject to continual or frequent removal of material by running water, the phenomena of landslips are best seen. The coast-line of the British Islands abounds with instructive examples. On the shores of Dorsetshire, for instance (Fig. 112), impervious Liassic clays (*a*) are overlain by porous greensand (*b*), above which lies chalk (*c*) capped with gravel (*d*). In consequence of the percolation of water through the sandy zone (*b*), the support of the overlying mass is destroyed, and hence, from time to time, segments are launched down toward the sea. In this way, a confused medley of mounds and hollows (*f*) forms a characteristic strip of ground termed the "Undercliff" on this and other parts of the English coasts. This recession of the upper or inland cliff through the operation of springs is here more rapid than that of the lower cliff (*g*) washed by the sea.[103] In the year 1839, after a season of wet weather, a mass of chalk on the same coast slipped over a bed of clay into the sea, leaving a rent three-quarters of a mile long, 150 feet deep, and 240 feet wide. The shifted mass, bearing with it houses, roads, and fields, was cracked, broken and tilted in various directions, and was thus prepared for further attack and removal by the waves.[104] In February, 1891, a mass of chalk-cliff, calculated to contain some 10,000 tons of material, gave way on the cliffs to the east of Brighton, and fell to the beach, breaking away part of the main road above. In March, 1893, by an extensive slipping of the Lower Greensand toward the beach a large part of the town of Sandgate on the coast of Kent was destroyed. The antiquity of many landslips is shown by the ancient buildings occasionally to be seen upon the fallen masses. The

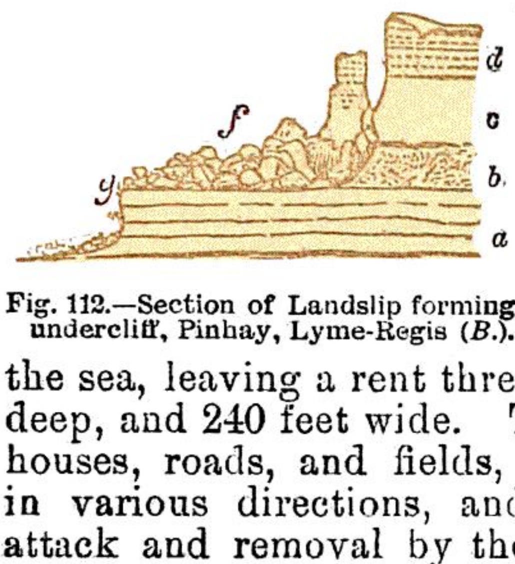


Fig. 112.—Section of Landslip forming undercliff, Pinhay, Lyme-Regis (*B.*).

[102] L. Borrell, Bull. Soc. Geol. France, ser. 3, vi. 1877, p. 47.

[103] De la Beche, "Geol. Observer," p. 22.

[104] Conybeare and Buckland's "Axmouth Landslip," London, 1840. Lyell, "Principles," i. p. 536.

undercliff of the Isle of Wight, the cliffs west of Brandon Head, county Kerry, the basalt escarpments of Antrim, and the edges of the great volcanic plateaus of Mull, Skye, and Raasay, furnish illustrations of such old and prehistoric landslips.

On a more imposing scale, and interesting from its melancholy circumstances being so well known, was the celebrated fall of the Rossberg, a mountain (*a*, Fig. 113) situated behind the Rigi in Switzerland, rising to a height of more than 5000 feet above the sea. After the rainy summer of 1806, a large part of one side of the mountain, consisting of steeply sloping beds of hard red sandstone and conglomerate (*b*), resting upon soft sandy layers (*c c*), gave way. The lubrication of the lower surface by the water having loosened the cohesion of the overlying mass, thousands of tons of solid rock, set loose by mere gravitation, suddenly swept across the valley of Goldau (*d*), burying about a square German mile of fertile land, four villages containing 330 cottages and outhouses, with 457 inhabitants.[105] In 1855 a mass of débris, 3500 feet long, 1000 feet wide, and 600 feet high, slid into the valley of the Tiber, which, dammed back by the obstruction, overflowed the village of San Stefano to a depth of 50 feet, until drained off by a tunnel.

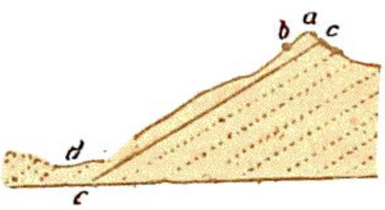


Fig. 113.—Section illustrating the Fall of the Rossberg.

§ 3. Brooks and Rivers

These will be considered under four aspects:—(1) sources of supply, (2) discharge, (3) flow, and (4) geological action.[106]

1. Sources of Supply.—Rivers, as the natural drains of a land-surface, carry out to sea the surplus water after evaporation, together with a vast amount of material worn off the land. Their liquid contents are derived partly from rain (including mist and dew) and melted snow, partly from springs. In a vast river-system, like that of the

[105] Zay, "Goldau und seine Gegend." Baltzer, Neues Jahrb. 1875, p. 15. Upward of 150 destructive landslips have been chronicled in Switzerland. Riedl, Neues Jahrb. 1877, p. 916.

[106] An excellent monograph on a river is C. Lenthéric's "Le Rhône, histoire d'un fleuve," 2 vols. Paris, 1892.

Mississippi, where the area of drainage is so extensive as to embrace different climates and varieties of rainfall, the amount of discharge, being in a great measure independent of local influences of weather, remains tolerably uniform, or is subject to regular periodically-recurrent variations. In smaller rivers, such as those of Britain, whose basins lie in a region having the same general features of climate, the quantity of water is regulated by the local rainfall. A wet season swells the streams, a dry one diminishes them. Hence, in estimating and comparing the geological work done by different rivers, we must take into account whether or not the sources of supply are liable to occasional great augmentation or diminution. In some rivers, there is a more or less regularly recurring season of flood followed by one of drought. The Nile, fed by the spring rains of Abyssinia, floods the plains of Egypt every summer, rising in Upper Egypt from 30 to 35 feet, at Cairo 23 to 24 feet, and in the seaward part of the delta about 4 feet. The Ganges and its adjuncts begin to rise every April, and continue doing so until the plains are converted into a vast lake 32 feet deep. In other rivers, sudden and heavy rains, occurring at irregular intervals, swell the usual volume of water and give rise to floods, freshets, or "spates." This is markedly the case with the rivers of Western Europe. Thus the Rhone sometimes rises 11½ feet at Lyons and 23 feet at Avignon; the Saône from 20 to 24½ feet. In the middle of March, 1876, the Seine rose 20 feet at Paris, the Oise 17 feet near Compiègne, the Marne 14 feet at Damery. The Ardèche at Gournier exceeded a rise of 69 feet during the inundations of 1827.[107] The cause of floods,

[107] For a graphic account of rivers swollen by heavy rainfall, see Sir T. D. Lauder's "Morayshire Floods." On torrents consult Surell and Cézanne, "Études sur les Torrents des Hautes Alpes."

not only as regards meteorological conditions, but in respect to the geological structure of the ground, merit the careful attention of the geological student. He may occasionally observe that, other things being equal, the volume of a flood is less in proportion to the permeability of a hydrographic basin, and the consequent ease with which rain can sink beneath the surface.

Were rivers entirely dependent upon direct supplies of rain, they would only flow in rainy seasons and disappear in drought. This does not happen, however, because they derive much of their water not directly from rain, but indirectly through the intermediate agency of springs. Hence they continue to flow even in very dry weather, because, though the superficial supplies have been exhausted, the underground sources still continue available. In a long drought, the latter begin at length to fail, the surface springs ceasing first, and gradually drying up in their order of depth, until at last only deep-seated springs furnish a perhaps daily diminishing quantity of water. Though it is a matter of great economic as well as scientific interest to know how long any river would continue to yield a certain amount of water during a prolonged drought, no rule seems possible for a generally applicable calculation, every area having its own peculiarities of underground drainage, and varying greatly from year to year in the amount of rain which is absorbed. The river Wandle, for instance, drains an area of 51 square miles of the chalk downs in the southeast of England. For eighteen months, from May, 1858, to October, 1859, as tested by gauging, there was very little absorption of rainfall over the drainage basin, and yet the minimum recorded flow of the Wandle was 10,000,000 gallons a day, which represents not more than ·4090 inch of rain absorbed on the 51 square miles of chalk. The rock is so saturated that it can continue to supply a large yield of water for eighteen months after it has ceased to receive supplies from the surface, or at least has received only very much diminished supplies.[108]

2. **Discharge.**—What proportion of the total rainfall is discharged by rivers is another question of great geological and industrial interest. From the very moment that water takes visible form, as mist, cloud, dew, rain, snow, or hail, it is subject to evaporation. When it reaches the ground, or flows off into brooks, rivers, lakes, or the sea, it undergoes continual diminution from the same cause. Hence in regions where rivers receive no tributaries, they grow smaller in volume as they move onward, till in dry hot climates they even disappear. Apart from temperature, the amount of evaporation is largely regulated by the nature of the surface from which it takes place, one soil or rock differing from another, and all of them probably from a surface of water. Full and detailed observations are still wanting for determining the relation of evaporation to rainfall and river discharge.[109] During severe storms of rain, the

---

[108] Lucas, "Horizontal Wells," London, 1874, pp. 40, 41. See also Braithwaite, Min. Proc. Inst. Civ. Engin. xx. It is much to be desired that such observations as those of Sir J. B. Lawes, Dr. Gilbert and Sir John Evans on the percolation of rain through soils and chalk (Min. Proc. Inst. Civ. Engin. xlv. p. 208; see also Greaves, op. cit. p. 19) should be tried in many different areas.

[109] In the present state of our information it seems almost useless to state any of the results already obtained, so widely discrepant and irreconcilable are they. In some cases, the evaporation is given as usually three times the rainfall; and that evaporation always exceeded rainfall was for many years the belief among the French hydraulic engineers. (See Annales des Ponts-et-Chaussees, 1850, p. 383.) Observations on a larger scale, and with greater precautions against the undue heating of the evaporator, have since shown, as might have been anticipated, that as a rule, save in exceptionally dry years, evaporation is lower than rainfall. As the average of ten years from 1860 to 1869,

water discharged over the land finds its way, to a very large extent, at once into brooks and rivers, by which it reaches the sea. Mr. David Stevenson remarks that, according to different observations, the amount carried off in floods varies from 1 to 100 cubic feet per minute per acre.[110]

In estimating and comparing, therefore, the ratios between rainfall and river discharge in different regions, regard must be had to the nature of the rainfall, whether it is crowded into a rainy season or diffused over the year. Thus, though floods cannot be deemed exceptional phenomena, forming as they do a part of the regular system of water-circulation over the land, they do not represent the ordinary proportions between rainfall and river discharge in such a climate as that of Britain, where the rainfall is spread more or less equally throughout the year. According to Beardmore's table,[111] the Thames at Staines has a mean annual discharge of 32·40 cubic inches per minute per square mile, equal to a depth of 7·31 inches of rainfall run off, or less than a third of the total rainfall. The most carefully collected data at present available are probably those given by Humphreys and Abbot for the basin of the Mississippi and its tributaries, as shown in the subjoined table:[112]

Mr. Greaves found that at Lea Bridge the evaporation from a surface of water was 20·946 inches, while the rainfall was 25·534 (Symons's British Rainfall for 1869, p. 162). But we need an accumulation of observations, taken in many different situations and exposures, in different rocks and soils, and at various heights above the sea. (For a notice of a method of trying the evaporation from soil, see British Rainfall, 1872, p. 206.)

110 "Reclamation and Protection of Agricultural Land," Edin. 1874, p. 15.

111 "Hydrology," p. 201. Comp. Report of Royal Commission on Water Supply, 1869, p. liii.

112 "Physics and Hydraulics of the Mississippi River," Washington, 1861, p. 136.

	Ratio of Discharge to Rainfall
Ohio River	0·24
Missouri River	0·15
Upper Mississippi River	0·24
Small Tributaries	0·90
Arkansas and White River	0·15
Red River	0·20
Yazoo River	0·90
St. Francis River	0·90
Entire Mississippi, exclusive of Red River	0·25

In the Mississippi basin, one-fourth of the rainfall is thus discharged into the sea. The Elbe, from the beginning of July, 1871, to the end of June, 1872, was estimated to carry off at most a quarter of the rainfall from Bohemia.[113] The Seine at Paris appears to carry off about a third of the rainfall. In Great Britain from a fourth to a third part of the rainfall is perhaps carried out to sea by streams.[114]

In comparing also the discharges of different rivers, regard should be paid to the influence of geological structure, and particularly of the permeability or impermeability of the rocks, as regulating the supply of water to rivers. Thus the Thames, from a catchment basin of 3670 square miles and with a rainfall of 27 inches, has a mean annual discharge at Kingston of 1250 millions of gallons a day, and rather more than 688 millions of gallons in summer. The Severn, on the other hand, which gathers its supplies mainly from the hard, impervious slate hills of Wales, has a drainage area above Gloucester of 3890 square miles, with an average rainfall of probably not less than 40 inches. Yet

---

113 Verhandl. Geol. Reichsanstalt, Vienna, 1876, p. 173.

114 In mountainous tracts having a large rainfall and a short descent to the sea, the proportion of water returned to the sea must be very much greater than this. Mr. Bateman's observations for seven years in the Loch Katrine district gave a mean annual rainfall of 87½ inches at the head of the lake, with an outflow equivalent to a depth of 81·70 inches of rain removed from the drainage basin of 71½ square miles. See a paper by Graeve on the quantity of water in German rivers, and on the relation between rainfall and discharge, Der Civil-Ingenieur, 1879, p. 591; Nature, xxiii. p. 94. J. Murray, Scott. Geog. Mag. 1887.

its daily summer discharge does not amount to 298 millions of gallons, and its minimum sinks as low as 100 millions of gallons, while that of the Thames in the driest season never falls below 350 millions. In the one case, the water is stored up within the rocks and is dispensed gradually; in the other, it in great measure runs off at once.[115] It is likewise deserving of note that the operations of man, particularly in draining land and deforesting, may materially alter the mean level of a river and increase the volume of floods. The mean level of the Elbe at Dresden is said to have been perceptibly diminished by human interference, while in the Rhine the low-water level has been lowered, and the floods have been augmented.[116]

3. **Flow.**—While, in obedience to the law of gravitation, a river always flows from higher to lower levels, great variations in the rate and character of its motion are caused by inequalities in the angle of slope of its channel. A vertical or steeply inclined face of rock originates a waterfall; a rocky declivity in the channel gives rise to rapids; a flat plain allows the stream to linger with a scarcely visible current; while a lake renders the flow nearly or altogether imperceptible. Thus the rate of flow is regulated in the main by the angle of inclination and form of the channel, but partly also by the volume of water, an increase of volume in a narrow channel increasing the rate of motion even without an increase of slope.[117]

The course of a great river may be divided into three parts: 1. *The Mountain Track*—where, amid clouds or snows,

---

[115] Prestwich, Q. J. Geol. Soc. xxviii. p. lxv. Compare the conditions of the catchment basin of the Seine as given by A. Delaire, Ann. Conserv. Arts et Metiers, No. 138, p. 335.

[116] Report of (Austrian) Committee on Diminution of Water in Springs and Rivers, Proc. Inst. Civ. Engineers, xlii., 1875, p. 271.

[117] See A. Tylor on the Laws of River-action, Geol. Mag. 1875, p. 443.

it takes its rise as a mere brook, and, fed by innumerable similar torrents, dashes rapidly down the steep sides of the mountains, leaping from crag to crag in endless cascades, and growing every moment in volume, until it enters lower ground. 2. *The Valley Track*—where, now flowing through lower hills or undulations, the stream is found at one time in a wide fertile valley, then in a dark gorge, now falling headlong into a cataract, now expanding into a broad lake. This is the part of its career where it assumes the most varied aspects, and receives the largest tributaries. 3. *The Plain Track*—where, having quitted the undulating region, the river finally emerges upon broad plains, probably wholly or in great part composed of alluvial formations deposited by its own waters. Here winding sluggishly in wide curves, it may eventually bifurcate, as it approaches the sea and spreads through its delta, inclosing tracts of flat meadow or marsh, and finally, amid banks of mud and sand, passing out into the great ocean. In Europe, the Rhine, Rhone and Danube; in Asia, the Ganges and Indus; in America, the Mississippi and Amazon; in Africa, the Nile and Niger—illustrate this typical course of a great river.

If we draw a longitudinal section of the course of any such river or of any of its tributaries from its source, or from the highest peaks around that source, to its mouth, we find that the line at first curves steeply from the mountain crests down into the valleys, but grows less and less inclined through the middle portion, until it finally can hardly be distinguished from a horizontal line. This feature, however, is not confined to stream courses but belongs to the architecture of the continents.

It is evident that a river must flow, on the whole, fastest in the first portion of its course, and slowest in the last.

The common method of comparing the fall or slope of rivers is to divide the difference of height between their source and the sea-level by their length, so as to give the declivity per mile. This mode, however, often fails to bring out the real resemblances and differences of rivers, even in regard to their angle of slope. For example, two streams rising at a height of 1000 feet, and flowing 100 miles to the sea, would each have an average slope of 10 feet per mile; yet they might be wholly unlike each other, one making its descent almost entirely in the first or mountain part of its course, and lazily winding for most of its way through a vast low plain; the other toiling through the mountains, then keeping among hills and table-lands, so as to form on the whole a tolerably equable and rapid flow. The great rivers of the globe have probably a less average slope than 2 feet per mile, or 1 in 2640. The Missouri, which has a descent of 28 inches per mile, is a tumultuous rapid current even down as far as Kansas City. The average slope of the channel of the Thames is 21 inches per mile; of the Shannon about 11 inches per mile, but between Killaloe and Limerick about 6¼ feet per mile; of the Nile, below Cairo, 3·25 to 5·5 inches per mile; of the Doubs and Rhone, from Besançon to the Mediterranean, 24·18 inches per mile; of the Volga from its source to the sea, a little more than 3 inches per mile. Higher angles of descent are those of torrents, as the Arve, with a slope of 1 in 616 at Chamounix, and the Durance, whose angle varies from 1 in 467 to 1 in 208. The Colorado River rushes through its cañons with an average declivity of 7·72 feet per mile, or 1 in 683. The slope of a navigable river ought hardly to exceed 10 inches per mile, or 1 in 6336.[118]

---

[118] D. Stevenson, "Canal and River-Engineering," p. 224.

But not only does the rate of flow of a river vary at different parts of its course, it is not the same in every part of the cross-section of the river taken at any given point. A river channel (Fig. 114) supports a succession of layers of water (*a*, *b*, *c*, *d*), moving with different velocities, the greatest movement being at the centre (*d*), and the least in the layer which lies directly on the channel. At the same vertical depth, therefore, the velocity is greater in proportion as the point approaches the centre of the stream. The water next the sides and bottom (*a a*), being retarded by friction against the channel, moves less rapidly than the layers (*b b*, *c c*) toward the centre (*d*). The central piers of a bridge have consequently a greater velocity of river-current to bear than those at the banks. The motion of the surface-water, however, is retarded, on the other hand, by upward currents, generated chiefly by irregularities of the bottom.[119] It follows that whatever tends to diminish the friction of the moving current will increase its rate of flow. The same body of water, other conditions being equal, will move faster through a narrow gorge with steep smooth walls than over a broad rough rocky bed. For the same reason, when two streams join, their united current, having in many cases a channel not much larger than that of one of the single streams, flows faster, because the water encounters now the friction of only one channel. The average rate of flow is much less than might be supposed even in what are termed swift rivers. A moderate current is about $1\frac{1}{4}$ miles in the

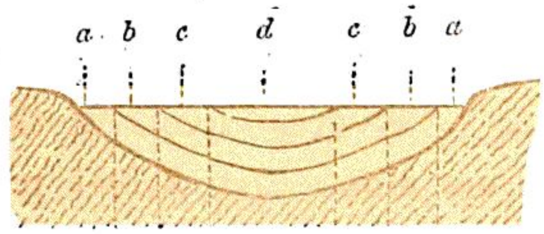


Fig. 114.—Cross-section of a River.

[119] J. Thomson, Proc. Roy. Soc. xxviii., 1878, p. 114. Comp. Collignon, "Cours d'Hydraulique," p. 301.

hour; even that of a torrent does not exceed 18 or 20 miles in the hour. Mr. D. Stevenson states that the velocity of such rivers as the Thames, the Tay, or the Clyde may be found to vary from about one mile per hour as a minimum to about three miles per hour as a maximum velocity.[120]

It may be remarked, in concluding this part of the subject, that elevations and depressions of land must have a powerful influence upon the slope of rivers. The upraising of the axis of a country, by increasing the slope, augments the rate of flow, which, on the contrary, is diminished by a depression of the axis or by an elevation of the maritime regions.

4. **Geological Action.**—Like all other forms of moving water, streams have both a *chemical* and *mechanical* action. The latter receives most attention, as it undoubtedly is the more important; but the former ought not to be omitted in any survey of the general waste of the earth's surface.

i. Chemical.—The water of rivers must possess the powers of a chemical solvent, like rain and springs, though its actual work in this respect can be less easily measured, seeing that river-water is directly derived from rain and springs, and necessarily contains in solution mineral substances supplied to it by them. Nevertheless, that streams dissolve chemically the rocks of their channels can be strikingly seen in limestone districts, where the lower portions of the ravines may be found enlarged into wide cavities or pierced with tunnels and arches, presenting in their smooth surfaces a great contrast to the angular jointed faces of the same rock where exposed to the influence only of the weather.[121]

---

[120] "Reclamation of Land," p. 18.

[121] For an illustration of this action by the Rhone in the marine molasse, see F. Cuvier, Bull. Soc. Geol. France, 3me ser. viii. p. 164.

Daubrée endeavored to illustrate the chemical action of rivers upon their transported pebbles by exposing angular fragments of felspar to prolonged friction in revolving cylinders of sandstone containing distilled water. He found that they underwent considerable decomposition, as was shown by the presence of silicate of potash, rendering the water alkaline. Three kilogrammes of felspar fragments made to revolve in an iron cylinder for a period of 192 hours, which was equal to a journey of 460 kilometres (287 miles), yielded 2·720 kilogrammes of mud, while the five litres of water in which they were kept moving contained 12·60 grammes of potash, or 2·52 grammes per litre.[122]

The mineral matter held in solution in river-water is, doubtless, partly derived from the mechanical trituration of rocks and detritus; for Daubrée's experiments show that minerals which resist the action of acid may be slowly decomposed by mere mechanical trituration, such as takes place along the bed of a river. But in sluggish streams the main supply of mineral solution is doubtless furnished by springs.

The proportion of mineral matter in river-water varies with the season, even for the same stream. It reaches its maximum when the water is mainly derived from springs, as in very dry weather and during frost; it attains its minimum in rainy seasons and after rain.[123] Its amount and composition depend upon the nature of the rocks forming the drainage-basin. Where these are on the whole impervious, the water runs off with comparatively slight abstraction of mineral ingredients; but where they are permeable, the water, in sinking through them and rising again in springs, dissolves their substance and carries it into the rivers.

---

122 "Geologie Experimentale," p. 271; Fayol, Bull. Soc. Geol. France, 3me ser. xvi. p. 996. postea, p. 652.

123 Roth, "Chem. Geol." i. p. 454.

The composition of the river-waters of Western Europe is well shown by numerous analyses. The substances held in solution include variable proportions of the atmospheric gases, carbonates of lime, magnesia, soda, iron, and ammonia; silica; peroxides of iron and manganese; alumina; sulphates of lime, magnesia, potash, and soda; chlorides of sodium, potassium, calcium, and magnesium; silicate of potash; nitrates; phosphoric acid; and organic matter. The minimum proportion of mineral matter among the analyses collected by Bischof was 2·61 in 100,000 parts of water in the Moll, near Heiligenblut—a mountain stream 3800 feet above the sea, flowing from the Pasterzen glacier over crystalline schists. On the other hand, as much as 54·5 parts in the 100,000 were obtained in the waters of the Beuvronne, a tributary of the Loire above Tours. The average of the whole of these analyses is about 21 parts of mineral matter in 100,000 of water, whereof carbonate of lime usually forms the half, its mean quantity being 11·34.[124] Bischof calculated that, assuming the mean quantity of carbonate of lime in the Rhine to be 9·46 in 100,000 of water, which is the proportion ascertained at Bonn, enough of this substance is carried into the sea by this river for the annual formation of three hundred and thirty-two thousand millions of oyster-shells of the usual size. The mineral next in abundance is sulphate of lime, which in some rivers constitutes nearly half of the dissolved mineral matter. Less in amount are sodium chloride,[125] magnesium carbonate and sulphate, and silica. Of the last-named, a percentage amounting to 4·88 parts in 100,000 of water has been found in the Rhine, near Strasburg.[126] The largest amount of alumina was 0·71 in the Loire, near Orleans. The proportion of mineral matter in the Thames, near London, amounts to about 33 parts in 100,000 of water.[127]

---

[124] Bischof, "Chem. Geol." i. chap. v. Of the analyses, chiefly of European rivers, published by Roth, the mean of thirty-eight gives a proportion of 19·983 in 100,000 parts of water. Op. cit. p. 456. Compare I. C. Russell, Bull. U. S. Geol. Surv. 1889.

[125] On the variations of the chlorine in the Nile and Thames, see J. A. Wanklyn, Chem. News, xxxii. 1875, pp. 207, 219.

[126] Of the total solid matter dissolved in the water of the River Uruguay as much as about 46 per cent consists of soluble silica, chiefly as hydrated silicic acid. Hence the "petrifying" property of the water. J. Kyle, Chem. News, xxxviii. 1878, p. 28.

[127] Bischof, op. et loc. cit.; Roth, op. cit. i. p. 454. For composition of British river-water, see "Rivers Pollution Commission Report."

It requires some reflection properly to appreciate the amount of solid mineral matter which is every year carried in solution from the rocks of the land and diffused by rivers into the sea. Accurate measurements of the amount of material so transported are still much required. The Thames carries past Kingston 19 grains of mineral salts in every gallon, or 1502 tons every twenty-four hours, or 548,230 tons every year. Of this quantity about two-thirds consist of carbonate of lime, the rest being chiefly sulphate of lime, with minor proportions of the other ordinary salts of river-water. Mr. Prestwich estimates that the quantity of carbonate of lime removed from the limestone areas of the Thames basin amounts to 140 tons annually from every square mile. This quantity, assuming a ton of chalk to measure 15 cubic feet, is equal to a loss of $\frac{8}{100}$ of an inch from each square mile in a century, or one foot in 13,200 years.[128] According to monthly observations and estimates made in the year 1866 at Lobositz, near the exit of the Elbe from its Bohemian basin, this river may be regarded as carrying every year out of Bohemia from an area of 880 German square miles, or, in round numbers, 20,000 English square miles, 6,000,000,000 cubic metres of water, containing 622,680,000 kilogrammes of dissolved and 547,140,000 of suspended matter, or a total of 1169 millions of kilogrammes. Of this total, 978 millions of kilogrammes consist of fixed and 192 millions of volatile (chiefly organic) matter. The proportions of some of the ingredients most important in agriculture were estimated as follows: lime, 140,380,000 kilogrammes; magnesia, 28,130,000; potash, 54,520,000; soda, 39,600,000; chloride of sodium, 25,320,000; sulphuric acid, 45,690,000; phosphoric acid, 1,500,000.[129]

Mr. T. Mellard Reade has estimated that a total of 8,370,630 tons of solids in solution is every year removed by running water from the rocks of England and Wales, which is equivalent to a general lowering of the surface of the country, from that cause alone, at a rate of ·0077 of a foot in a century, or one foot in 12,978 years. The same writer computes the annual discharge of solids in solution

---

[128] Prestwich, Q. J. Geol. Soc. xxviii. p. lxvii.

[129] Breitenlohner, Verhand. Geol. Reichsanst. Vienna, 1876, p. 172. Taking the 978,000,000 kilogrammes to be mineral matter in solution and suspension, this is equal to an annual loss of about 48 tons per English square mile. But it includes all the materials discharged by the drainage of an abundant population.

by the Rhine to be equal to 92·3 tons per square mile, that of the Rhone at Avignon 232 tons, that of the Danube 72·7 tons, and that of the Mississippi 120 tons. He supposes that on an average over the whole world there may be every year dissolved by rain about 100 tons of rocky matter per English square mile of surface.[130]

If the average proportion of mineral matter in solution in river-water be taken as only 2 parts in every 10,000 by weight, then it is obvious that in every 5000 years the rivers of the globe must carry to the sea their own weight of dissolved rock.

ii. Mechanical.—The mechanical work of rivers is threefold:—(1) to transport mud, sand, gravel, or blocks of stone from higher to lower levels; (2) to use these loose materials in eroding their channels; and (3) to deposit these materials where possible, and thus to make new geological formations.[131]

1. *Transporting Power.*[132]—One of the distinctions of river-water, as compared with that of springs, is that, as a rule, it is less transparent, in other words, contains more or less mineral matter in suspension.[133] A sudden heavy shower, or a season of wet weather, suffices to render turbid a river which was previously clear. The mud is washed into the main streams by rain and brooks, but is partly produced by the abrasion of the water-channels through the operations of the streams themselves. The channels of the mountain-tributaries of a river are choked with large fragments of rock disengaged from cliffs and crags on either

[130] Addresses, Liverpool Geol. Soc. 1876 and 1884.

[131] On the behavior of rivers, consult Dausse, "Études relatives aux inondations," Paris, 1872.

[132] See Login, Nature, i. pp. 629, 654; ii. p. 72.

[133] The brown color of river or estuary water is not always due to mud. In the Southampton water it is caused in summer by the presence of protozoa (Peredinium fuscum). A. Angell, Brit. Assoc. 1882, Sects. p. 589.

side. Traced downward, the blocks become gradually smaller and more rounded. They are ground against each other and upon the rocky sides and bottom of the channel, becoming more and more reduced as they descend, and at the same time abrading the rocks over or against which they are driven. Of the detritus thus produced, the finer portions are carried in suspension, and impart the characteristic turbidity to rivers; the coarser sand and gravel are driven along the river-bottom.[134]

The presence of a moving stratum of coarse detritus on the bed of a brook or river may be detected in transit, for though invisible beneath the overlying discolored water, the stones of which it is composed may be heard knocking against each other as the current sweeps them onward. Above Bonn, and again a little below the Lurelei Rock, while drifting down the Rhine, the observer, by laying his ear close to the bottom of the open boat, may hear the harsh grating of the gravel-stones over each other, as the current pushes them onward along the bottom. On the Moselle also, between Cochem and Coblentz, the same fact may be noticed.

The transporting capacity of a stream depends (*a*) on

---

[134] These operations of running water may be studied with great advantage on a small scale, where brooks descend from high grounds into valleys, rivers, or lakes. A single flood suffices for the transport of thousands of tons of stones, gravel, sand and mud, even by a small streamlet. At Lybster, for example, on the coast of Caithness, as the author was informed by Mr. Thomas Stevenson, C.E., a small streamlet carries down annually into a harbor which has there been made, between 400 and 500 cubic yards of gravel and sand. A weir or dam has been constructed to protect the harbor from the inroad of the coarser sediment, and this is cleaned out regularly every summer. But by far the greater portion of the fine silt is no doubt swept out into the North Sea. The erection of the artificial barrier, by arresting the seaward course of the gravel, reveals to us what must be the normal state of this stream and of similar streams descending from maritime hills. The area drained by the stream is about four square miles; consequently the amount of loss of surface, which is represented by the coarse gravel and sand alone, is $\frac{1}{12000}$ of a foot per annum.

the volume and velocity of the current, (*b*) on the size, shape, and specific gravity of the sediment, and (*c*) partly on the chemical composition of the water. (*a*) According to the calculation of Hopkins,[185] the capacity of transport increases as the sixth power of the velocity of the current; thus the motive power of the current is increased 64 times by the doubling of the velocity, 729 times by trebling, and 4096 times by quadrupling it. If a stream which, in its ordinary state, can just move pebbles weighing an ounce, has its velocity doubled by a flood, it can then sweep forward stones weighing 4 lb. Mr. David Stevenson[186] gives the subjoined table of the power of transport of different velocities of river currents:

In. per Second.		Mile per Hour.	
3	=	0·170	will just begin to work on fine clay.
6	=	0·340	will lift fine sand.
8	=	0·4545	will lift sand as coarse as linseed.
12	=	0·6819	will sweep along fine gravel.
24	=	1·3638	will roll along rounded pebbles 1 inch in diameter.
36	=	2·045	will sweep along slippery angular stones of the size of an egg.

It is not the surface velocity, nor even the mean velocity, of a river which can be taken as the measure of its power of transport, but the bottom velocity—that is, the rate at which the stream overcomes the friction of its channel. (*b*) The average specific gravity of the stones in a river ranges between two and three times that of pure fresh water; hence these stones when borne along by the river lose from a half to a third of their weight in air. Huge blocks which could not be moved by the same amount of energy applied to them on dry ground, are swept along when they have found their way into a strong river-

[185] Q. J. Geol. Soc. viii. p. xxvii.

[186] "Canal and River Engineering," p. 315. See also Thoulet, "Ann. des Mines," 1884, p. 507.

current. The shape of the fragments greatly affects their portability, when they are too large and heavy to be carried in mechanical suspension. Rounded stones are of course most easily transported: flat and angular ones are moved with comparative difficulty (see p. 653). (*c*) Pure water will retain fine mud in suspension for a long time; but the introduction of mineral matter in solution diminishes its capacity to do so, probably by lessening the molecular cohesion of the liquid. Thus the mingling of salt with fresh water causes a rapid precipitation of the suspended mud (p. 673). Probably each variety of river-water has its own capacity for retaining mineral matter in suspension, so that the mere mingling of these varieties may be one cause of the precipitation of sediment.[137]

Besides inorganic sediment, rivers sweep seaward the remains of land-animals and vegetation. The great rafts of the Mississippi and its tributaries are signal examples of this part of river-action. The Atchafalaya has been so obstructed by driftwood as to be fordable like dry land, and the Red River for more than a hundred miles flows under a matted cover of dead and living vegetation. The Amazon, Ganges, and other tropical rivers furnish abundant examples of the transport of a terrestrial fauna and flora to the sea. Minute forms of life sometimes constitute a considerable proportion of the so-called "solid impurity" of river-water. The mud of the Ganges, for instance, is esti-

[137] T. Sterry Hunt, Proc. Boston Nat. Hist. Soc. 1874; W. Durham, Chem. News, xxx., 1874, p. 57; xxxvii., 1878, p. 47; W. Ramsay, Quart. Journ. Geol. Soc. xxxii., 1876, p. 129; C. Barus, Bull. U. S. Geol. Surv. No. 36, 1886; Thoulet, Ann. Mines, xix., 1891, p. 5. In this last memoir M. Thoulet concludes as the result of his experiments that the precipitation of clays takes place in fresh water which has had an addition of ten per cent of sea-water (and consequently of density equal to 1·002) exactly as in pure sea-water, and that this observation furnishes a measure for determining the true limits of the ocean and the continents.

mated to contain from 12 to 25 per cent of infusoria, and that of the Nile 4·6 to 10 per cent.

Beyond their ordinary powers of transport, rivers gain at times considerable additional force from several causes. Those liable to sudden and heavy falls of rain, or to a rapid augmentation of their volume by the quick melting of snow, acquire by flooding an enormous increase of transporting and excavating power. More work may thus be done by a stream in a day than could be accomplished by it during years of its ordinary condition.[138] Another cause of sudden increase in the efficacy of river-action is provided when, from landslips formed by earthquakes, by the undermining influence of springs, or otherwise, a stream is temporarily dammed back, and the barrier subsequently gives way. The bursting out of the arrested waters produces great destruction in the valley. Blocks as big as houses may be set in motion, and carried down for considerable distances. Again, the transporting power of rivers may be greatly augmented by frost (see postea, p. 701). Ice forming along the banks or on the bottom, incloses gravel, sand, and even blocks of rock, which, when thaw comes, are lifted up and carried down the stream. In the rivers of northern Russia and Siberia, which, flowing from south to north, have the ice thawed in their higher courses before it breaks up further down, much disaster is sometimes caused by the piling up of the ice, and then by the bursting of the impeded river through the temporary ice-barrier. In another way, ice sometimes vastly increases the destructive power

---

[138] The extent to which heavy rains can alter the usual characters of rivers is forcibly exemplified in Sir T. Dick Lauder's "The Morayshire Floods." In the year 1829 the rivers of that region rose 10, 18, and in one case even 50 feet above their common summer level, producing almost incredible havoc. See also G. A. Koch, "Ueber Murbrüche in Tyrol," Jahrb. Geol. Reichsanst. xxv., 1875, p. 97.

of small streams, where avalanches or an advancing glacier cross a valley and pond back its drainage. The valley of the Dranse, in Switzerland, has several times suffered from this cause. In 1818, the glacier-barrier extended across the valley for more than half a mile, with a breadth of 600 and a height of 400 feet. The waters above the ice-dam accumulated into a lake containing 800,000,000 cubic feet. By a tunnel driven through the ice, the water was drawn off without desolating the plains below.

The amount of sediment borne downward by a river is not necessarily determined by the carrying power of the current. The swiftest streams are not always the muddiest. The proportion of sediment is partly dependent upon the hardness or softness of the rocks of the channel, the number of tributaries, the nature and slope of the ground forming the drainage-basin, the amount and distribution of the rainfall, the size of the glaciers (where such exist) at the sources of the river, the chemical composition of the water, and probably other causes. A rainfall spread with some uniformity throughout the year may not sensibly darken the rivers with mud, but the same amount of fall crowded into a few days or weeks may be the means of sweeping a vast amount of earth into the rivers, and sending them down in a greatly discolored state to the sea. Thus the rivers of India, swollen during the rainy season (sometimes by a rainfall of 25 inches in 40 hours, as at the time of the destructive landslip at Naini Tal in September, 1880), become rolling currents of mud.[139]

---

[139] In his journeys through equatorial Africa, Livingstone came upon rivers which appear usually to consist more of sand than of water. He describes the Zingesi as "a sand-rivulet in flood, 60 or 70 yards wide and waist deep. Like all these sand-rivers, it is for the most part dry; but, by digging down a few feet, water is to be found which is percolating along the bed on a stratum of

The amount of mineral matter transported by rivers can be estimated by examining their waters at different periods and places, and determining their solid contents. A complete analysis should take into account what is chemically dissolved, what is mechanically suspended, and what is driven or pushed along the bottom. We have already dealt with the chemically dissolved ingredients. In determinations of the mechanically mixed constituents of river-water, it is most advantageous to obtain the proportion first by weight, and then from its average specific gravity to estimate its bulk as an ingredient in the water. According to experiments made upon the water of the Rhone at Lyons, in 1844, the proportion of earthy matter held in suspension was by weight $\frac{1}{17000}$. Earlier in the century the results of similar experiments at Arles gave $\frac{1}{7000}$ as the proportion when the river was low, $\frac{1}{230}$ during floods, and $\frac{1}{2000}$ in the mean state of the river. The greatest recorded quantity is $\frac{1}{45}$ by weight, which was found "when the river was two-thirds up, with a mean velocity of probably about 8 feet per second."[140] A. Guérard, who has more recently made observations at the mouth of this river, estimates the total annual discharge of sediment to amount to 23,540,000 cubic yards, or $\frac{1}{2166}$ of the volume of the water.[141] Lombardini gives $\frac{1}{300}$ as the proportion by volume of the sediment in the water of the Po. In the Vistula, according to Spittell, the proportion by volume reaches a maximum of $\frac{1}{48}$.[142] The Rhine, according to Hartsoeker, contains $\frac{1}{100}$ by volume as it passes through Holland, while at Bonn the experiments of L. Horner gave a proportion of only $\frac{1}{16000}$ by volume.[143] Stiefensand found that, after a sudden flooding, the water of the Rhine at Uerdingen contained $\frac{1}{1282}$ by weight. Bischof measured the quantity of sediment in the same river at Bonn during a turbid state of the water, and found the proportion to be $\frac{1}{4878}$ by weight, while at another time, after several weeks of continuous dry weather,

clay. In trying to ford it," he remarks, "I felt thousands of particles of coarse sand striking my legs, which gave me the idea that the amount of matter removed by every freshet must be very great. . . . These sand-rivers remove vast masses of disintegrated rock before it is fine enough to form soil. In most rivers where much wearing is going on, a person diving to the bottom may hear literally thousands of stones knocking against each other."

[140] Surell, "Memoire sur l'amelioration des embouchures du Rhône." Humphreys and Abbot, "Report upon the Physics and Hydraulics of the Mississippi, 1861," p. 147.

[141] Min. Proc. Inst. Civ. Engin. lxxxii., 1884–85, p. 309.

[142] Ibid. p. 148.

[143] Edin. New Phil. Journ. xviii. p. 102.

and when the water had become clear and blue, he detected only $\frac{1}{67800}$.[144] In the Meuse, according to the experiments of Chandellon, the maximum of sediment in suspension in the mouth of December, 1849, was $\frac{1}{2100}$, the minimum $\frac{1}{71420}$, and the mean $\frac{1}{10000}$.[145] In the Elbe, at Hamburg, the proportion of mineral matter in suspension and solution has been found by experiment to average about $\frac{1}{7400}$. The Danube, at Vienna, yielded to Bischof about $\frac{1}{4200}$ of suspended and dissolved matter.[146] The Durance has ordinarily a maximum of 30 grammes of sediment to one litre of water, or $\frac{1}{33}$ by weight. In exceptional floods it rises to 100 grammes per litre of water, or $\frac{1}{10}$ by weight. In extreme low water the proportion may sink to about $\frac{1}{1000}$; the average for nine years from 1867 to 1875 was about $\frac{1}{550}$.[147] The Garonne is estimated to contain perhaps $\frac{1}{100}$.[148] In the Avon, which falls into the Severn, the mean amount of suspended mud is estimated at $\frac{1}{378}$.[149] The observations of Mr. Everest upon the water of the Ganges show that, during the four months of flood in that river, the proportion of earthy matter is $\frac{1}{428}$ by weight, or $\frac{1}{856}$ by volume; and that the mean average for the year is $\frac{1}{510}$ by weight, or $\frac{1}{1021}$ by volume.[150] According to Mr. Login, the waters of the Irrawaddy contain $\frac{1}{1700}$ by weight of sediment during floods, and $\frac{1}{5725}$ during a low state of the river.[151] In the Yangtse the proportion of sediment by weight is estimated by Mr. H. B. Guppy at $\frac{1}{2188}$.[152] The amount in the water of the River Plate is computed to be $\frac{1}{7752}$ by weight.[153] The Nile has been estimated to contain 159 parts of solid material in every 100,000 parts of water.

With regard to the amount of coarser and heavier sediment pushed along the bottom of a river by the downward current, it is more difficult to obtain accurate measurements. But it must sometimes constitute a large proportion of the total bulk of solid material discharged into the sea. In

---

144 "Chemical Geology," i. p. 122.

145 Annales des Travaux publics de Belgique, ix. 204.

146 Op. cit. i. p. 130. More recent observations by Sir Charles Hartley show that the mean proportion of sediment by weight in the Danube water for ten years from 1862 to 1871 was $\frac{1}{3060}$, or (at specific gravity 1·9) $\frac{1}{5814}$ by volume.

147 G. Wilson, Min. Proc. Inst. Civ. Engin. li., 1877–78, p. 216.

148 Baumgarten, cited by Réclus, "La Terre."

149 T. Howard, Brit. Assoc. 1875, p. 179.

150 Journ. Asiatic Society of Calcutta, March, 1832.

151 Proc. Roy. Soc. Edin. 1857.

152 Nature, xxii. p. 486. According to Dr. A. Woeikoff, this estimate is much under the truth; xxiii. p. 9. See also op. cit. p. 584.

153 G. Higgin, Nature, xix. p. 555.

the case of the Rhone, for example, it is concluded by M. Guérard, that the quantity of sand rolled along the bed of this river into the Mediterranean in the course of a year is much greater than the lighter matter held in suspension in the water, and that "when the river, on approaching the sea, is no longer confined by embankments, the greater part of its alluvium is rolled along its bed." In flood-time it is not uncommon for whole banks of sand to travel bodily down the river.[154]

The most extensive and accurate determinations yet made upon the physics and hydraulics of a river are those of the United States Government upon the Mississippi. As the mean of many observations carried on continuously at different parts of the river for months together, Humphreys and Abbot, the engineers charged with the investigation, found that the average proportion of sediment contained in the water of the Mississippi is $\frac{1}{1500}$ by weight, or $\frac{1}{2900}$ by volume.[155] But besides the matter held in suspension, they observed that a large amount of coarse detritus is constantly being pushed along the bottom of the river. They estimated that this moving stratum carries every year into the Gulf of Mexico about 750,000,000 cubic feet of sand, earth, and gravel. Their observations led them to conclude that the annual discharge of water by the Mississippi is 19,500,000,000,000 cubic feet, and consequently that the weight of mud annually carried into the sea by this river must reach the sum of 812,500,000,000 pounds. Taking the total annual contributions of earthy matter, whether in suspension or moving along the bottom, they found them to equal a prism 268 feet in height with a base of one square mile.

The value of these data to the geologist consists mainly in the fact that they furnish him with materials for an approximate measurement of the rate at which the surface of the land is lowered by subaerial waste. This subject is discussed at p. 771.

2. *Excavating Power.*—It was a prominent part of the teaching of Hutton and Playfair, that rivers have excavated the channels in which they flow. Experience in all parts of the world has confirmed this doctrine. The mechanical

---

154 Mem. Proc. Inst. Civ. Engin. lxxxii., 1884–85, p. 309.

155 "Report," p. 148. The specific gravity of the silt of the Mississippi is given as 1·9.

erosive work of running water depends for its rate and character upon (*a*) the friction of the detritus driven by the current against the sides and bottom of a water-course, modified by (*b*) the varying declivity and the geological structure of the ground.

(*a*) Driven downward by the descending water of a river, the loose grains and stones are rubbed against each other, as well as upon the rocky bed, until they are reduced to fine sand and mud, and the sides and bottom of the channel are smoothed, widened, and deepened. The familiar effect of running water upon fragments of rock, in reducing them to rounded pebbles, is expressed by the common epithet "water-worn." A stream which descends from high rocky ground may be compared to a grinding mill; large bowlders and angular blocks of rock, disengaged by frosts, springs, and general atmospheric waste, fall into its upper end; fine sand and silt are discharged into the sea.

In the series of experiments already referred to (p. 640), Prof. Daubrée made fragments of granite and quartz to slide over each other in a hollow cylinder partially filled with water, and rotating on its axis with a mean velocity of 0·80 to 1 metre in a second. He found that after the first 25 kilometres (about 15½ English miles) the angular fragments of granite had lost $\frac{4}{10}$ of their weight, while in the same distance fragments already well rounded had not lost more than $\frac{1}{100}$ to $\frac{1}{400}$. The fragments rounded by this journey of 25 kilometres in a cylinder could not be distinguished either in form or in general aspect from the natural detritus of a river-bed. A second product of these experiments was an extremely fine impalpable mud, which remained suspended in the water several days after the cessation of the movement. During the production of this fine sediment, the water, even though cold, was found in a day or two to have acted chemically upon the granite fragments. After a journey of 160 kilometres, 3 kilogrammes (about 6½ lbs. avoirdupois) yielded 3·3 grammes (about 50 grains) of soluble salts, consisting chiefly of silicate of potash. A third product was an extremely fine angular sand consisting almost wholly of quartz, with scarcely any felspar, nearly the whole of the latter mineral having passed into the state of clay. The sand grains, as they are continually pushed onward over each other upon the bottom of a river, become rounded as the larger pebbles do. But a limit is placed to this attrition by the size and specific gravity of the grains.[156] As a rule, the smaller particles suffer proportionately less loss than the larger, since the friction on the bottom varies directly as the weight and therefore as the cube of the diameter, while the surface exposed to attrition varies as the square of the diameter. Mr. Sorby, in calling attention to this relation, remarks that a grain $\frac{1}{10}$ of an inch in diameter would be worn ten times as much as one $\frac{1}{100}$ of an inch in diameter, and a pebble 1 inch in diameter would be worn relatively more by being drifted a few hundred yards than a sand grain $\frac{1}{1000}$ of an inch in diameter would be by being drifted for a hundred miles.[157] So long as the particles are borne along in suspension, they will not abrade each other, but remain angular. Prof. Daubrée found that the milky tint of the Rhine at Strasburg in the months of July and August was due, not to mud, but to a fine angular sand (with grains about $\frac{1}{20}$ millimetre in diameter) which constitutes $\frac{2}{100000}$ of the total weight of water. Yet this sand had travelled in a rapidly flowing tumultuous river from the Swiss mountains, and had been tossed over waterfalls and rapids in its journey. He ascertained also that sand grains with a mean diameter 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, is rounded, and loses about $\frac{1}{10000}$ of its weight in every kilometre travelled.[158]

The effects of abrasion upon the loose materials on a river-bed are but a minor part of the erosive work performed by the stream. A layer of débris, only the upper portion of which is pushed onward by the normal current, will protect the solid rock of the river-channel which it covers, but

156 "Geologie Experimentale," p. 250 *et seq.*
157 Q. J. Geol. Soc. xxxvi. p. 59.
158 "Geologie Experimentale," pp. 256, 258.

it is apt to be swept away from time to time by violent floods. Sand, gravel, and bowlders, in those parts of a river-channel where the current is strong enough to keep them moving along, 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 the rocks, this erosive ac-

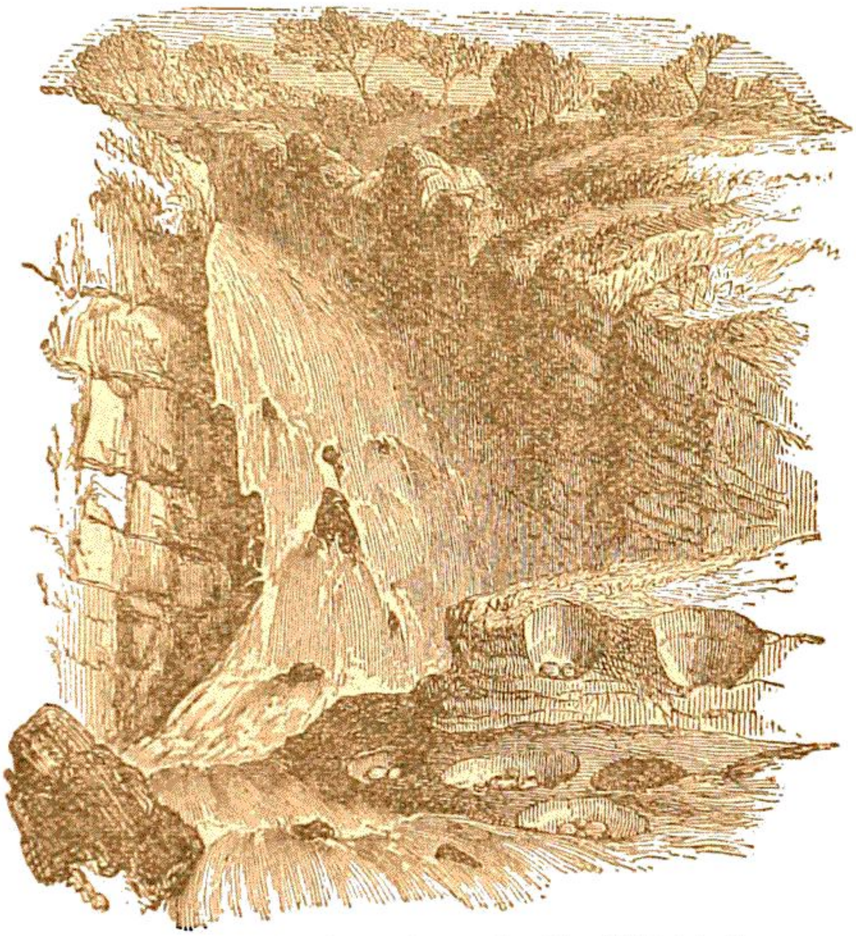


Fig. 115.—Rocky river-channel with old Pot-holes.

tion is liable to continual modifications. It advances 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 (Fig. 115). Such *pot-holes*, as they are termed, vary in size from mere cup-like depressions to huge caldrons 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.

That a river erodes its channel by means of its transported sediment and not by the mere friction of the water, is sometimes admirably illustrated in the course of streams filtered by one or more lakes. As the Rhone escapes from the Lake of Geneva, it sweeps with a swift clear current over ledges of rock that have not yet been very deeply eroded. The Niagara supplies a still more impressive example. Issuing from Lake Erie, and flowing through a level country for a few miles, it approaches its falls by a series of rapids. The water leaves the lake with hardly any appreciable sediment, and has too brief a journey in which to gather it, before beginning to rush down the rocky channel toward the cataract. The sight of the vast body of clear water, leaping and shooting over the sheets of limestone in the rapids, is in some respects quite as striking a scene as the great falls. To a geologist it is specially instructive; for he can observe that, notwithstanding the tremendous rush of water which has been rolling over them for so many centuries, these rocks have been comparatively little abraded. The smoothed and striated surface left by the ice-sheet of the Glacial Period can be traced upon them almost to the water's edge, and the flat ledges at the rapids are merely a prolongation of the ice-worn surface which passes under the banks of drift on either side. The river has hardly eroded more than a mere superficial skin of rock here since it began to flow over the glaciated limestone.

Similar evidence is offered by the St. Lawrence. This majestic river leaves Lake Ontario as pure as the waters of the lake itself. The ice-worn hummocks of gneiss at the Thousand Islands still retain their characteristic smoothed and polished surface down to and beneath the surface of the current. In descending the river, I was astonished to observe that the famous rapids of the St. Lawrence are actually hemmed in by islets and steep banks of bowlder-clay, and not of solid rock. So little obvious erosion does the current perform, even in its tumultuous billowy descent, that a raw scar of clay betokening a recent slip is hardly to be seen. The banks are so grassed over, or even covered with trees, as to prove how long they have remained undisturbed in their present condition. That very considerable local destruction of these clay-islands, however, has been caused by floating ice will be alluded to further on.

Mere volume and rapidity of current, therefore, will not cause much erosion of the channel of a stream unless sediment be present in the water. A succession of lakes, by detaining the sediment, must necessarily enfeeble the direct excavating power of a river. On the other hand, by the disintegrating action of the atmosphere, and by the operations of springs and frosts, loose detritus as well as portions of the river-banks are continually being launched into the currents, which, as they roll along are thus supplied with fresh materials for erosion.

(*b*) Besides the obvious relation between the angle of slope of a river-bed and the scouring force of the river, a dominant influence, in the gradual excavation of a river-channel, is exercised by the lithological nature and geological structure of the rocks through which the stream flows. This influence is manifested in the form of the channel, the angle of declivity of its banks, and in the details of its erosion. On a small but instructive scale these phenomena are revealed in the operations of brooks. Thus, 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 round which the upper water sweeps with increased velocity, while under-currents tend to carry sediment across to the opposite side. The outer bank is accordingly worn away, while the inner or concave side of the bed is not attacked, but is even protected by a deposit of sand or gravel.[159] Thus, 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 proportionately diminishes, until, before quitting the plain, the stream may become a lazy, creeping current, in England commonly bordered with sedges and willows. A stream may eventually cut through the neck of land between two loops, as at *a*, *b*, and *c*, in Fig. 116, and thus for a while shorten its channel. Instances of this nature may frequently be observed in streams flowing through alluvial land. The old deserted loops[160] are converted, first into lakes, and by degrees into stagnant pools or bogs, until finally, by growth of vegetation and infilling of sediment by rain and wind, they become dry ground.

---

159 J. Thomson, Proc. Roy. Soc. xxv., 1876, p. 5.
160 "Aigues-mortes," or dead waters. See p. 680, note.

Although most frequent in soft alluvial plains, serpentine water-courses may also be eroded in solid rock if the original form of the surface was tolerably flat. The windings of the gorges of the Moselle (Fig. 117) and Rhine through the table-land between Trèves, 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 water-

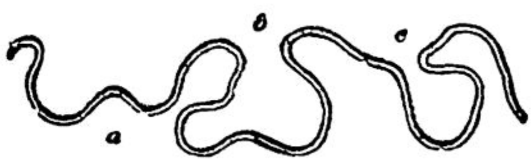


Fig. 116.—Meandering course of a brook.

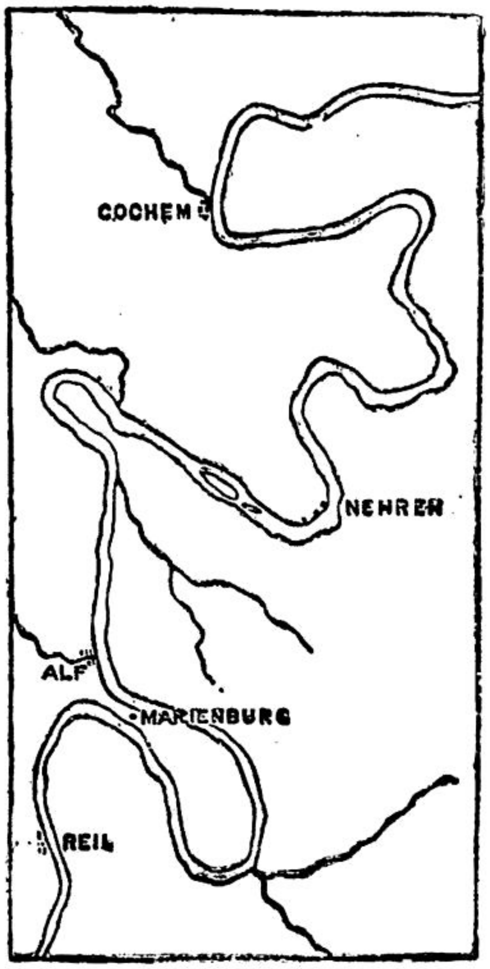


Fig. 117.—Windings of the gorge of the Moselle above Cochem.

falls. In many cases, this feature of river-scenery has 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. The occurrence of horizontal, tolerably compact strata, traversed by marked lines of joint, and resting upon softer beds, presents a structure well adapted for showing the part played by waterfalls in river-erosion. The waterfall acts with special potency against the softer underlying materials at its base. These are hollowed out, and as the foundations of the superincumbent more solid rocks are destroyed, slices of the latter from time to time fall off into the boiling whirlpool, where they are reduced to fragments, and carried down the stream. Thus the waterfall cuts its way backward up the stream, and as it advances it prolongs the excavation of the ravine into which it descends. The student will frequently observe, in the recession of waterfalls and consequent erosion of ravines, the important part taken by lines of joint in the rocks. These lines have often determined the direction of the ravine, and the vertical walls on either side depend for their precipitousness mainly upon these divisional planes in the rock.

The gorge of the Niagara affords a magnificent and remarkably simple illustration of these features of river-action. At its lower end, where it enters the wide plain that extends to Lake Ontario, there stretches away, on either side of the river, a line of cliff and steep wooded bank, formed by the escarpment of the massive Niagara limestone. Back from this line of cliff, through which it issues into the lacustrine plain, the gorge of the river extends for about 7 miles, with a width of from 200 to 400 yards, and a depth of from 200 to 300 feet. At the upper end lie the world-renowned falls. The whole of this great ravine has unquestionably been cut out by the recession of the falls. When the river first began to flow, it may have found the escarpment running across its course, and may then have begun the excavation of its gorge. More probably, however, the escarpment and waterfall began to arise simultaneously and from the same geological structure. As the former 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 while at present the cliff, worn down by atmospheric disintegration, stands at Queenstown, the ravine dug by the river extends 7 miles further inland. The waterfall will continue to cut

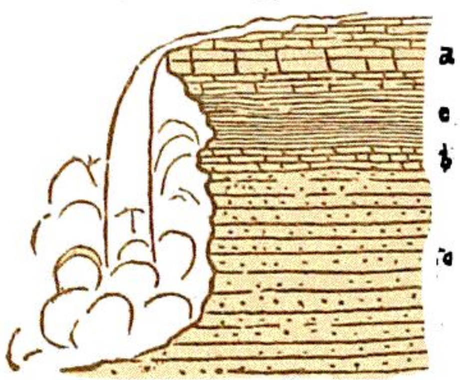


Fig. 118.—Section at the Horseshoe Falls, Niagara.

a, Medina Sandstone, 300 feet; *b*, Clinton Limestone and Shale, 30 feet; *c*, Niagara Shale, 80 feet; *d*, Niagara Limestone, 165 feet, of which 85 feet are visible at the fall.

its way back as long as the structure of the gorge continues as it is now—thick beds of limestone resting horizontally upon soft shales (Fig. 118). The softer strata at the base are undermined, and slice after slice is cut off from the cliff over which the cataract pours. The parallel walls of this great gorge owe their direction and mural character to parallel joints of the strata. The lesser or American fall (A in Fig. 119) enters by the side of the ravine and falls over its lateral wall. The larger or Canadian (Horseshoe) fall (C) occupies the head of the ravine, and owes its form to the intersection of two sets of joints. The structure of the gorge being the same at both falls, it seems reasonable to infer that as the American fall, which appears to be diminishing in volume, has cut back only somewhere about

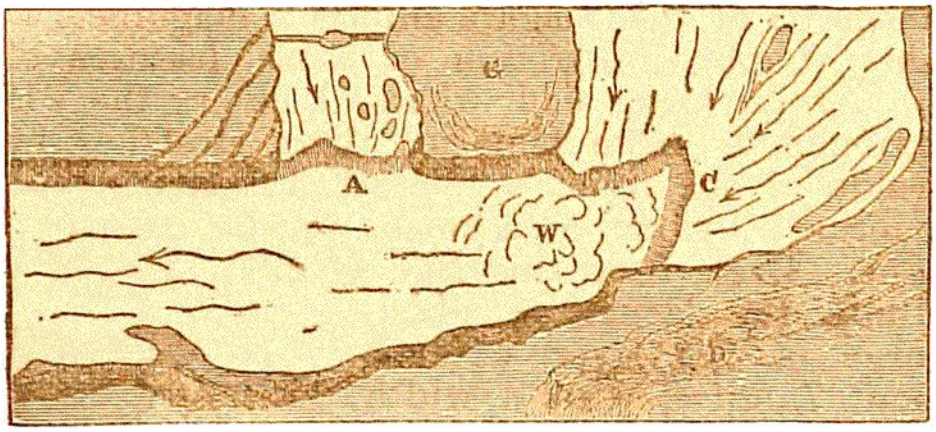


Fig. 119.—Plan of the Ravine of Niagara at the Falls.
A, American Fall; C, Canadian Fall; W, Whirlpool; G, Goat Island; D, Bank of Drift resting on ice-worn sheets of Limestone.

140 feet from the original face of the ravine, this branch of the river has, comparatively speaking, only recently begun to work. Goat Island, which now separates the two falls, is an outlier of drift resting on the limestone. It has been cut off from the rest of the ground on the right bank of the river by the branch which rejoins the main stream by the American fall. From the position of the glacial striæ it may be concluded that a great part, if not the whole of the ravine has been excavated since the Glacial Period. There are indications, indeed, of a pre-glacial valley by which the waters of Lake Erie joined those of Ontario, before the erosion of the present gorge. Bakewell, from historical notices and the testimony of old residents, inferred that the rate of recession of the falls is three feet in a year. Lyell, on no better kind of evidence, concluded that "the average of one foot a year would be a much more

probable conjecture," and estimated the length of time required for the excavation of the whole Niagara ravine at 35,000 years.[161] A commission recently appointed to survey the falls and to ascertain the rate of recession has reported (1890) that since 1742, when the first survey was made, the total mean recession of the Horseshoe falls has been 104 feet 6 inches. The maximum recession at one point is 270 feet. The mean recession of the American falls is 30 feet 6 inches. The length of the crest has increased from 2260 to 3010 feet by the washing away of the embankment. The total area of recession of the American falls is 32,900 square feet, and that of the Horseshoe falls 275,400 feet.

A feature of interest in the future history of the Niagara river deserves to be noticed here. It is evident that if the structure of the gorge continued the same from the falls

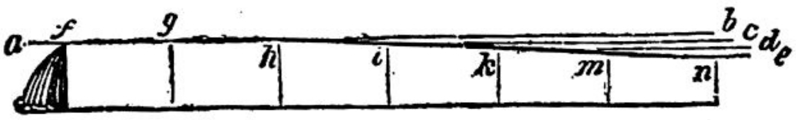


Fig. 120.—Section to illustrate the lowering of Lake Erie by the recession of Niagara Falls.

to Lake Erie, the recession of the falls would eventually tap the lake, and reduce its surface to the level of the bottom of the ravine. Successive stages in this retreat of the falls are shown in Fig. 120, by the letters *f* to *n*, and in the consequent lowering of the lake by the letters *a*, *b* to *e*. It is believed, however, that a slight inclination of the strata carries the soft underlying shale out of possible reach of the fall, which will retard indefinitely the lowering of the lake.

A waterfall may occasionally be observed to 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 in-

---

[161] Lyell, "Travels in North America," i. p. 32; ii. p. 93. "Principles." i. p. 358. Compare Lesley's "Coal and its Topography," 1856, p. 169. On recent changes at the falls, see Marcou, Bull. Soc. Geol. France (2), xxii. p. 290. The Falls of St. Anthony on the Mississippi show, according to Winchell, a rate of recession varying from 3·49 to 6·73 feet per annum, the whole recession since the discovery of the falls in 1680 to the present time being 906 feet. Q. J. Geol. Soc. xxxiv. p. 899.

trusive dike or mass of basalt, or where, as in the case of the Rhine at Schaffhausen, and possibly in that of the Niagara, the stream has been diverted out of its ancient course by glacial or other deposits, so as to be forced to carve out a new channel, and rejoin its older one by a fall.[162] 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 resemblance of a deep narrow river-gorge to a rent opened in the ground by subterranean agency, has often

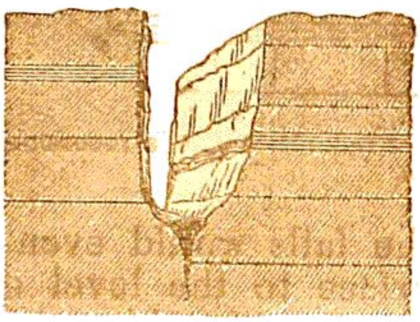


Fig. 121.—River-gorge in line of Fault.

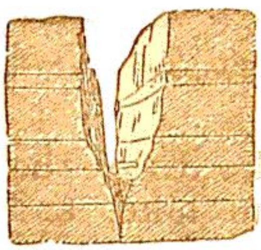


Fig. 122.—River-gorge in fissured strata.

led to a mistaken belief that such marked superficial features could only have arisen from actual violent dislocation. Even where something is conceded to the river, there is a natural tendency to assume that there must have been a line of fault and displacement as in Fig. 121, or at least a line of crack, and consequent weakness (Fig. 122). But the existence of an actual fracture is not necessary for the formation of a ravine of the first magnitude. The gorge of the Niagara, for example, has not been determined by any dislocation. Still more impressive proof of the same fact is furnished by the most marvellous river-gorges in the world—those of the Colorado region in North America.

[162] Würtemberger, Neues Jahrb. 1871, p. 582.

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 depth. In many instances there are two cañons, the upper being several miles wide, with vast lines of cliff-walls and a broad plain between them, in which runs the second cañon as another deep gorge with the river winding over its bottom. 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.[163] Some idea of the vastness of the erosion of these plateaus may be formed from Fig. 123, the Frontispiece to this work, and the illustrations in Book VII.

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 effective than that of the atmospheric agents. The sides of the ravine consequently retain their vertical character, which, where they coincide with lines of joint, is further preserved by the way in which atmospheric weathering acts along the joints. But where, from the nature of the ground or of the climate, 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, carrying away the materials washed into it from the surrounding slopes by rain and brooks.

3. *Reproductive Power*.—Every body of water which,

---

[163] For descriptions and figures of this remarkable region, see Ives and Newberry, "Explorations of the Colorado River of the West," 1861; J. W. Powell, "Exploration of the Colorado River of the West and its Tributaries," 1875; Captain Dutton, "Tertiary History of the Grand Cañon of the Colorado"; Monograph II. U. S. Geological Survey, 4to, 1882; and postea, Book VII.

when in motion, carries along sediment, drops it when at rest. The moment a current has its rapidity checked, it is

Fig. [illegible].—View of the erosion of the San Juan, Colorado Basin (Newberry).

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 Fig. 124 the river in flowing from *a* to *b* has a less angle of declivity and a smaller transporting power, and will therefore have a greater tendency to throw down sediment, than in descending the steeper gradient from *b* to *c*.

In the course of every brook and river, there are fre-

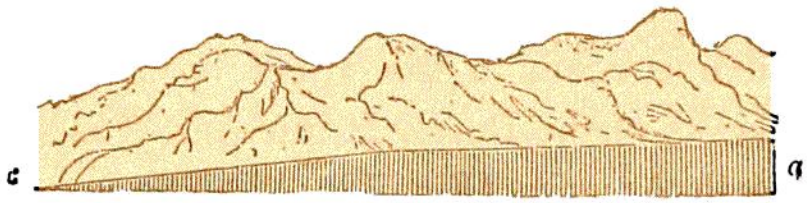


Fig. 124.—Section of part of a river-channel (*B.*).

quent 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

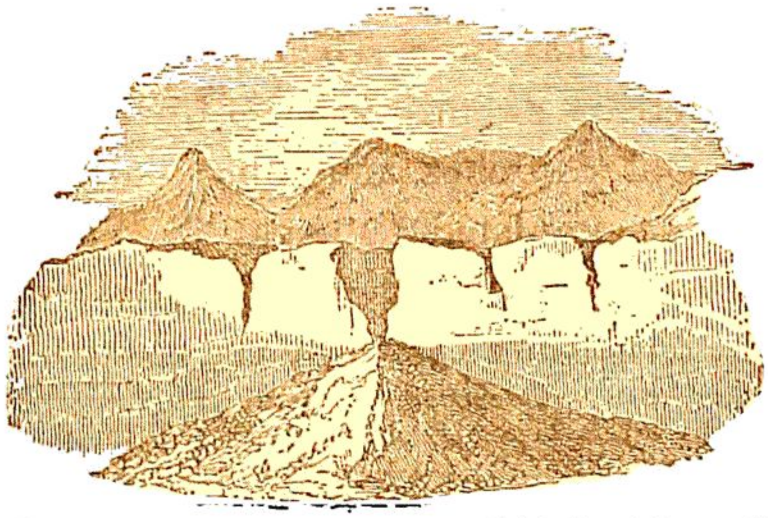


Fig. 125.—Tributary torrent sending a cone of detritus into a valley (*B.*).

torrent descends a steep declivity it tears down the soil and rocks, cutting a gash out of the side of the mountain (Fig. 125). On reaching the more 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 ("*cone de déjection*"; "*Murbrüche*"[164]), with the apex pointing up the water-course. Huge accumulations of bowlders and shingle may thus be seen at the foot of such torrents—the water flowing through them, often in several channels which reunite in the plain beyond. From the deposits of small streams, every gradation of size may be traced up to huge fans many miles in diameter and several hundred feet thick, such as occur in the upper basin of the Indus[165] and on the flanks of the Rocky Mountains,[166] as well as other ranges in North America (Fig. 126).[167] The level of the val-

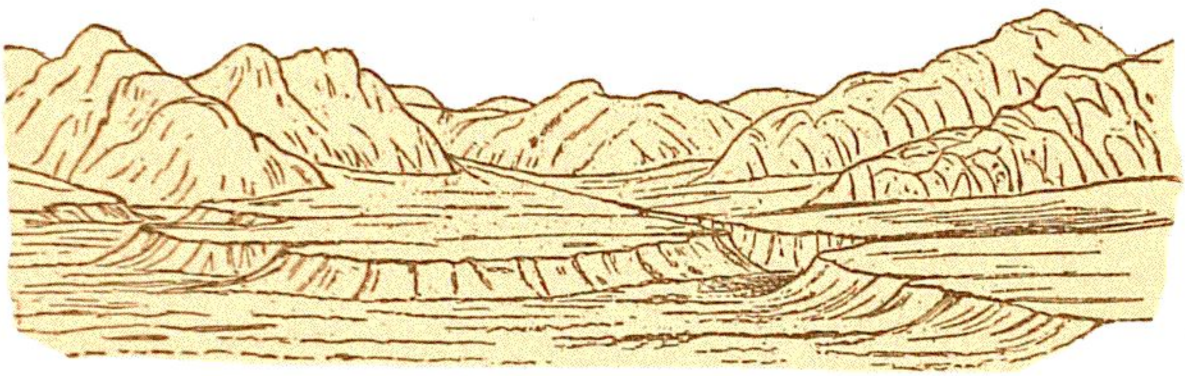


Fig. 126.—Fans of Alluvium. Madison River, Montana.

leys in the Tyrol has been sensibly raised within historic times by the detritus swept into them from the surrounding mountains. Old churches and other buildings are half-buried in the accumulated sediment.[168]

(*b*) In River-beds.—The deposition of alluvium on river-beds is characteristically shown by the accumulation of sand

---

[164] G. A. Koch, Jahrb. Geol. Reichsanst. xxv., 1875, p. 97, describes the debacles of the Tyrol. Consult also the work of Surell and Cézanne cited on p. 630.

[165] On the alluvial deposits of this region, see Drew, Q. J. Geol. Soc. xxix. p. 441; also his "Jummoo and Kashmere Territories," 1875.

[166] See Dutton's "High Plateaus of Utah." Hayden's "Reports of the U. S. Geological and Geographical Surveys of the Territories."

[167] In the great inland basin of North America, which includes the arid tracts of Great Salt Lake and other saline waters, the depth of accumulated detritus must amount in many places to several thousand feet. See on this subject I. C. Russell, Geol. Mag. 1889, and Gilbert's Essay on Lake-Shores in the 5th Annual Report of the U. S. Geol. Surv.

[168] G. A. Koch, Jahrb. Geol. Reichsanst. xxv., 1875, p. 123.

or shingle at the concave side of each sharp bend of a river-course. While the main upper current is making a more rapid sweep round the opposite bank, undercurrents pass across to the inner side of the curve and drop their freight of loose detritus, which, when laid bare in dry weather, forms the familiar sand-bank or shingle-beach. Again,

Fig. 127.—Section of a River-plain, showing heightening of channel by deposits of sediment (*B.*).

when a river, well supplied with sediment, leaves mountainous ground where its course has been rapid, and enters a region of level plain, it begins to drop its burden on the channel, which is thereby heightened, till it may actually rise above the level of the surrounding plains (Fig. 127).

This tendency is displayed by the Adige, Reno, and Brenta, which, descending from the Alps well supplied with detritus, debouch on the plains of the Po.[169] The Po itself has been quoted as an instance of a river continuing to heighten its bed, while man in self-defence heightens its embankments, until the surface of the river becomes higher than the plains on either side. It has been shown by Lombardini, however, that the bed of this river has undergone very little change for centuries; that only here and there does the mean height of the water rise above the level of the plains, being generally considerably below it, and that even in a high flood the surface of the river is scarcely ten feet above the pavement in front of the Palace at Ferrara.[170] The Po and its tributaries have been carefully embanked, so that much of the sediment of the rivers, instead of accumulating on the plains of Lombardy, as it naturally would do, is

[169] It is in the north of Italy that the struggle between man and nature has been most persistently waged. See Lombardini in Ann. des Ponts-et-Chaussees, 1847. Beardmore's "Tables," p. 172. The bed of the Yangtse-Kiang has been raised in places far above the level of the surrounding country by embanking. E. L. Oxenham, Journ. Geog. Soc. xlv., 1875, p. 182.

[170] Between Mantua and Modena the Po is said to have raised its bed more than 5½ metres since the 15th century. Dausse, Bull. Soc. Geol. France, iii. (3me ser.) p. 137.

carried out into the Adriatic. Hence, partly, no doubt, the remarkably rapid rate of growth of the delta of the Po. But in such cases, man needs all his skill and labor to keep the banks secure. Even with his utmost efforts, a 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. The most stupendous example of the gradual heightening of a plain by river deposits, and of the devastation caused by the bursting of the artificial barriers raised to control the stream, is that of the Hoang Ho or Yellow River. So frequently has this river changed its course across the great eastern plain, and so appalling has been the consequent devastation, that it has received the name of "China's sorrow." The last great inundation took place in the autumn of 1887, when hundreds of villages were submerged and more than a million human beings were drowned. Breaking down its frail embankment, the stream poured through the breach, which was some 1200 yards wide, and spread out over a width of 30 miles in a current ten to twenty feet deep in the middle.

(*c*) On River-banks and Flood-plains.—As is partly implied in the action described in the foregoing paragraph, alluvium is laid down on the level tracts or flood-plain over which a river spreads in flood. It consists usually of fine silt, mud, earth, or sand; though close to the channel, it may be partly made up of 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 more or less of their mud and sand. If the plains happen to be covered with wood, bushes, scrub, or tall grass, the vegetation acts the part of a sieve, and filters the muddy water, which may rejoin the main stream comparatively clear. The height of the plain is thus increased by every flood, until, partly from this cause and partly, in the case of a rapid stream, from the erosion of the channel, the plain can no longer be overspread by the river. 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, and from the behavior of water flowing in irregular channels, to wind from side to side in wide curves and loops,

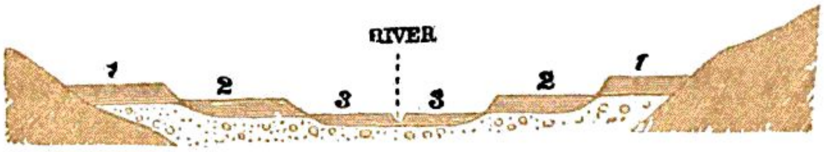


Fig. 128.—Section of River-terraces.

and cuts into its old alluvium, making eventually a newer plain at a lower level. Prolonged 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 (Fig. 128), the surface of 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. On the Seine and other rivers of the North of France, there is a marked terrace at a height of 12 to 17 metres above the present water-level. 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* (Fig. 129). The modern alluvium of the Mississippi, from the mouth of the Ohio to the Gulf of Mexico, covers an area of 19,450 miles, and has a breadth of from 25 to 75 miles and a depth of from 25 to 40 feet. The old alluvium of the Amazon likewise forms extensive lines of cliff for hundreds of miles, beneath which a newer platform of detritus is being formed.[171]

[171] The stages of terrace-making in the regime of a great river are well brought out in the case of the Amazon. C. B. Brown, Q. J. Geol. Soc. xxxv. p. 763. The subject of the origin of river-terraces is discussed by Mr. H. Miller of the Geological Survey in Proc. Roy. Phys. Soc. Edin. 1883, p. 263.

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 deeper and broader than now, before the formation of the terraces, Fig. 128); 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 upheaval of the interior of the country, which would accelerate the erosive action of the

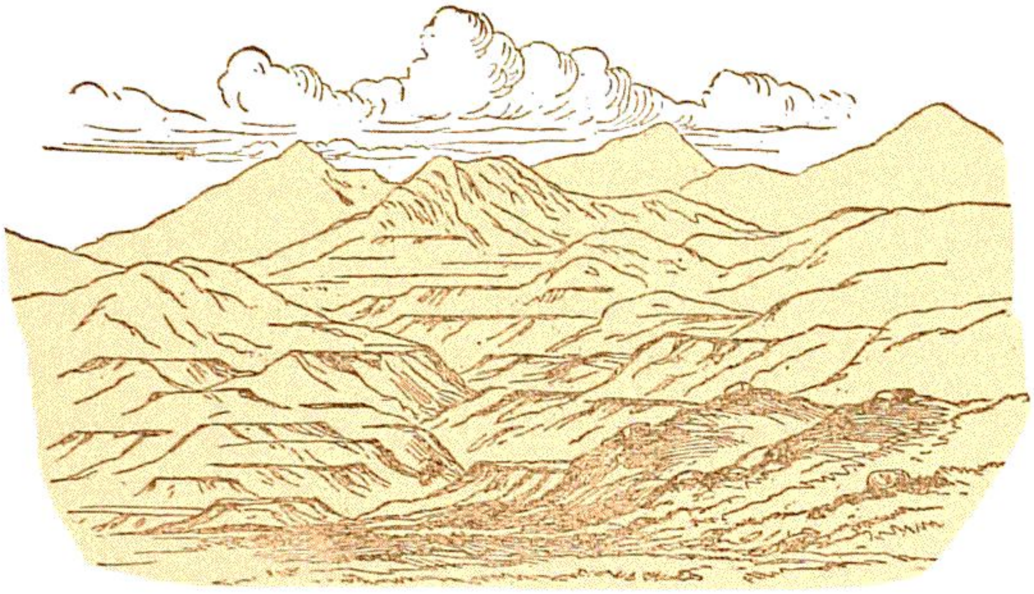


Fig. 129.—Old Terraces on the left bank of the Yellowstone River, above the first Canon, Montana.

streams, or to depression of the interior or rise of the sea-ward tracts, which would diminish that action and increase the deposition of alluvium. Prof. Dana has connected the terraces of America with the elevation of the axis of that continent. There can be no doubt that both in Europe and North America the rivers at a comparatively recent geological period had a much greater volume than they now possess.

(*d*) In Lakes.—When a river enters a lake or inland sea its current is checked, and its sediment begins to spread in fan-shape over the bottom (*c* in Fig. 130). Every tributary stream brings in its contribution of detritus. In this way, a series of shoals is pushed out into the lake (Fig. 131 and p. 685). This phenomenon may frequently be instructively observed from a height overlooking a small lake among mountains. At the mouth of each torrent or brook lies a little tongue of its alluvium (a true *delta*), through which the streamlet winds in one or more branches, before mingling its waters with those of the lake. Two streams entering from opposite sides (as at *c*, *d*, Fig. 131) may join their alluvia and divide a lake into two, like the once united

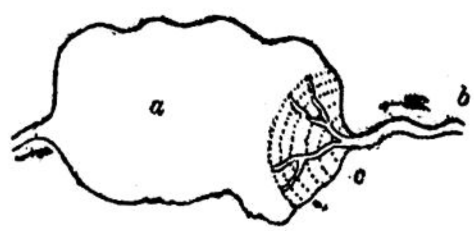


Fig. 130.—Streamlet (*b*) entering a small lake (*a*), and depositing a fan of sediment (*c*).

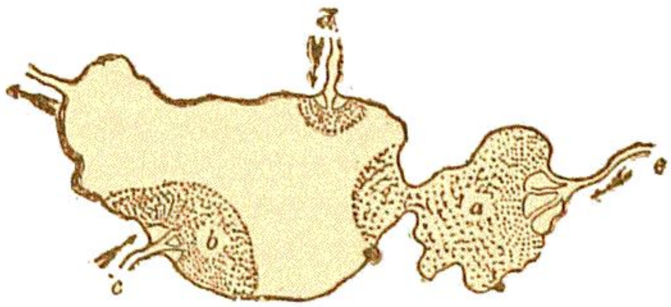


Fig. 131.—Plan of a lake entered by three streams (*c*, *d*, *e*), each of which deposits a cone of sediment (*a*, *b*) at its mouth.

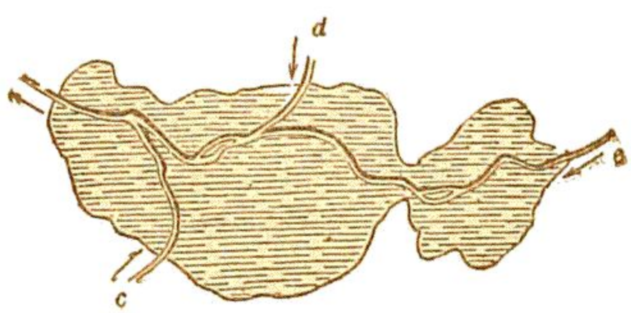


Fig. 132.—Lake (as in Fig. 131) filled up and converted into an alluvial plain by the three streams, *c*, *d*, *e*.

lakes of Thun and Brienz at Interlaken. Or, by the advance of the alluvial deposits, the lake may be finally filled up altogether, as has happened in innumerable cases in all mountainous countries (Fig. 132).

The rapidity of the infilling is sometimes not a little remarkable. Since the year 1714, the Kander is said to have thrown into the Lake of Thun a delta measuring 230 acres, now partly woodland, partly meadow and marsh. The Aar, at its entrance into the Lake of Brienz, has deposited a delta 3500 to 4000 feet broad, formed of detritus which at the mouth of the river has an outward slope of 30°, that gradually falls to the nearly level lake floor. In twenty-seven years after its rectification the Reuss had laid down in the Lake of Lucerne a delta estimated to contain upward of 141 million of cubic feet of sediment, which is equivalent to a discharge of 19,350 cubic feet in a day, or nearly 7,000,000 cubic feet in a year.[172]

In the case of a large lake whose length is great in proportion to the volume of the tributary river, the whole of the detritus may be deposited, so that, at the 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 escapes at Geneva as blue translucent water. Its sediment is laid down on the floor of the lake, and chiefly at the upper end, as an important delta which quite rivals that of a great river in the sea. Hence, lakes act as filters or sieves to intercept the sediment which is travelling in the rivers from the high grounds to the sea (p. 684).[173]

(*e*) Estuarine Deposits; Bars and Lagoon-barriers.—If we take a broad view of terrestrial degradation, we must admit that the deposit of any sediment on the land is only temporary; the inevitable destination of all detrital material is the floor of the sea. Where a gently flowing river comes within the influence of the alternate rise and fall of the tides, a new set of conditions is established in regard to the disposal of the sediment. During the flow of the tide in the Severn, for example, the suspended mud is carried up the estuary, and sometimes far up its tributaries. For

[172] A. Heim, Jahrb. Schweizer Alpenklubs, 1879.

[173] Consult a suggestive essay, G. K. Gilbert on the topographic features of lake-shores, 5th Ann. Rep. U. S. Geol. Surv. 1885, p. 75.

two-thirds of the ebb, though the surface-water is running out rapidly, the bottom-water is practically at rest: only during the remaining third of the ebb does the bottom-water flow outward and with sufficient velocity to scour the channel. But this lasts for so short a time that it hardly removes as much mud or sand as has been laid down during flood and the earlier part of ebb-tide. Hence the sediment is in a state of continual oscillation upward and downward in the estuary. At the lower end, some portion of it is continually being swept out to sea. At the upper end, fresh material of similar kind is being supplied by the river. But, between these two limits, the same sediment may be kept in suspension or may be alternately deposited and removed for many weeks or months before it finally escapes to sea and is spread out on the bottom. To this cause, doubtless, the remarkable turbidity of many estuaries is to be attributed.[174]

Where a river, with a considerable velocity of current, enters the sea, its mouth is commonly obstructed by a bar of gravel, sand, or mud. The formation of this barrier results from the conflict between the river and the ocean. 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 at the bottom, which therefore accumulates and tends to form a bar. Moreover, as already mentioned (p. 646), though fresh water can for a long time retain 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 current at the river-mouth, the mere mingling of

---

[174] See an interesting paper by Prof. Sollas, Q. J. Geol. Soc. xxxix., 1883, p. 611, and authorities there cited.

a river with the sea must of itself be a cause of the deposit of sediment. 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 further to sea, or even temporarily destroy it; storms from the sea, on the other hand, drive it further up the stream.

Some of these facts in the economy of rivers have been well studied at the mouths of the Mississippi. At the south-west pass, the bar is equal in bulk to a solid mass one mile square and 490 feet thick, and advances at the rate of 338 feet each year. It is formed where the river water begins to ascend over the heavier salt water of the gulf, and consists mainly of the sediment that is pushed along the bed of the river. A singular feature of the Mississippi bars is the formation upon them of "mud lumps." These are masses of tough clay, varying in size from mere protuberances like tree-trunks, up to islands several acres in extent. They rise suddenly, and attain heights of from 3 to 10, sometimes even 18 feet above the sea-level. Salt springs emitting inflammable gas rise upon them. After the lapse of a considerable time, the springs cease to give off gas, and the lumps are worn away by the currents of the river and the gulf. The origin of these excrescences has been attributed to the generation of carburetted hydrogen by the decomposing vegetable matter in the sediment underlying the tenacious clay of the bars.[175]

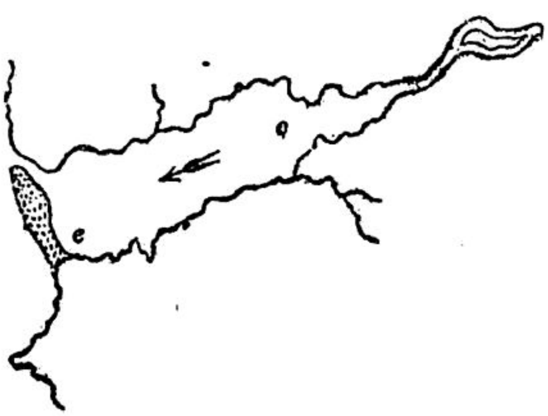


Fig. 133.—Shingle and sand-spit (*e*) at the mouth of an estuary (*c*), entered by a river, and opening upon an exposed rocky coast-line (*B*.).

Conspicuous examples of the formation of detrital bars may occasionally be observed at the mouths of narrow estuaries, as at *e* in Fig. 133. A constant struggle takes place in such situations between the tidal currents and waves which tend to heap up the bar and block the entrance to the

---

[175] Humphreys and Abbot, "Report on Mississippi River," 1861, p. 452.

estuary, and the scour of the river and ebb-tide which endeavors to keep the passage open.

Another remarkable illustration of the contest between alluvium-carrying streams and the land-eroding ocean is shown by the vast lines of bar or bank which stretch along the coasts both of the Old and the New World. The streams do not flow straight into the sea, but run sometimes for many miles parallel to the shore-line, accumulating behind the

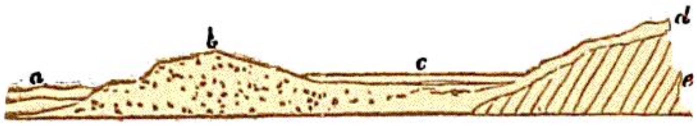


Fig. 134.—Section of bar and lagoon. Slapton Pool, Start Bay, Devon (*B.*).

barriers into broad and long lagoons, but eventually breaking through the barriers of alluvium and entering the sea. On a small scale, examples occur on the coasts of the British Islands, as at Start Bay, Devon (Fig. 134), where the slates (*e*) with their weathered surface (*d*) are flanked by a fresh-water lake (*c*), ponded back by a bar (*b*) from the sea (*a*). The lagoons of the shores of the Mediterranean,[176] and the

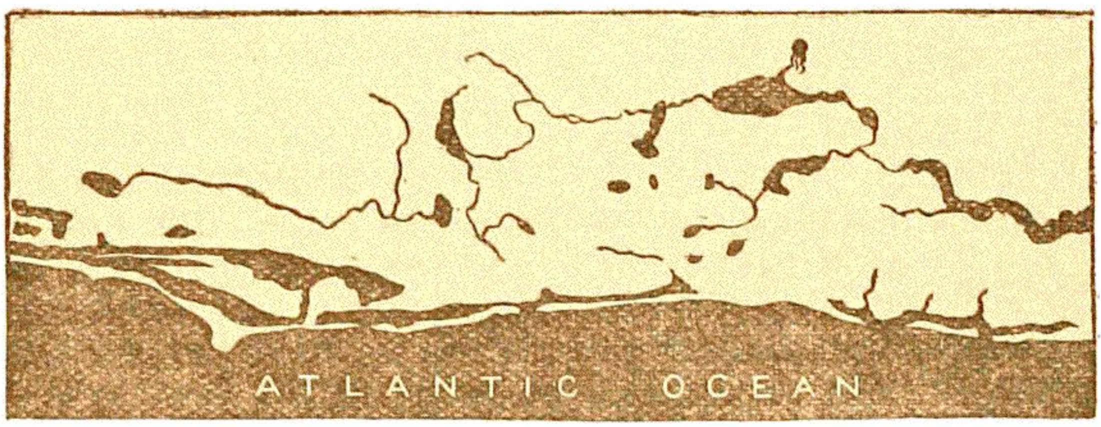


Fig. 135.—Plan of coast-bars and lagoons. Coast of Florida.

Kurische and Frische Haf in 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 (Fig. 135).[177] A space of several hundred miles on the east coast of India is similarly bordered. Élie de Beaumont, indeed, estimated that about

[176] For an account of these see Ansted, Min. Proc. Inst. Civ. Engin. xxviii., 1869, p. 287.

[177] See Report by H. D. Rogers, Brit. Assoc. iii. p. 13.

a third of the whole of the coast-lines of the continents is fringed with such alluvial bars.[178]

On a coast-line such as that of Western Europe, subject both to powerful tidal action and to strong gales of wind, many interesting illustrations may be studied of the struggle between the rivers and the sea, as to the disposal of the sediment borne from the land. De la Beche described an example from the coast of South Wales where two streams, the Towey and Nedd (*a* and *b*, Fig. 136), enter Swansea Bay, bearing with them a considerable amount of sandy and

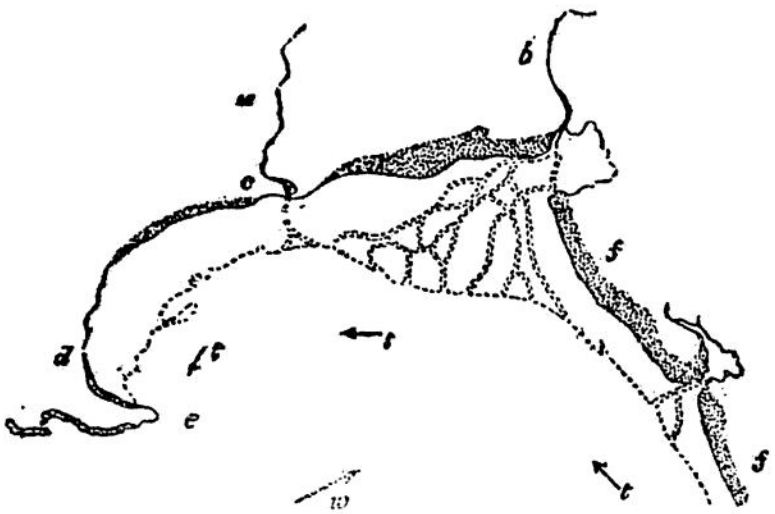


Fig. 136.—Action of rivers, tides, and winds in Swansea Bay (*B.*).

muddy sediment. The fine mud is carried by the ebb-tide (*t t t*) into the sheltered bay between Swansea (*c*) and the Mumble Rocks (*e*) but is partly swept round this headland into the Bristol Channel. The coarser sandy sediment, more rapidly thrown down, is stirred up and driven shoreward by the breakers caused by the prevalent west and southwest winds (*w*). The sandy flats thereby formed are partly uncovered at low water, and being then dried by the wind, supply it with the sand which it blows inland to form the lines of sand-dunes (*f f*).[179]

(*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 vaster scale where the great rivers of the continents enter the sea. It was to one of these mari-

---

[178] "Leçons de Geologie pratique," i. p. 249. In this volume some interesting examples of this kind of deposit are described.

[179] "Geological Observer," p. 88.

time 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 become their general designation. A delta consists of successive layers of detritus, brought down from the land and spread out 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 floods. Large quantities of driftwood 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.

A delta does not necessarily form at every river-mouth, even where there is plenty of sediment. In particular, where the coast-line on either side is lofty, and the water deep, or where the coast is swept by powerful tidal currents, there is no delta.[180] In some cases, too, the sediment spreads out over the sea-bottom without being allowed by the sea to build itself up into land, as happens at the mouths of some of the rivers in the northwest of France. Considerable influence may be exerted by tides and currents in arresting or facilitating the spread of sediment over the sea-floor. The deltas of the Rhone, Nile, Tiber, and Danube are formed in tideless or nearly tideless seas.[181]

---

[180] Consult Admiral Spratt's memoir, "An investigation of the effect of the prevailing wave influence on the Nile's deposit," folio, London, 1859.

[181] For a discussion on non-tidal rivers, see Min. Proc. Inst. Civ. Engin. lxxxii., 1885, pp. 2–68, where information is given about the Tiber and some other rivers.

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 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 inclosing 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 are 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 outward 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.

These features are nowhere more strikingly displayed than by the great delta of the Mississippi (Fig. 137). The area of this vast expanse of alluvium is given at 12,300 square miles, advancing at the rate of 262 feet yearly into the Gulf of Mexico at a point which is now 220 miles from the head of the delta.[182] On a smaller scale the rivers of Europe 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, which has deposited an important delta in the Mediterranean Sea, is computed to furnish every year (by the Petit Rhône) about four millions of cubic metres of sediment to the shores.[183] The upper reaches of the Adriatic Sea are being so rapidly shallowed and filled up by the Po, Adige, and other streams, that Ravenna, originally built in a lagoon like Venice, is now 4 miles from

182 Humphreys and Abbot, op. cit.; see also C. Hartley, Min. Proc. Inst. Civ. Engin. xl. p. 185. The tide has a mean rise of 15 inches every 24 hours at the Mississippi mouths.

183 For this delta and its lagoons, see the paper by Ansted, quoted ante, p. 675. Reclus, "Geographie Universelle," tome ii. (France), chaps. ii. and iii., and A. Guérard, Min. Proc. Inst. Civ. Engin. lxxxii., 1884–85, p. 305.

the sea; and 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 on other parts of that coast-line the breadth of land gained within the last 1800 years has been as much as 20 miles. Borings for water near Venice to a depth of 572 feet have disclosed a succession of nearly horizontal clays, sands, and lignitiferous beds. Marine shells (*Cardium*, etc.) occur in the sandy layers; the lignites and lignitiferous clays contain land-vegetation and terrestrial shells (*Succinea*, *Pupa*, *Helix*), the whole succession of de-

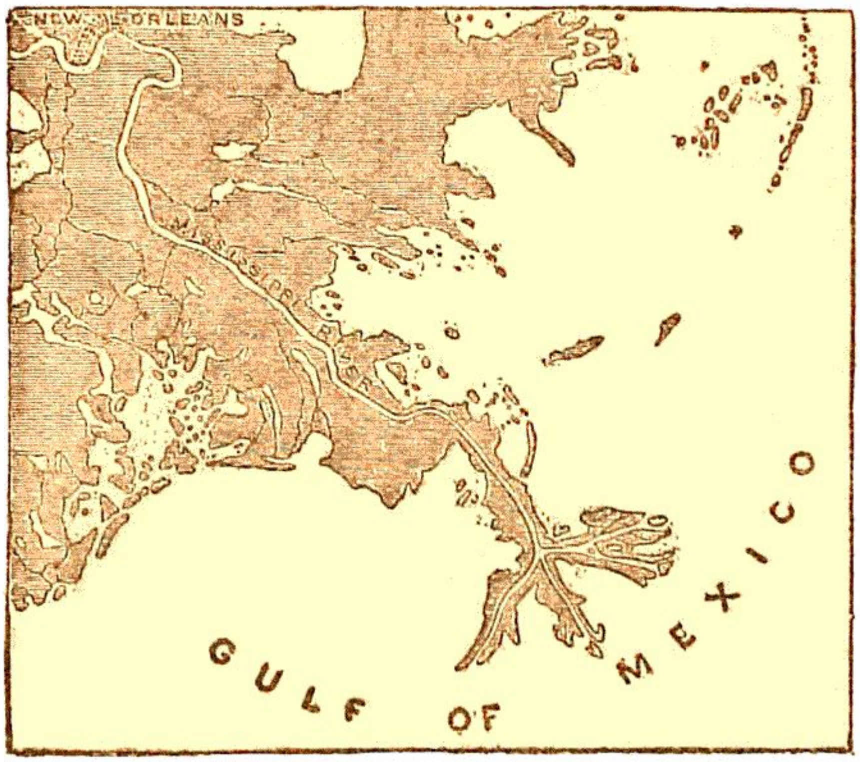


Fig. 137.—Map of Delta of Mississippi.

posits indicating an alternation of marine and terrestrial or fresh-water conditions.[184] On the opposite side 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 color to the abundance of the sediment which it carries to sea. It has long been adding to the coast-line around its mouth at the rate of from 12 to 13 feet per annum. The ancient harbor of Ostia is now consequently more than 3 miles

---

[184] Élie de Beaumont, "Leçons de Geologie pratique," i. p. 323. Geol. Mag. ix., 1872, p. 486.

inland. Its ruins have been partially excavated, but every flood of the river leaves a thick deposit of mud on the streets and on the floors of the uncovered houses. Hence 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.[185] In the Black Sea, a great delta is rapidly growing at the mouths of the

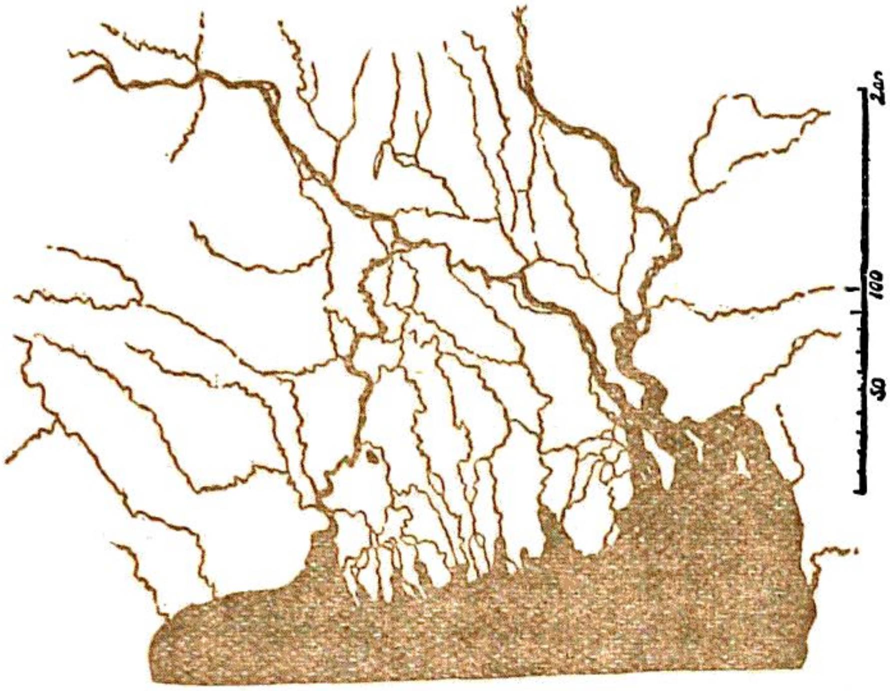


Fig. 138.—Delta of the Ganges and Brahmaputra (with Scale of Miles).

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.[186] 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.[187]

[185] See an interesting article by Prof. Charles Martins on the Aigues-Mortes (*i.e.* dead waters or disused river-channels), in "Revue des Deux Mondes," 1874, p. 780. I 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 favorable situations. In the article just cited, and in another in Comptes Rend. lxxviii. p. 1748, some valuable information is given regarding the progress of the delta of the Rhone in the Mediterranean. Interesting historical data as to geological changes at the mouths of the Rhine, Meuse, Elbe, Po, Rhone and other European rivers, as well as of the Nile, will be found in Élie de Beaumont's "Leçons de Geologie pratique," vol. i. p. 253.

[186] Hartley, Min. Proc. Inst. Civ. Engin. xxxvii. p. 216.

[187] For a detailed study of the Nile delta in its geological aspects, see an essay by Dr. J. Jankó, Mittheil. Jahrb. Kön. Ungarischen Geol. Anst. viii., 1890, p. 236.

The united delta of the Ganges and Brahmaputra (Fig. 138) covers a space of between 50,000 and 60,000 square miles, and has been bored through to a depth of 481 feet, the whole mass of deposits consisting of fine sands and clays, with occasional pebble-beds, a bed of peat and remains of trees, but with no trace of any marine organism.[188]

(*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. In none of the numerous soundings and dredgings in the Gulf of Mexico has Mississippi mud been obtained from the bottom more than 100 miles eastward from the mouth of the river.[189] The soundings taken by the "Challenger," however, brought up land-derived detritus from depths of 1500 fathoms—200 miles or more from the nearest shores (p. 764). The sea fronting the Amazon is sometimes discolored for 300 miles by the mud of that river.

§ 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. For the most part, they do not belong to the normal system of erosion in which running water is the prime agent, and to which the excavation of

[188] For a full account of the alluvium of the Indo-Gangetic plain, see Medlicott and Blanford's "Geology of India," chap. xvii., and authorities there cited; also a more recent paper by Mr. Medlicott, Records Geol. Surv. India, 1881, p. 220.

[189] A. Agassiz, Amer. Acad. xii., 1882, p. 108.

valleys and ravines must be attributed. On the contrary, they are exceptional to that system, for 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 Book 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.**—In the northern parts of Europe and America, as first emphasized by Sir Andrew C. Ramsay, lakes are prodigiously abundant on ice-worn rock-surfaces, irrespective of dominant lines of drainage. They seem to be distributed as it were at random, being found now on the summits of ridges, now on the sides of hills, and now over broad plains. They lie for the most part in rock-basins, but many of them have barriers of detritus. Their connection with the operations of the glacial period will be afterward alluded to. In the mountainous regions of temperate and polar latitudes, lakes abound in valleys, and are connected with main drainage-lines. In North America and in Equatorial Africa, vast sheets of fresh water occur in depressions of the land, and are rather inland seas than lakes.

The water of many lakes has been observed to rise above its normal level for a few minutes or for more than an hour, then to descend beneath that level, and to continue this vibration for some time. In the Lake of Geneva, where these movements, locally known there as *Seiches*, have long been noticed, the amplitude of the oscillation ranges up to a metre or even sometimes to two metres. These disturbances may sometimes be due to subterranean movements; but probably they are mainly the effect of atmospheric perturbations, and, in particular, of local storms with a vertical descending movement.[190]

The distribution of temperature in lakes is a question of considerable geological interest, in regard to which careful measurements are much needed.

The observations of Sir Robert Christison, at Loch Lomond in Scotland, show that in this sheet of water, which lies 25 feet above sea-level, with a depth of about 600 feet, and is in great measure surrounded with high hills, a tolerably constant temperature of about 42° Fahr. is found to pervade the lowest 100 feet of water.[191] More extended observations have since been made by Dr. John Murray and the staff of the Scottish Marine Station in Lochs Ness, Oich, Morar, and Shiel, as well as in some of the fjords and sounds of the west of Scotland, and the earlier observations have been confirmed. The surface of Loch Morar in September, 1887, was found to have a temperature of 57·8° Fahr., but at a depth of 160 fathoms the thermometer had fallen to 42·1°. The surface temperature of Loch Ness in the same month was 54°, but at 120 fathoms 42·1°.[192] Again, in the Lake of Geneva the surface temperature in autumn is 78° Fahr., while the bottom water at a depth of 950 feet was found to mark 41° 7′. The Lago Sabatino near Rome has a temperature of 77° at the surface, but one of 44° at a depth of 490 feet. Similar observations on other deep lakes in Switzerland and Northern Italy indicate the existence in all of them of a permanent mass of cold water at the bottom. The cold heavy water of the surface in winter must sink down, and as the upper layers cannot be heated by the direct rays of the sun, save to a trifling and superficial extent, the temperature of the deep parts of these basins is kept permanently low.

---

[190] F. A. Forel, Comptes Rend. lxxx. 1875, p. 107, lxxxiii. 1876, p. 712, lxxxvi. 1878, p. 1600, lxxxix. 1879, p. 859; Assoc. Française, 1879, p. 493. P. du Bois, Comptes Rend. cxii. 1891, p. 122. For a valuable monograph on the regime of a typical lake, see Forel's "Le Léman," Lausanne, 1892.

[191] For observations on the freezing of this and other lakes, see J. Y. Buchanan, Nature, xix. p. 412. On the deep-water temperature of lakes, A. Buchan, Brit. Assoc. 1872, Sects. p. 207.

[192] Proc. Roy. Soc. Edin. xviii., 1890–91, p. 139.

Geological functions.—Among the geological functions discharged by lakes the following may be noticed:

1st. Lakes equalize the temperature of the localities in which they lie, preventing it from falling as much in winter and rising as much in summer as it would otherwise do.[193] The mean annual temperature of the surface water at the outflow of the Lake of Geneva is nearly 4° warmer than that of the air.

2d. Lakes regulate the drainage of the area below their outfall, thereby preventing or lessening the destructive effects of floods.[194]

3d. Lakes filter river-water and permit the undisturbed accumulation of new deposits, which in some modern cases may cover thousands of square miles of surface, and may attain a thickness of nearly 3000 feet (Lake Superior has an area of 32,000 square miles; Lago Maggiore is 2800 feet deep). How thoroughly lakes can filter river-water is typically displayed by the contrast between the muddy river which flows in at the head of the Lake of Geneva, and the "blue rushing of the arrowy Rhone," which escapes at the foot. The mouths of small brooks entering lakes afford excellent materials for studying the behavior of silt-bearing streams when they reach still water. Each rivulet may be

---

193 The lakes of Sweden, which cover one-twelfth of the surface of the country, exercise an important influence on climate according as they are frozen or open. See Prof. Hildebrandsson on the freezing and breaking-up of the ice on the Swedish lakes. Ann. Bur. Central Meteorol. France, 1878.

194 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 escaping 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.

observed pushing forward its delta composed of successive sloping layers of sediment (ante, p. 671). On a shelving bank, the coarser detritus may repose directly upon the solid rock of the district (Fig. 139). But as it advances into the lake, it may come to rest upon some older lacus-

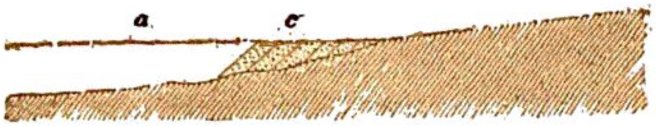


Fig. 139.—Section of a delta-cone pushed by a brook into a lake.

trine deposit (Fig. 140). The river Linth since 1860 has annually discharged into Lake Wallenstadt some 62,000 cubic metres of detritus.

A river which flows through a succession of lakes cannot carry much sediment to the sea, unless it has a long course

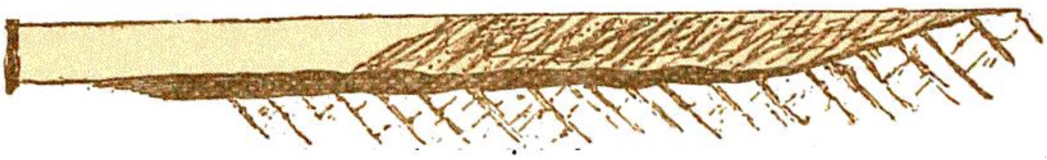


Fig. 140.—Stream-detritus pushed forward over a previous lacustrine silt (*B.*).

to run after it has passed the lowest lake, and receives one or more muddy tributaries (see p. 671). Let us suppose, for example, that, in a hilly region, a stream passes through a series of lakes (as *a*, *b*, *c*, in Fig. 141). As the highest

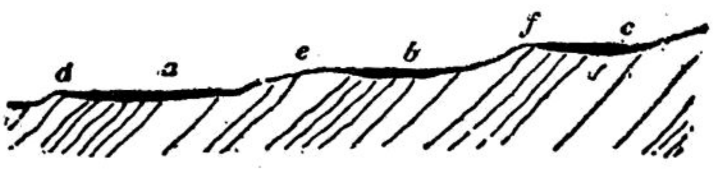


Fig. 141.—Filling up of a succession of lakes (*B.*).

lake will intercept much, perhaps all, of this sediment, the next in succession will receive little or none until the first is either filled up or has been drained by the cutting of a gorge through the intervening rock at *f*. The same process will be repeated at *e* and *d* until the lakes are effaced, and their places are taken by alluvial meadows. Examples of this sequence of events are of frequent occurrence in Britain.

Besides the detrital accumulations due to the influx of streams, there are some which may properly be regarded as the work of lakes themselves. Even on small sheets of water, the eroding influence of wind-waves may be observed; but 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 other familiar features of the meeting-line between land and sea, reappear along the margins of such great fresh-water seas as Lake Superior. Beneath the level of the water a terrace or platform is formed, of which the distance from shore and depth vary with the energy of the waves by which it is produced. This platform is well developed in the Lake of Geneva.[195]

Some of the distinctive features of the erosion and deposition that take place in lake-basins have been admirably laid open for study in those basins of vanished lakes which have been so well described by Gilbert, Dutton, Russell, and Upham in the Western Territories of the United States. They have been treated of in a masterly way by Gilbert in his essay on "The Topographic features of Lake-shores." [196]

4th. Lakes serve as basins in which chemical deposits

---

[195] D. Colladon, Bull. Soc. Geol. France (3), iii. p. 661.

[196] 5th Ann. Report U. S. Geol. Survey, 1885. See also Dutton, in 2d Report of same Survey, 1880–81, p. 169; I. C. Russell, 3d Report U. S. Survey, 1881–82, p. 195; 4th Report, 1882–83, p. 435; 8th Report, 1886–87, p. 201; and Monograph XI., 1885, of same Survey. W. Upham on the beaches and terraces of a former glacial lake (Lake Agassiz) Bull. U. S. Geol. Survey, No. 39, 1887; also 8th Ann. Report Geol. and Nat. Hist. Survey Minnesota, 1879, pp. 84–87; H. W. Turner on a vanished lake in Mohawk Valley, Plumas County, California, Bull. Phil. Soc. Washington, xi., 1891, p. 385.

may take place. Of these the most interesting and extensive are those of iron-ore, which chiefly occur in northern latitudes (pp. 254, **810**).[197]

5th. Lakes furnish an abode for a lacustrine fauna and flora, receive the remains of the plants and animals washed down from the surrounding country, and entomb these organisms in the growing deposits, so as to preserve a record of the lacustrine and terrestrial life of the period during which they continue. Besides the more familiar pond-snails and fishes, lakes possess a peculiar pelagic fauna, consisting in large measure of entomostracous crustaceans, distinguished more especially by their transparency.[198] These, as well as the organisms of shallower water, doubtless furnish calcareous materials for the mud or marl of the lake bottoms. But it is as receptacles of sediment from the land, and as localities for the preservation of a portion of the terrestrial fauna and flora, that lakes present their chief interest to a geologist. Their deposits consist of alternations of sand, silt, mud, gravel, and occasional irregular seams of vegetable matter, together with layers of calcareous marl formed of lacustrine shells, *Entomostraca*, etc. (p. **812**). In lakes receiving much sediment, little or no marl can accumulate during the time when sediment is being deposited. In small, clear, and not very deep lakes, on the other hand, where there is little sediment, or where it only comes occasionally at intervals of flood, thick beds of white marl, formed entirely of organic remains, may gather on the bottom, as has happened in numerous districts of Scotland

---

[197] For an elaborate paper on these lake-ores (See-erze), see Stapff, Z. Deutsch. Geol. Ges. xviii. pp. 86–173; also A. F. Thoreld, Geol. Fören. Stockholm. Forh. iii. p. 20; and postea, Section iii.

[198] F. A. Forel, Archives d. Sciences, Sept. 1882. O. E. Imhof, Ann. Mag. Nat. Hist., 1884, p. 69.

and Ireland. The fresh-water limestones and clays of some old lake-basins (those of Miocene time in Auvergne and Switzerland, and of Eocene age in Wyoming, for example) cover areas occasionally hundreds of square miles in extent, and attain a thickness of hundreds, sometimes even thousands of feet.

Existing lakes are of geologically recent origin. Their disappearance is continually in progress by infilling and erosion. Besides the displacement of their water by alluvial accumulations, they are lowered and eventually drained by the cutting down of the barrier at their outlets. Where they are effaced merely by erosion, it must be an excessively slow process, owing to the filtered character of the water (p. 684); but where it is performed by the retrocession of a waterfall at the head of an advancing gorge, it may be relatively rapid after it has once begun.[199] In a river-course it is usual to find a lake-like expansion of alluvial land above each gorge. These plains may be regarded as old lake-bottoms, which have been drained by the cutting out of the ravines (p. 662). Successive terraces often fringe a lake and mark former levels of its waters. It is when we reflect upon the continued operation of the agencies which tend to efface them, that we can best realize why the lakes now extant must necessarily be of comparatively modern date. Their modes of origin are discussed in Book VII.

2. **Saline Lakes,** considered chemically, may be grouped as *salt lakes*, where the chief constituents are sodium and magnesium chlorides with magnesium and calcium sul-

---

[199] The level of the Lake of Geneva is said to have been lowered about six and a half feet since Roman times (Dausse, Bull. Soc. Geol. France (3), iii. p. 140); but this may be explicable by diminution in the water-supply.

phates: and *bitter lakes*, which are usually distinguished by their large percentage of sodium carbonate as well as chloride and sulphate (natron-lakes), sometimes by their proportion of borax (borax lakes). From a geological point of view they may be divided into two classes—(1) those which owe their saltness to the evaporation and concentration of water poured into them by their feeders; and (2) those which were originally parts of the ocean.

(*a*) Salt and bitter lakes of terrestrial origin are abundantly scattered over inland areas of drainage in the heart of continents, as in Utah and adjacent territories of North America, and on 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, there is no escape for its dissolved salts, which consequently remain in the increasing concentrated liquid. In Ladâkh, extensive lakes formed by the ponding back of valley waters by alluvial fans, have grown saline and bitter, and have become the site of deposits of rock-salt and soda.[200]

The Great Salt Lake of Utah, which has now been so carefully studied by Gilbert and other geologists, may be taken as a typical example of an inland basin, formed by unequal subterranean movement that has intercepted the drainage of a large area, wherein rainfall and evaporation on the whole balance each other, and where the water becomes increasingly salt from evaporation, but is liable to fluctuations in level, according to oscillations of meteorological conditions. The present lake occupies an area of rather more than 2000 square miles, its surface being at a height of 4250 feet above the sea. It is, however, merely the shrunk remnant of a once far more extensive sheet of water, to which the name of Lake Bonneville has been given by Gil-

[200] F. Drew, "Jummoo and Kashmir Territories."

bert. It is partly surrounded with mountains, along the sides of which well-defined lines of terrace mark former levels of the water (Fig. 142). The highest of these terraces lies about 940 feet above the present surface of the lake, so that when at its greatest dimensions, this vast sheet of water must have stood at a level of about 5200 feet above the sea, and covered an area of 300 miles from north to south, and 180 miles in extreme width from east to west. It was then certainly fresh, for, having an outlet to the north, it drained into the Pacific Ocean, and in its stratified deposits an abundant lacustrine molluscan fauna has been found.[201] According to Gilbert there are proofs that, pre-

Fig. 142.—Terraces of Great Salt Lake, on the flanks of the Wahsatch Mountains.

vious to the great extension of Lake Bonneville, there was a dry period, during which considerable accumulations of subaerial detritus were formed along the slopes of the mountains. A great meteorological change then took place, and the whole vast basin, not only that termed Lake Bonneville, but a second large basin, Lake Lahontan of King, lying to the west and hardly inferior in area, was gradually filled with fresh water. Again, another meteorological revolution supervened and the climate once more became dry. The waters shrank back, and in so doing, when they had sunk below the level of their outlet, began to grow increasingly saline. The decrease of the water and the increase of salinity were in direct relation to each other until the present de-

---

[201] For an account of this fauna see R. E. Call, Bull. U. S. Geol. Surv. No. 11, 1884.

gree of concentration has been reached, as shown in the table (p. 694). The Great Salt Lake, at present having an extreme depth of less than 50 feet, is still subject to oscillations of level. When surveyed by the Stansbury Expedition in 1849, its level was 11 feet lower than in 1877, when the Survey of the 40th Parallel examined the ground. From 1866, however, a slow subsidence of the lake has been in progress, consequent upon a diminution of the rainfall. Large tracts of flat land, formerly under water, are being laid bare. As the water recedes from them and they are exposed to the remarkably dry atmosphere of these regions, they soon become crusted with a white saliferous and alkaline deposition, which likewise permeates the dried mud underneath. So strongly saline are the waters of the lake, and so rapid the evaporation, as I found on trial, that one floats in spite of one's self, and the under surfaces of the wooden steps leading into the water at the bathing-places are hung with short stalactites of salt from the evaporation of the drip of the emergent bathers.[202]

Some of the smaller lakes in the great arid basin of North America are intensely bitter, and contain large quantities of carbonate and sulphate as well as chloride of sodium. The Big Soda Lake near Ragtown in Nevada contains 129·015 grammes of salts in the litre of water. These salts consist largely of chloride of sodium (55·42 per cent of the whole), sulphate of soda (14·86 per cent), carbonate of soda (12·96 per cent), and chloride of potassium (3·73 per cent). Soda is obtained from this lake for commercial purposes.[203]

(*b*) S a l t l a k e s o f o c e a n i c o r i g i n 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

---

202 Much information regarding the Great Basin and its lakes is to be found in vol. iii. of Wheeler's Survey West of 100th Meridian, vols. i. and iv. of the Survey of the 40th Parallel, and Report of U. S. Geol. Survey, 1880–81, I. C. Russell, "Geological History of Lake Lahontan," U. S. Geol. Survey Monographs, No. XI., and in the papers cited ante, p. 686.

203 Bull. U. S. Geol. Surv. No. 9, 1884, p. 25. T. M. Chatard, Amer. Journ. Sci. xxxvi. 1888, p. 148, and xxxviii. 1889, p. 59.

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 living in its waters are chiefly the same as those of the Black Sea. Banks of them may be traced between the two seas, with salt lakes, marshes, and other evidences to prove that the Caspian was once joined to the Black Sea, and had thus communication with the main ocean. In this case also there are proofs of considerable changes of water-level. At present the surface of the Caspian is 85½ feet below that of the Black Sea. The Sea of Aral, also sensibly salt to the taste, was once probably united with the Caspian, but now rests at a level of 242·7 feet above that sheet of water. The steppes of southeastern Russia are a vast depression with numerous salt lakes and abundant saline and alkaline deposits. It has been supposed that this depression continued far to the north, and that a great firth, running up between Europe and Asia, stretched completely across what are now the steppes and plains of the Tundras, till it merged into the Arctic Sea. Seals of a species (*Phoca caspica*) which may be only a variety of the common northern form (*Ph. fœtida*), abound in the Caspian, which is the scene of one of the chief seal-fisheries of the world.[204] On the west side of the Ural chain, even at present, by means of canals connecting the rivers Volga and Dwina, vessels can pass from the Caspian into the White Sea.[205]

The cause of the isolation of the Caspian and the other saline basins of that region is to be sought in underground movements which, according to Helmersen, are still in progress, but partly, and, in the case of the smaller basins, probably chiefly in a general diminution of the water-supply all

---

[204] Another variety or species of seal inhabits Lake Baikal. For an account of the structure and distribution of seals see an interesting monograph by J. A. Allen in Miscellaneous Publications of U. S. Geological and Geographical Survey of the Territories. Washington, 1880.

[205] Count von Helmersen, however, has stated his belief that for this extreme northern prolongation of the Aralo-Caspian Sea there is no evidence. The shells, on the presence of which over the Tundras the opinion was chiefly based, are, according to him, all fresh-water species, and there are no marine shells of living species to be met with in the plains at the foot of the Ural Mountains.

over Central Asia and the neighboring regions. The rivers that flow from the north toward Lake Balkash, and that once doubtless emptied into it, now lose themselves in the wastes and are evaporated before reaching that sheet of water, which is fed only from the mountains to the south. The channels of the Amur Darya, Syr Darya, and other streams bear witness also to the same general desiccation.[206] At present, the amount of water supplied by rivers to the Caspian Sea appears on the whole to balance that removed by evaporation, though there are slight yearly or seasonal fluctuations. In the Aral basin, however, there can be no doubt that the waters are progressively diminishing, the rate in the ten years between 1848 and 1858 having been 18 inches, or 1·8 inch per annum.

Owing to the enormous volume of fresh water poured into it by its rivers, the Caspian Sea is not as a whole so salt as the main ocean, and still less so than the Mediterranean Sea. 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-colored crystals on the bottom, or gradually getting dry and covered with drift-sand. This concentration of the water is particularly marked in the great offshoot called the Karaboghaz, which is connected with the middle basin of the Caspian Sea 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 the bottom, where they have formed a salt bed of unknown extent, and the sounding line, when scarcely out of the water, is covered with saline crystals.[207]

The following table shows the proportions of saline ingredients in 1000 parts of the water of some salt lakes:

---

[206] Bull. Acad. Imp. St. Petersbourg, xxv. p. 535, 1879. For an account of these rivers and Lake Aral, see H. Wood, Journ. Roy. Geog. Soc. xlv. 1875, p. 367, where an estimate is given of the annual amount of evaporation.

[207] Von Baer, Bull. Acad. St. Petersbourg, 1855–56. See also Carpenter, Proc. Roy. Geog. Soc. xviii. No. 4. For the composition of the water of salt and bitter lakes, see the analyses collected by Roth in his "Chemische Geologie," i. p. 463 *et seq.*

Constituents (except where otherwise stated)	Caspian Sea		In-dertsch Lake (Gobel)	Great Salt Lake, Utah (O. D. Allen)	Elton Lake, Kir-ghis Steppe (H. Rose)	Dead Sea, from a depth of 185 fathoms
	Near mouth of R. Ural (Gobel)	At Baku (Abich)				
Chlor. of Sodium .	3·673	8·5267	239·28	118 628	38·3	78·554
" Magnesium	0·632	0·3039	17·36	14·908	197.5	145·897
" Calcium .	0 013 ($MgCO_3$)	. .	. .	. .	. .	31·075
" Potassium	0·076	trace	1·01	{ 0·862 (excess Chlorine) }	2·3	6·586
Brom. of Magnesium	trace	. .	0 05	. .	. .	1·374
Sulph. of Calcium .	0·490	1·0742	0·42	0·858	. .	0·701
" Potassium	0·171 ($CaCO_3$)	0·0554 ($CaCO_3$)	. .	5·363	. .	. .
" Magnesium	1·239	3·2493	3·46	9·321 ($NaSO_4$)	53·2	. .

Deposits in Salt and Bitter Lakes.—The study of the precipitations which take place on the floors of modern salt lakes is important in throwing light upon the history of a number of chemically-formed rocks. The salts in these waters accumulate until their point of saturation is reached, or until by chemical reactions they are thrown down. The least soluble are naturally the first to appear, the water becoming progressively more and more saline till it reaches a condition like that of the mother-liquor of a salt work. Gypsum begins to be thrown down from sea-water, when 37 per cent of water has been evaporated, but 93 per cent of water must be driven off before chloride of sodium can begin to be deposited. Hence the concentration and evaporation of the water of a salt lake having a composition like that of the sea would give rise first to a layer or sole of gypsum, followed by one of rock-salt. This has been found to be the normal order among the various saliferous formations in the earth's crust. But gypsum may be precipitated without rock-salt, either because the water was diluted before the point of saturation for rock-salt was reached, or because the salt, if deposited, has been subsequently dissolved and removed. In every case where an alternation of layers of gypsum and rock-salt occurs, there must have been repeated renewals of the water-supply, each gypsum zone marking the commencement of a new series of precipitates.

But from what has now been adduced it is obvious that the composition of many existing saline lakes is strikingly unlike that of the sea in the proportions of the different constituents. Some of them contain carbonate of sodium; in others the chloride of magnesium is enormously in excess of the less soluble chloride of sodium. These variations modify the effects of the evaporation of additional supplies of water now poured into the lakes. The presence of the sodium-carbonate causes the decomposition of lime salts, with the consequent precipitation of calcium-carbonate accompanied with a slight admixture of magnesium-carbonate, while by further addition of the sodium-carbonate a hydrated magnesium-carbonate may be eventually precipitated. Hunt has shown that solutions of bicarbonate of lime decompose sulphate of magnesia with the consequent precipitation of gypsum, and eventually also of hydrated carbonate of magnesia, which, mingling with carbonate of lime, may give rise to dolomite.[208] By such processes the marls or clays deposited on the floors of inland seas and salt lakes may conceivably be impregnated and interstratified with gypseous and dolomitic matter, though in the Trias and other ancient formations which have been formed in inclosed saline waters, the magnesium-chloride has probably been the chief agent in the production of dolomite (ante, p. 546).

The Dead Sea, Elton Lake, and other very salt waters of the Aralo-Caspian depression, are interesting examples of salt lakes far advanced in the process of concentration.[209]

---

[208] Sterry Hunt, in "Geology of Canada," 1863, p. 575.
[209] The Dead Sea, like the Great Salt Lake, was originally fresh, as proved

The great excess of the magnesium-chloride shows, as Bischof pointed out, that the waters of these basins are a kind of mother-liquor, from which most of the sodium-chloride has already been deposited. The greater the proportion of the magnesium-chloride, the less sodium-chloride can be held in solution. Hence, as soon as the waters of the Jordan and other streams enter the Dead Sea, their proportion of sodium-chloride (which in the Jordan water amounts to from ·0525 to ·0603 per cent) is at once precipitated. With it gypsum in crystals goes down, also the carbonate of lime which, though present in the tributary streams, is not found in the waters of the Dead Sea. In spring, the rains bring large quantities of muddy water into this sea. Owing to dilution and diminished evaporation, a check must be given to the deposition of common salt, and a layer of mud is formed over the bottom. As the summer advances and the supply of water and mud decreases, while evaporation increases, the deposition of salt and gypsum begins anew.[210] As the level of the Dead Sea is liable to variations, parts of the bottom are from time to time exposed, and show a surface of bluish-gray clay or marl full of crystals of common salt and gypsum. Beds of similar saliferous and gypsiferous clays, with bands of gypsum, rise along the slopes for some height above the present surface of the water, and mark the deposits left when the Dead Sea covered a larger area than it now does. Save occasional impressions of drifted terrestrial plants, these strata contain no organic remains.[211] Interesting details regarding saliferous deposits of recent origin, on the site of the Bitter Lakes, were obtained during the construction of the Suez Canal. Beds of salt, interleaved with laminæ of clay and gypsum-crystals, were found to form a deposit upward of 30 feet thick extending along 21 miles in length by about 8 miles in breadth. No fewer than 42 layers of salt, from 3 to 18 centimetres thick, could be counted in a depth of 2·46 metres. A deposit of earthy gypsum and clay was ascertained to have a thickness of 367 feet (112 metres), and another bed of

---

by shells of Melania, etc., found in lacustrine terraces 1300 feet above its present level. Hull, "Mount Seir," 1885, pp. 100, 180.

210 Bischof, "Chem. Geol." i. p. 397. Roth, "Chem. Geol." i. p. 476.

211 Lartet, Bull. Soc. Geol. France (2), xxii. p. 450 *et seq.* Below the high terraces, containing lacustrine shells, evidence of shrinkage and concentration is supplied by gypseous marls and a bed of salt (30 to 50 feet), 600 feet above the present water-level.

nearly pure crumbling gypsum to be about 230 feet (70 metres) deep.[212]

The desiccated floors of the great saline lakes of Utah and Nevada have revealed some interesting facts in the history of saliferous deposits. The ancient terraces marking former levels of these lakes are cemented by tufa, which appears to have been abundantly formed along the shores where the brooks, on mingling with the lake, immediately parted with their lime. Even at present, oolitic grains of carbonate of lime are to be found in course of formation along the margin of Great Salt Lake, though carbonate of lime has not been detected in the water of the lake, being at once precipitated in the saline solution. The site of the ancient salt lake which has been termed Lake Lahontan displays areas several square miles in extent covered with deposits of calcareous tufa, 20 to 60 and even 150 feet thick. This tufa, however, presents a remarkable peculiarity. It is sometimes almost wholly composed of what have been determined to be calcareous pseudomorphs after gaylussite (a mineral composed of carbonates of calcium and sodium with water)—the sodium of the mineral having been replaced by calcium. When this variety of tufa, distinguished by the name of *thïnolite*, was originally formed, the waters of the vast lake must have been bitter, like those of the little soda-lakes which now lie on its site—a dense solution in which carbonate of soda predominated. On the margin of one of the present Soda Lakes, crystals of gaylussite now form in the drier season of the year. Yet no trace of carbonate of lime has been detected in the water. The carbonate of lime in the crystals must be derived from water which on entering the saline lakes is at once deprived of its lime.[213]

§ 5. Terrestrial 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 per-

[212] Lesseps, Comptes Rend. lxxviii. p. 1740, Ann. Chim. et Phys. (5), iii. p. 139. Bader, Verh. Geol. Reichsanst. 1869, p. 288.

[213] King, Exploration of the 40th Parallel, i. p. 510. See also on the crystallographic form and chemical composition of the thinolite and its original mineral, E. S. Dana, Bull. U. S. Geol. Surv. No. 12, 1884.

forms 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.

Frost.—Water, if perfectly still, may fall below the freezing-point without freezing, but when it is then moved, it at once freezes over. In freezing, water expands. If it be confined in such a way that expansion is impossible, it remains liquid even at temperatures below the freezing-point; but the instant that the pressure is removed this chilled water becomes ice. There is a constant effort on the part of the water to expand and become solid, very considerable pressure being needed to counterbalance this expansive power, which increases as the temperature sinks. At 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 inclosing 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. 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 considerably below 32° Fahr. before freezing. But ice forming in cavities at even two or three degrees below the freezing-point exerts an enormous disruptive force.

Soils and rocks, being all porous, and usually containing a good deal of moisture, have their particles pushed asunder

by the freezing of this interstitial water. Stones, stumps of trees, or other objects imbedded in the ground, are squeezed out of it. When a thaw comes, the soil seems as if it had been ground down in a mortar. Water, freezing in the innumerable joints and fissures of rocks, 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, much 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 so frequently lie at the foot of crags and steep slopes. At Spitzbergen, and on the coast of Greenland, the observed amount of destruction caused by frost is enormous. The short warm summer, melting the snow, fills the pores and joints of the rocks with water, which when it freezes splits off large blocks, launching them to the base of the declivities, where they are further broken up by the same cause. In some countries, where the winters are severe, the soil-cap has been observed to be pushed or to creep downhill from the action of frost.[214]

Frozen Rivers and Lakes.—In countries such as Canada, the lakes and rivers are frozen over in winter with a cake of ice $1\frac{1}{2}$ to $2\frac{1}{2}$ feet thick. This cake as it forms expands and presses against the shores. A continuance of frost leads to a contraction of the ice already formed and to the consequent opening of vertical fissures, into which the water

[214] Kerr, Amer. Journ. Sci. xxi. 1881, p. 345; C. Davidson, Geol. Mag. 1889, p. 255.

from below ascends and freezes. When a subsequent rise in temperature causes an expansion of the superficial crust, the ice once more presses against the shores. When these are steep the ice yields and either breaks up along its margin or assumes an undulating surface over the lake; but where they are sloping it is pushed up the slope, carrying with it earth and bowlders. Similar results are repeated during subsequent rises and falls of temperature, the débris being driven further up the shore, until it sometimes accumulates in a mound or wall along the outer edge of the broken ice. When the ice melts this embankment of displaced material is left as a memorial of the severity of the climate. Such "shore-walls" are of common occurrence on the margins of many lakes in Canada and the United States.[215] Under certain conditions, also, what is called "anchor-ice" forms on the bottoms of the rivers and rises to the surface.[216] In several ways, geological changes are thus effected. Mud, gravel, and bowlders incased in the anchor-ice or pushed along by it on the bottom, are moved from their position. This ice, formed in considerable quantity in the rapids of the Canadian rivers, is carried down stream and accumulates against the bars and banks, or is pushed over upon the surface of the upper ice. By its accumulation a temporary barrier is formed, the bursting of which causes destructive floods. When the ice breaks up in early summer, cakes of it which have been formed along shore, and have inclosed beach-pebbles and bowlders,

---

[215] C. A. White, Amer. Naturalist, ii. 1868, p. 148; G. K. Gilbert, 5th Ann. Rep. U. S. Geol. Survey, 1885, p. 109.

[216] These conditions, according to Dr. Rae (Nature, xxi. p. 538), are: 1st, a rocky or stony bottom; 2d, shallow water as compared with that higher up the stream; 3d, a swifter current and rougher water, in comparison with a smooth and slower motion immediately above. It is a loose, slushy, adhesive kind of ice. See also Nature, xxi. p. 612; xxii. 31, 54.

float off so as either to drop these in deeper water or to strand them on some other part of the shore.

This kind of transport takes place on a great scale on the St. Lawrence. The islets of bowlder-clay and solid rock are fringed with blocks which have been stranded by ice and which are ready to be again inclosed, and floated off further down stream. Should a gale arise during the breaking up of the frost, vast piles of ice, with mingled gravel and bowlders, may be driven ashore and pushed up the beach; even blocks of stone of considerable size are sometimes forced to a height of several yards, tearing up the soil on their way, and helping to form a bank above the water-level. In the same river, great destruction of banks has been caused by rafts of ice, and particularly of anchor-ice. Crab Island, for example, which was about an acre and a half in extent at the beginning of this century, has entirely disappeared, its place being indicated merely by a strong ripple of the water, which is every year getting deeper over the site.[217] Other islands have also been destroyed. Great damage is frequently done to quays and bridges in the same region, 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 frozen rivers, and especially when, as in Siberia, their ice breaks up in the higher parts of their courses, before it gives way in the lower (p. 647).

Hail, the formation of which is not yet well understood,[218] falls chiefly in summer and during thunderstorms. 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.

Snow.—In those parts of the earth's surface where, either from geographical position or from elevation into the upper

---

[217] Bleasdell, Q. J. Geol. Soc. xxvi. p. 669; xxviii. p. 292.

[218] For an account of the different theories proposed to account for hail, see Prof. Viguier, Assoc. Française, 1879, p. 543; 1880, p. 436.

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, termed the *snow-line*, can be traced, below which the snow disappears in summer, but above which it continues to cover the whole or great part of the surface. The snow-line comes down to the sea around the poles. Between these limits it rises gradually in level till it reaches its highest elevation in tropical latitudes. South of lat. 78° N. it begins to retire from the sea-level, so that on the coast of northern Scandinavia it is already nearly 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 behavior: (1) conservative, and (2) destructive. (1) 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. (2) *a*. 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. Great destruction is thus caused in dense forests. *b*. Snow accumulating on gentle slopes and slowly sliding downward, pushes soil or loose stones down-hill. Considerable transport of rotted rock and bowlders may thus arise.[219] *c*. Snow on steep mountain slopes is frequently during spring and summer detached in sheets from 10 to more than 50 feet thick and several hundred yards broad and

[219] H. Y. Hind, Canadian Naturalist, viii. 1878, pp. 967, 976.

long, which rush down as *avalanches* (Lawinen), sweep away trees, soil, or rocks, and heap them up in the valleys.[220] Besides the destruction caused by the avalanche itself, sometimes much damage arises from the sudden violent wind to which it gives rise.[221] *d.* Another indirect effect of snow is seen in the sudden rise of rivers when warm weather rapidly melts the mountain snows. Many summer freshets are thus caused in Switzerland. It is to the melting of the snows, rather than to rain, that rivers descending from snowy mountains owe their periodical floods. Hence such rivers attain their greatest volume in summer. *e.* A curious destructive action of snow has been observed on the sides of the Rocky Mountains, where the drifting of snow-crystals by the wind in some of the passes has damaged and even killed the pine-trees, wearing away the foliage, cutting off the bark, and even sawing into the wood for several inches.[222]

Glaciers[223] and Ice-sheets. — Glaciers are rivers of ice formed by the slow movement and compression of the snow, which, by gravitation, creeps downward into valleys descending from snow-fields. The snow in the higher regions is loose and granular. As it moves downward it

---

[220] An avalanche near Ormons Dessus, Canton Vaud (Dec. 1882), piled up a mass of ice and snow 200 feet thick (some of the ice-blocks being 18 feet long), and covered 3 square km. of ground. Nature, xxvii. p. 181. Streams may be thus blocked up, as the Inn was at Süs in 1827. For accounts of avalanches, see J. Coaz, "Die Lawinen in den Schweizeralpen," Berne, 1881.

[221] Geol. Mag. 1888, p. 155.

[222] Clarence King, Exploration of 40th Parallel, i. p. 527.

[223] On glaciers and their geological work, see De Saussure, "Voyages dans les Alpes," § 535; Agassiz, "Études sur les Glaciers," 1840; Rendu, "Theorie des Glaciers de la Savoie," Mem. Acad. Savoie, x., translated into English, 1875; J. D. Forbes, "Travels in the Alps," 1843; "Norway and its Glaciers," 1853; "Occasional Papers on Glaciers," 1859; Tyndall, "Glaciers of the Alps," 1857; Mousson, "Gletscher der Jetztzeit," 1854; A. Heim, "Handbuch der Gletscherkunde," Stuttgart, 1885; E. Richter, "Gletscher der Ostalpen," Stuttgart, 1888.

becomes firmer, passing into the condition of *névé* or *firn* (p. 258). Gradually, as the separate granules are pressed together and the air is squeezed out, the mass assumes the character of blue compact crystalline ice. From a geological point of view, a glacier may be regarded as the drainage of the snowfall above the snow-line, as a river is the drainage of the rainfall. A glacier, like a river, is always in motion, though so slowly that it seems to be solid and stationary. It descends as a brittle, thick-flowing substance, like pitch or resin. The motion is unequal in the different parts, the centre moving faster than the sides and bottom, as 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. Helland has observed that on the west coast of Greenland the glacier of Jacobshavn has a remarkably rapid motion, its rate for twenty-four hours ranging from 48·2 feet to 64·8 feet. The ice of the fjord of Torsukatak, nearly five miles wide, moves with a mean rate of 24 feet in a day; that of Karajak, four and a half miles broad, moves 30 feet daily. G. F. Wright, from observations made by him in Alaska, inferred that the Muir glacier there enters a sea-inlet at an average rate of forty feet per day (70 feet in the centre and 10 feet near the margin) in the month of August;[224] but a more recent measurement by Dr. Reid in the summer of 1890 gives a maximum rate of only seven feet in a day.

The consequence of this differential motion is seen in

[224] Amer. Journ. Sci. xxxiii. 1887, p. 10. For the glaciers of the United States see Wright's "Ice-Age in America"; H. P. Cushing, American Geologist, 1891, p. 207; Hayes, National Geographic Magazine, iv. 1892, p. 150; Russell, Amer. Journ. Sci. xliii. 1892, p. 169. 5th Ann. Rep. U. S. Geol. Surv. 1885.

the internal banded structure of a glacier, in the downward curvature of the transverse fissures (crevasses), and in the arrangement of the lines of rubbish thrown down at the termination, which often present a horseshoe shape, corresponding to that of the end of the ice by which they were discharged.[225]

Under the term Ice-sheet is included the deep mantle of snow and ice which, in the Polar regions, covers the land and creeps out to sea. In high Arctic, and still more in Antarctic latitudes, land-ice, formed from the drainage of a great snow-field, attains its greatest dimensions. The land in these regions is buried under an ice-cap which ranges up to a thickness (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 only the steep mountain-crests and peaks near the coast, 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 that float away as icebergs.[226] As far back

[225] The cause of glacier motion has been a much-vexed question in physics. See, besides the works cited in the foregoing note, J. Thomson, Proc. Roy. Soc. 1856–57; Mosely, op. cit. 1869; Croll, "Climate and Time," 1875; Hopkins, Phil. Mag. 1845; Phil. Trans. 1862; Helmholtz, Heidelberg Verhandl. Nat. Med. 1865, p. 194; Phil. Mag. 1866, p. 22; Pfaff, Akad. Bayer. 1876. A valuable history of the controversy regarding glacier motion has been prepared by Sir H. H. Howorth, Mem. Proc. Manchester Lit. Phil. Soc. iv. 1891. The conclusion to which the most recent researches point coincides essentially with that enunciated upward of 40 years ago by J. D. Forbes, that the motion of a glacier "is that of a slightly viscous mass, partly sliding upon its bed, partly shearing upon itself under the influence of gravity." Trotter, Proc. Roy. Soc. xxxviii. p. 107. The banded structure of glacier-ice may be compared with shear-structure (see p. 538, and Fig. 256).

[226] The Greenland snow-fields and glaciers are well described in the "Meddelelser om Grönland"—the detailed report of a Danish commission appointed to investigate that country. The first volume was published in 1879, and ten

as 1777, Captain Cook gave interesting descriptions of the glaciers of South Georgia (Lat. 54° S.), which reach the sea in a line of cliffs (Fig. 149).

Glaciers, though naturally most abundantly developed in Arctic and Antarctic regions, may be met with in any latitude wherever a sufficiently extensive area of snow accumulates and remains permanent throughout the year. They occur even in equatorial regions where the ground rises sufficiently high above the snow-line. They are found in great force among the Himalaya mountains, while among the Andes of Quito, close to the equator, many glaciers have been noted; the great mountain of Chimborazo (20,498 feet), for example, being capped with ice and sending glaciers out in all directions.[227] Hence the peculiar geological results effected by glacier-ice are not restricted to definite latitudes, but may be encountered, under the necessary limitations, from the equator to the poles.

Some features of geological importance in the behavior of a glacier as it descends its valley deserve mention here. When the ice 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, as is remarkably displayed in the Greenland ice where it flows round the isolated rocks or "Nunatakker" which rise out of it. It

---

have subsequently appeared. See also Nordenskiöld, Geol. Mag. 1872, Marr, Geol. Mag. 1887, p. 151. H. Rink, Edin. Geol. Soc. v. 1887, p. 286. E. von Drygalski, Zeitsch. Gesell. f. Erdkunde, Berlin, 1892. See also Nansen, Petern. Mittheil. Erganzungsheft, No. 105, 1892.

[227] On glaciers of Ecuador see Whymper, "Travels amongst the Great Andes," p. 348.

there acquires in some places a remarkably beautiful banded structure, which in lenticular banding and folding presents a close resemblance to the characteristic banded and plicated structure of many ancient gneisses.[228] In descending by a steep slope to a 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, with all its chaos of pinnacles, bastions, and chasms, is pressed together again, and by regelation becomes once more a solid mass (Fig. 143).

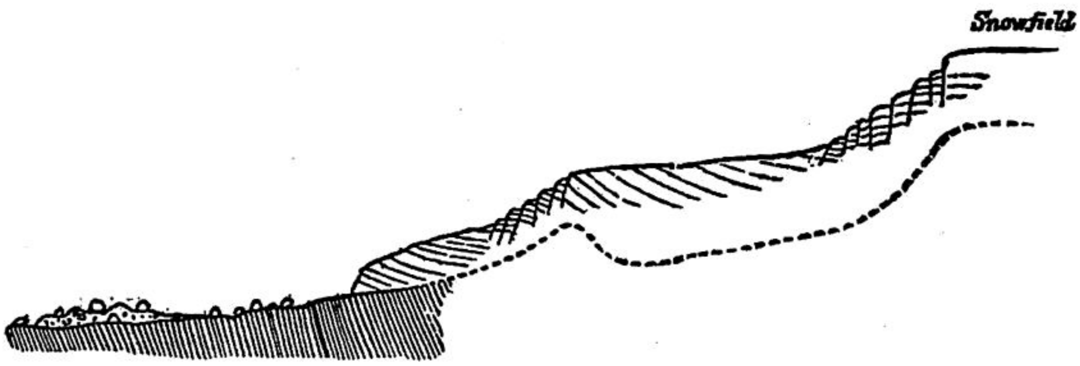


Fig. 143.—Section of Glacier with Ice-falls, Fondalen, Holands Fjord, Arctic Norway.

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 its rate of advance is just equalled by its liquefaction. There it ends, its place down

[228] See by way of illustration plates ix.–xii. of a paper on the glaciers and inland ice of Greenland by E. von Drygalski, Zeitsch. Gesell. f. Erdkunde, Berlin, 1892.

the rest of the valley being taken by the tumultuous river of muddy water which escapes from under the melting extremity of the ice. A prolonged augmentation of the snowfall will send the foot of the glacier further down the valley; a diminution of the snowfall or a general rise of temperature will cause it to retreat further up.

Considerable variations in the thickness and length of glaciers have been observed within the last two or three generations, due to oscillations of temperature and wetness. Thus the glacier of La Brenva, on the Italian side of Mont Blanc, shrank to such an extent in the twenty-four years succeeding 1818, that its surface at one place was found to have subsided no less than 300 feet.[229] The glaciers of Mont Blanc had ceased to advance about 1854, and in twelve years, from 1854 to 1865, the Glacier des Bossons had receded 332 metres, that of Bois 188 metres, that of Argentière 181 metres, and that of Tour 520 metres. Similar facts have been observed in the Bernese Oberland and the Tyrol, but with some local exceptions, in particular the Gorner and Aar glaciers.[230] At the Pasterzen glacier, which shrank back about 6 or 8 metres annually, the retreat was changed in 1883 into a forward movement, possibly indicating that the minimum had been reached and that a new advance of the ice had begun.[231] Since 1855 the glaciers of the Pyrenees and Caucasus have also shrunk.[232] The glaciers of Greenland and Alaska were formerly much larger than they are now. The Muir glacier in Alaska is said to have retreated half a mile in four years preceding 1890.[233]

In a mountainous region such as the Alps, or a tableland like Scandinavia, where a considerable mass of ground lies above the snow-line, three varieties of glaciers may be observed.

---

[229] J. D. Forbes, "Travels in the Alps," p. 205.

[230] L. Gruner, Comptes Rend. lxxxii. p. 632. Bull. Soc. Geol. Fran. iv. (3e ser.). On periodic variations of Alpine Glaciers, see Forel, Arch. Sci. Bib. Univ. Geneva, July, 1881.

[231] F. Seeland, Zeitsch. Deutsch-Oesterr. Alpenvereins, 1884, p. 51.

[232] Ch. Dufour, Assoc. Française, 1880, p. 449. The Norwegian glaciers are now retreating.

[233] H. P. Cushing, American Geologist, 1891, p. 215.

(1) Glaciers of the first order (valley-glaciers) come down well below the snow, and extend into the valleys. In high latitudes they reach the sea. The Humboldt Glacier in North Greenland presents a wall of ice 60 miles long and rising 300 feet above the sea, which washes the base of the cliff. The spiry peaks and sharp crests of the Alps rise through the snow, which they thus isolate into distinct

Fig. 144.—Snow-Fields and Glaciers of Mont Blanc, seen from the top of Mount Brévent.

basins (Firnmulden), averaging perhaps two square miles in area, whence glaciers proceed. The number of glaciers among the Alps has been estimated at 2000, covering a total area of from 3000 to 4000 square kilometres (Figs. 144, 145). They average perhaps from 3 to 5 miles in length. The Great Aletsch Glacier is nearly 10 (or, including the snow-field, nearly 15) miles long, with a mean breadth of 5900 feet, and descending to 4439 feet above the sea. The thickness of the ice in the Alpine glaciers must often be as much as 800 to 1200 feet. It has been computed that the Gorner Glacier is large enough to make three cities as big as London. The great snow-fields of Arctic Norway accumulate on broad table-lands, from which they send glaciers down into the valleys (Figs. 143, 146).

(2) Glaciers of the second order (Corrie-glaciers, Hänge-

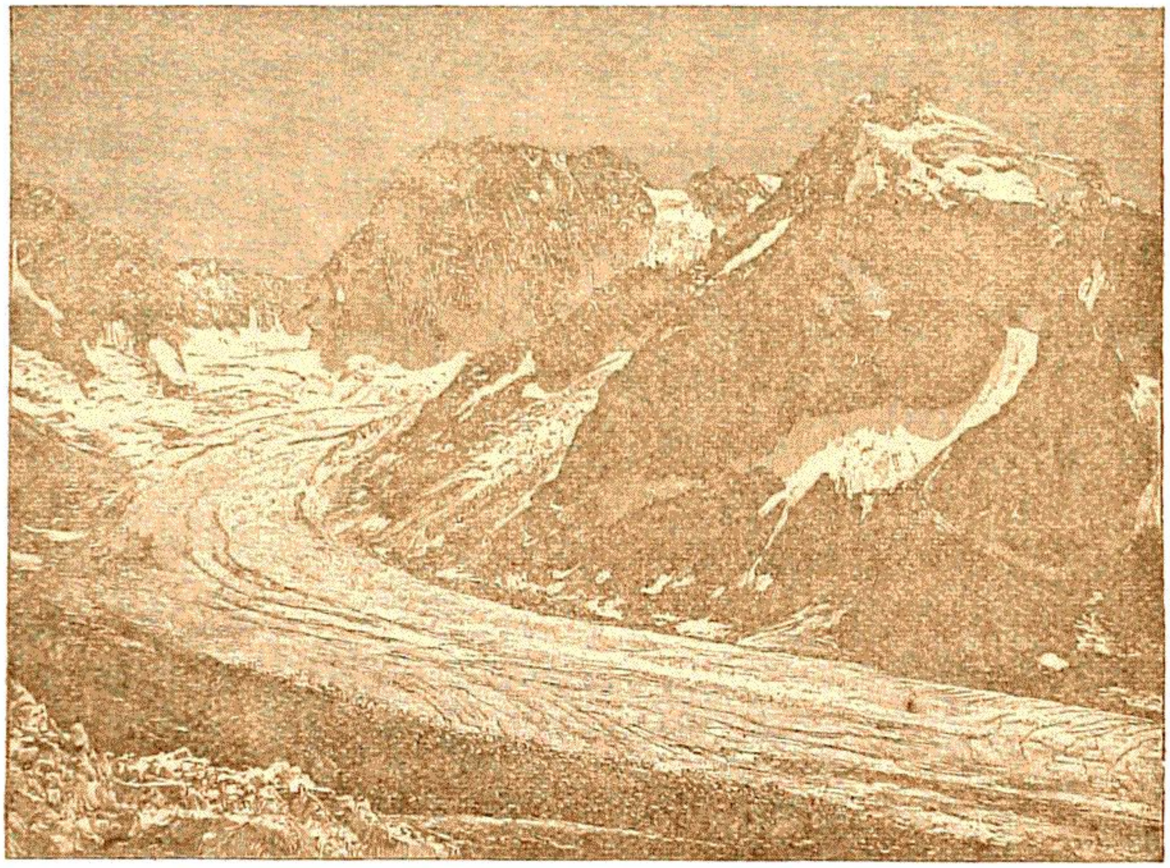


Fig. 145.—Glacier de Lechaud, with the Grandes Jorasses and Aiguille de Tacul.

gletscher) 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.

(3) Recemented Glaciers (*Glaciers remaniés*).—These consist of fragments which, falling from an ice-cliff crowning precipices of rock, are refrozen at the bottom into a solid

mass that creeps downward as a glacier usual.y 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 "firn" resting on blue ice appears at the top of the precipice—the edge of the great "sneefond," or snow-field—while several hundred feet below, in the corrie or cwm at the bottom, lies the recemented glacier, white at its upper edge, but acquiring somewhat of the characteristic blue gleam of compact ice as it moves toward its lower margin. A beautiful example of this kind

Fig. 146.—View of the two Glaciers of Fondalen, Holands Fjord, Arctic Norway.

was visited by me at the head of the Jokuls Fjord in Arctic Norway in 1865. When making the sketch from which Fig. 147 is taken, I observed that the ice from the edge of the snow-field above slipped off in occasional avalanches, which sent a roar as of thunder down the valley, while from the shattered ice, as it rushed down the precipices, clouds of white snow-dust rose into the air. The débris thus launched into the defile beneath accumulates there by mutual pressure into a tolerably solid mass, which moves downward as a glacier, and actually reaches the sea-level—the only example, so far as I am aware, of a glacier on the continent of Europe which attains so low an altitude. As it descends it is crevassed, and when it comes to the edge of the fjord, slices from time to time slip off into the water, where they form fleets of miniature icebergs, with which the surface of the fjord (*f* in Fig. 148) is covered.

Great destruction is sometimes caused by the breaking off of the end of glaciers which terminate on steep ground. The sudden dislocation of the ice and its reduction to fragments, and even to powder, causes a considerable proportion of it to melt. A mingled mass of ice and water is thus discharged, which, meeting with loose moraine stuff, may

Fig. 147.—View of recemented Glacier, Jokuls Fjord, Arctic Norway.

speedily become a moving debacle of mud. Such, according to M. Forel, was the origin of the destructive avalanche which on 12th July, 1892, swept away some thirty houses and killed about 150 people, in the valley of Montjoie, which joins that of the Arve, not far below Chamouni.[934]

Another incidental effect of the movement of glaciers is to be seen when the ice, barring the mouth of a tributary valley, dams back the streams flowing therein, and causes

934 Comptes Rend. cxv. 1892, p. 193. Other writers assign the bursting of a glacier-lake as the cause.

a lake to form. This result may be observed at the Märjelen See, on the great Aletsch Glacier, and elsewhere on the Alpine chain. If this arrest of the water is temporary, great damage may be done by the bursting of the ice-dam and the consequent sudden rush of the liberated water. If, on the other hand, the glacier is massive enough to form a permanent barrier, the water may rise behind it so as to fill the tributary valley, and even escape by a pass at its head. Successive diminutions of the mass of ice will lead to corresponding lowerings of the level of the lake, each prolonged rest of the water at one level being marked by a shelf or terrace formed as a beach-line along the shore.

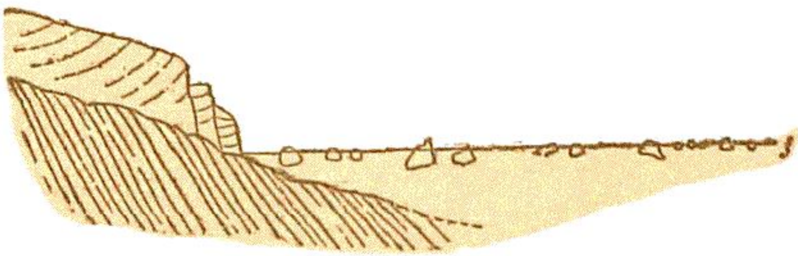


Fig. 148.—Section showing the production of Icebergs at the foot of the Jokuls Fjord Glacier.

The famous "parallel roads" of Glen Roy are a striking illustration of this kind of geological history. (Book VI. Part V. Sect. i. § 1.)

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

(*a*) *Transport.*—This takes place chiefly on the surface of the ice. 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. 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, 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

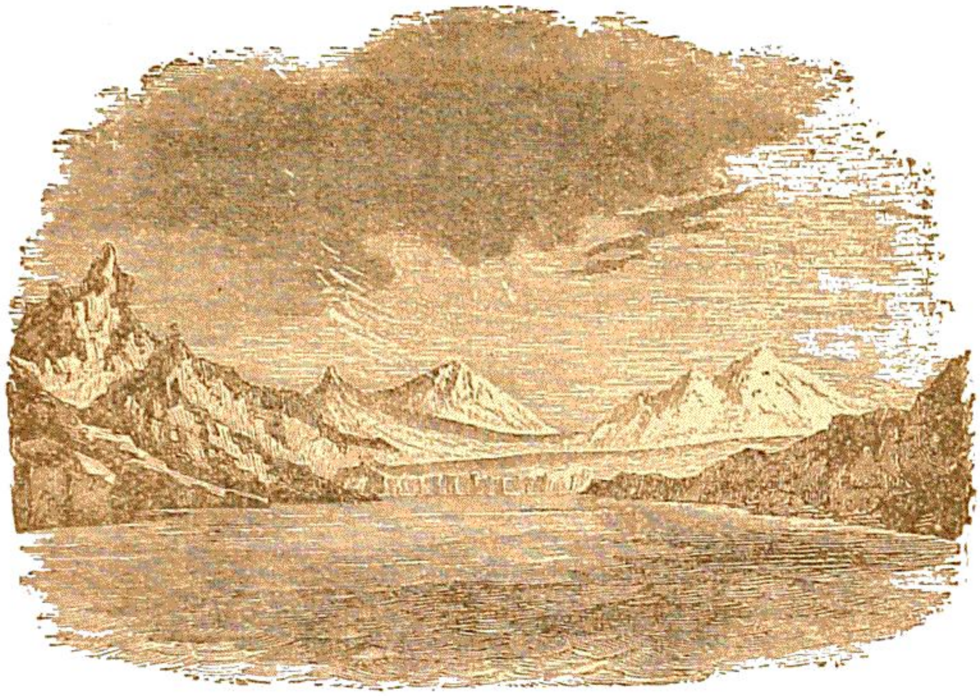


Fig. 149.—View of Glacier in Possession Bay, South Georgia.

the fate of a large proportion of the smaller stones and sand. But 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 toward 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*. In Fig. 150 the left lateral moraine (3) of glacier B unites with the right lateral moraine (2) of A to form the medial moraine *b*, while the other moraines (1, 4) continue their course and become respectively the right and left lateral moraines (*c*, *a*) of the united glacier. A glacier formed by the union of many tributaries in its upper parts, may have numerous medial lines of moraine, so many indeed as sometimes to be covered with débris, to the complete concealment of the ice. At such parts the glacier appears to be a bare field or

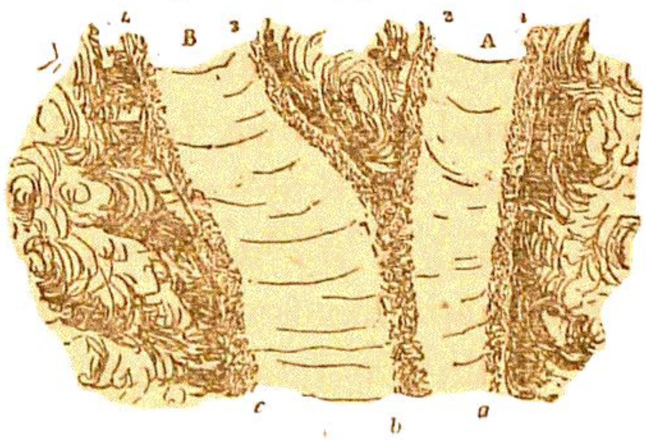


Fig. 150.—Map of the union of two glaciers, showing junction of two lateral into one medial Moraine.

earthy plain, rather than a solid mass of clear ice of which only the surface is dirty with rubbish. At the end of the glacier, the pile of loose materials is tumbled upon the valley in what is called the *terminal moraine*.

Beneath the ice of the Swiss glaciers lies a thin inconstant layer of fine wet mud, sand, and stones, derived partly from the descent of materials from the surface down the crevasses, partly from the rocks of the sides and bottom of the glacier-bed. These materials may be seen fixed sometimes in the ice itself. Though it may locally accumulate, this layer is apt to be removed by the ice or by the water that flows under the glacier. It is known to

Swiss geologists as the *moraine profonde* or *Grundmoräne* (=bowlder clay, till or bottom-moraine). The sheet of ice that once filled the broad central plain of Switzerland, between the Alps and the Jura, certainly pushed a vast deal of mud, sand, and stones over the floor of the valley, and this material has been left as a covering, like the till of Northern Europe.[235]

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*. Those of each valley belong to the rocks of that valley; and if there be any difference between the rocks on the two sides, the perched blocks, carried far down from their sources, still point to that difference, for they remain on their own original side. But during a former great extension of the glaciers of the northern hemisphere, blocks of rock have been carried out of their native valleys, across plains, valleys, and even considerable ranges of hills.

Such "erratics" (Findlinge) not only abound in the Swiss valleys, but cross the great plain of Switzerland, and appear 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. Thousands of them form a great belt of bowlders extending for miles at an average height of 800 feet above the Lake of Neufchâtel (Fig. 151). These consist of the protogene granite of the Mont Blanc group of mountains, and must have travelled at least 60 or 70 miles. One of the most noted of them, the Pierre à Bot (toad-stone),

[235] In 1869 I examined a characteristic section of an ancient moraine profonde near Solothurn, full of scratched stones, and lying on the striated pavement of rock to be immediately described as further characteristic of ice-action. It closely resembled the bowlder-clay of Northern Europe.

which lies about two miles west of Neufchâtel, measures 50 (French) feet in length by 20 in width, and 40 in height. It is estimated to contain 40,000 cubic feet, and to weigh about 3000 tons.[236] The celebrated "blocks of Monthey" consist of huge masses of granite, disposed in a belt, which extends for miles along the mountain slopes on the left

Fig. 151.—Pierre à Bot—a granitic block from the Mont Blanc range, stranded above Neufchatel (J. D. Forbes).

bank of the Rhone, near its union with the Lake of Geneva. On the southern side of the Alps, similar evidence of the transport of blocks from the central mountains is to be found. On the flanks of the limestone heights on the further side of the Lake of Como, blocks of granite, gneiss, and other crystalline rocks lie scattered about in hundreds (Fig. 152).

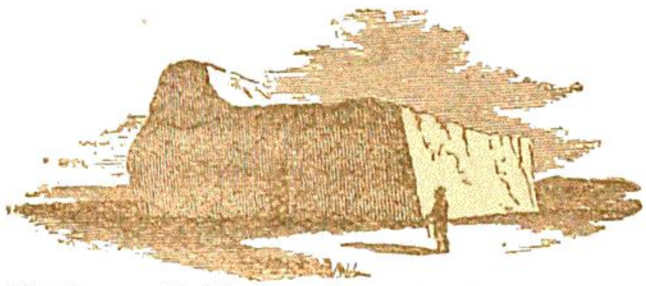


Fig. 152.—Angular erratic block on the north side of the Alpi di Pravolta, Lake of Como (*B.*).

Before the numerous facts had been collected and understood which prove a former great augmentation in the size of the Alpine glaciers, it was believed by many geologists that the erratics stranded along the flanks of the Jura mountains had been transported on floating ice, and that Central Europe was then in great part submerged beneath an icy

[236] Forbes, "Travels in the Alps," p. 49.

sea. It is now universally admitted, however, that the transport has been entirely the work of glaciers. Instead of being confined, as at present, to the higher parts of their valleys, the glaciers extended down into the plains. As already stated, they filled the great depression between the Oberland and the Jura, and, rising high upon the flanks of the latter chain, actually overrode some of its ridges. Similar evidence in the hilly parts of Britain, as well as in other parts of Europe and America, no longer the abode of glaciers, shows that a great extension of snow and ice at a recent geological period prevailed in the northern hemisphere, as will be described in the account of the

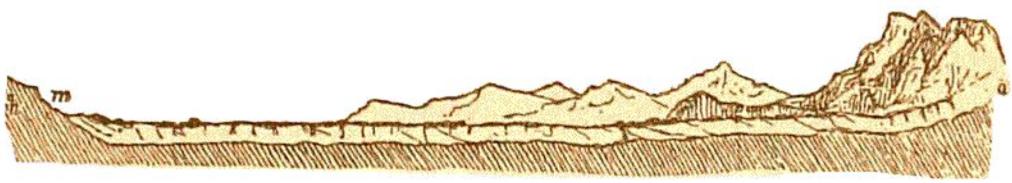


Fig. 153.—Section to show the extension of the Alpine Glaciers (*a*) across the Plain of Switzerland, and the transport of blocks to the sides of the Jura (*m*) (*B.*).

Glacial Period in Book VI. Extensive as are the present ice-sheets and glaciers of Greenland, they are undoubtedly much reduced from their former size, for bare ice-worn rocks are found beyond their limits, as in Scandinavia.[237] There is proof also that the glaciers of New Zealand were formerly much larger.[238]

As De la Beche has well pointed out, the student must be on his guard lest he be led to mistake for true erratics mere weathered blocks belonging to a rock that has disintegrated *in situ*. If, for example, he should encounter a

---

[237] Meddelelser om Grönland. H. Rink, Petermann's Mittheilungen, 1884, p. 136, gives some recent results of Greenland exploration. Much useful information regarding the Arctic regions is given in the "Manual and Instructions for the Arctic Expedition," 1875.

[238] For New Zealand glaciers see A. P. Harper, Geograph. Journ. i. 1893, p. 32.

block like that represented in Fig. 154, he would properly conclude that it had travelled, because it did not belong to the rock on which it lay. But he would require to prove further that there was no rock in the immediate neighborhood from which it could have fallen as the result of mere weathering. The granite (*c*) shown in Fig. 155 disintegrates at the summit, and the blocks into which it splits find their way by gravitation down the slope.[239]

Fig. 154.—Block of granite resting on inclined strata (*B.*).

(*b*) *Erosion.*—The manner and results of erosion in the channel of a glacier differ from those associated with other geological agents, and form therefore distinguishing features of ice-action. This erosion is effected not by the mere contact and pressure of the ice upon the rocks (though undoubt-

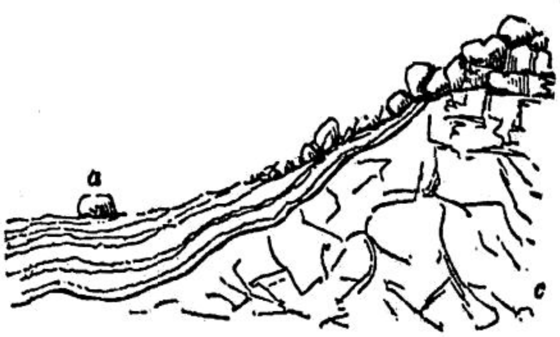


Fig. 155.—Granite (*c*) decomposing into blocks (*a*) which gradually roll down upon the surrounding stratified rocks (*B.*).

edly blocks of rock may thereby be detached), but by means of the fine sand, stones, and blocks of rock that fall between the ice and the rocks on which it moves. The detritus thus introduced is, for the most part, fresh and angular. Its trituration by the glacier reduces the size of the particles, but retains their angular character, so that, as Daubrée has

239 De la Beche, "Geological Observer," p. 257. The surface of some parts of the granite districts of Cornwall are strewn with large bowlders of granite, schorl-rock, vein-quartz, etc., but these, though resembling erratics in form, are all due to decomposition of the parent-rocks *in situ*.

pointed out, the sand that escapes from the end of a glacier appears in sharp freshly-broken grains, and not as rounded water-worn particles.[240]

The surface of a glacier being often strewn with earth and stones, these materials are frequently precipitated into the crevasses, and may thus reach the rocky floor over which the ice is moving. They likewise fall into the narrow space which sometimes intervenes between the margin of a glacier and the side of the valley (*a* in Fig. 156). Held by the ice as it creeps along, they 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 glacier. Here and there the ice, with grains of sand and pieces of stone imbedded in its surface, can be caught in the very act of polishing and scoring the rocks. In Fig. 157 a view is given of the "angle" on the Mer de Glace, Chamouni, where blocks of granite are jammed between the mural edge of the ice and the precipice of rock along which it moves, and which is scored and polished in the direction of motion of the blocks. Under the slow, continuous, and enormously erosive power of the creeping ice, the most compact resisting rocks are ground down, smoothed, polished, and striated (Fig. 158). The striæ vary from such fine lines as may be made by the smallest grains of quartz up to deep ruts and grooves. They

Fig. 156.—Section of a Glacier in its rocky channel,

With a medial moraine at *d*, a lateral moraine partly on the ice and partly stranded on a sloping declivity (*b*), a mass of rocks fallen between the ice and the precipitous rocks at *a*, and a group of perched blocks at *c* (J. D. Forbes).

240 "Geologie Experim." p. 254.

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

Fig. 157.—View of part of the side of the Mer de Glace (J. D. Forbes).

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 (Fig. 160). It will be seen, when we come to notice the traces of former glaciers, how important is the evidence given by these striated stones.

Besides its proper and characteristic rock-erosion, a glacier is aided in a singular way by the co-operation of running water. Among the Alps, during day in summer, much ice is melted, and the water courses over the glaciers in brooks which, as they reach the crevasses, tumble down in rushing waterfalls, and are lost in the depths of the ice. Directed, however, by the form of the ice-passage against the rocky floor of the valley, the water descends at a particular spot, carrying with it the sand, mud, and stones

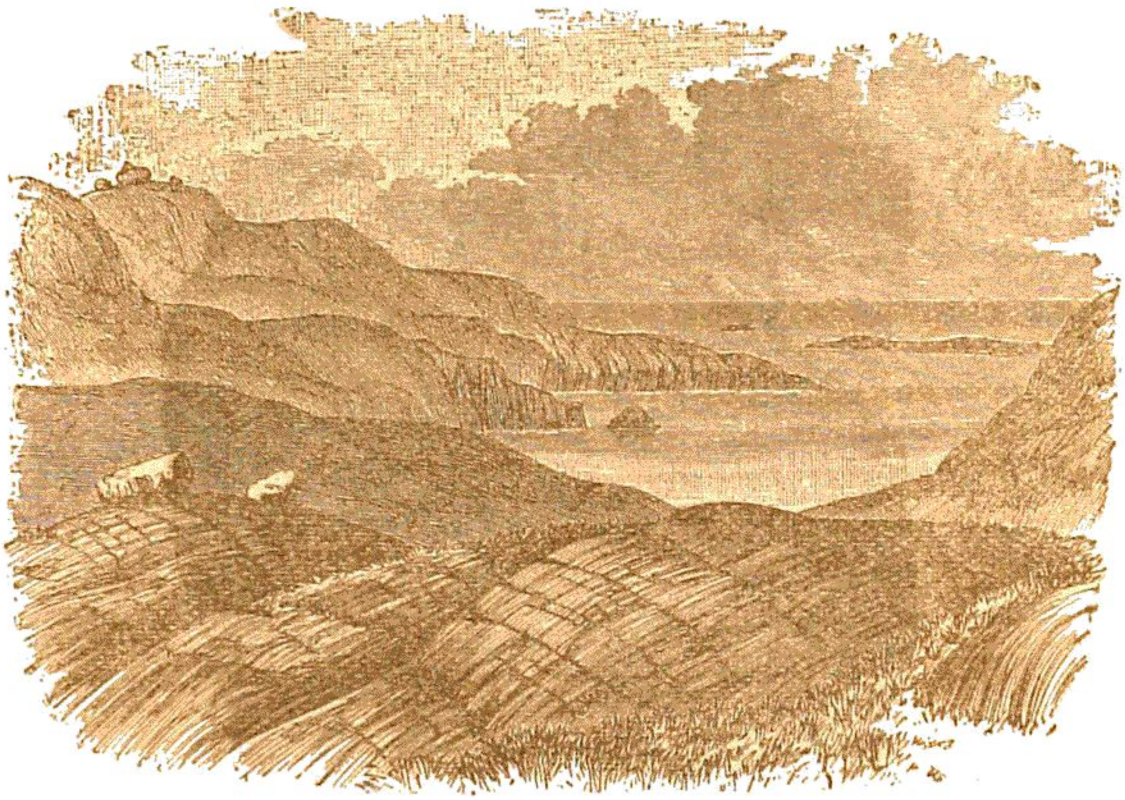


Fig. 158.—Ice-worn surface of rock, showing Polish, Striæ, Groovings, and Erratics, Sutherland.

which it may have swept away from the surface of the glacier. By means of these materials it erodes deep pot-holes (moulins) in the solid rock, in which the rounded detritus is left as the crevasse closes up or moves down the valley. On the ice-worn surface of Norway, singular cavities of this kind, known as "giants' kettles" or "caldrons" (Riesentopfe, Riesenkessel, Fig. 159), exist in great numbers.[241]

[241] S. A. Sexe, Universit. Program. Christiania, 1874. Brögger and Reusch, Q. J. Geol. Soc. xxx. 750.

There can be little doubt that they have had an origin under the massive ice-cover which once spread over that peninsula. Similar cavities filled with transported bowlders occur in the molasse sandstone near Bern,[242] and a large group of them is now one of the sights of Lucerne. They have been recognized in North Germany[243] and generally over the glaciated areas of Europe. As the Greenland ice-sheet is traversed in summer by powerful rivers which are swallowed up in the crevasses, excavations of the same nature are no doubt also in progress there.

Since 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 a local augmentation of the 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.

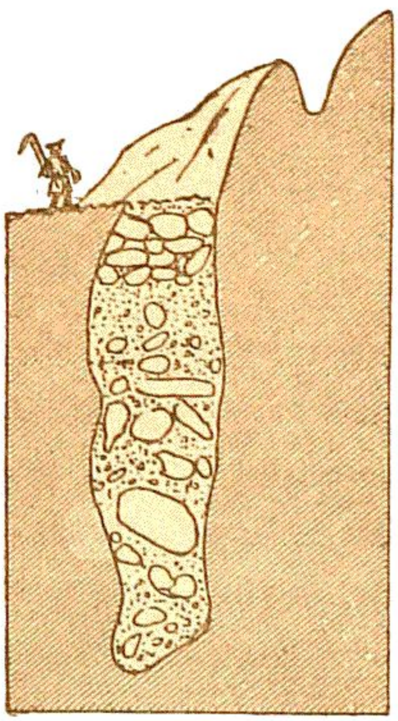


Fig. 159.—Section of "Giant's Kettle," near Christiania.

[242] Bachmann, Neues Jahrb. 1875, p. 53.
[243] Jahrb. Preuss. Geol. Landesanst. 1880, p. 275.

Among the proofs of great erosion by ice on hard rocky surfaces the existence of basins scooped out of the solid rock are perhaps the most striking. The striæ and scorings may in such cases be traced down below the water at the end of a tarn or lake, and may be found emerging at the other end with the same steady direction as on the surrounding ground or inclosing valley. In the year 1862 the late Sir 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

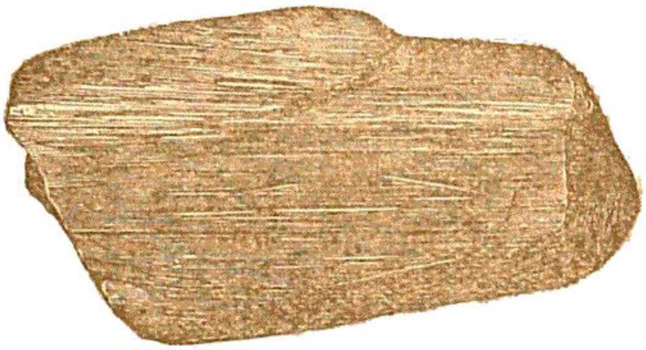


Fig. 160.—Striated stone from Bowlder-Clay.

eroded by sheets of land-ice, when the more northern parts of the two continents were in a condition like that of North Greenland at the present day.[244] It is among the ice-fields of Greenland, rather than among the valley-glaciers of isolated mountain-groups, that the operations which produced the widespread general glaciation of the period of the rock-basins find their nearest modern analogies. A single valley-

[244] Q. J. Geol. Soc. xviii. 1862, p. 185. See also a paper by A. Helland (op. cit. xxxiii. p. 142), on the Ice-fjords of North Greenland, and the formation of Fjords, Lakes and Cirques. That glaciers rub down rocks is demonstrated by the roches moutonnées which they leave behind them. That they can dig out hollows has been denied by some able observers, but that they can do so to some extent at least, seems to be proved by the way in which the ice-striæ descend into and rise out of rock-basins. For arguments against this view see especially W. D. Freshfield, Proc. Roy. Geog. Soc. 1888, p. 779, and authorities there cited.

glacier retires toward 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 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 obscured. But in the case of a vast sheet of land-ice covering continuously a wide region, there can be but little superficial débris. When such a mass of ice retires, it must leave behind it an ice-worn surface of country, more or less strewn with the detritus which accumulated under the ice and was pushed along by it. This infra-glacial débris forms the *Grundmoräne* (*moraine profonde*), or bottom-moraine above referred to (p. 716). 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 bowlder-clay in more southern latitudes, which is believed to represent the bottom-moraine of an ancient ice-sheet. In countries where true bowlder-clay occurs, numerous rock-basins are commonly to be met with among the uncovered portions of the rocks. These and other features of glaciated Europe and America will be more fully described in the account of the Glacial Period (Book VI.).[245]

But while the proofs of great erosion by land-ice are indisputable, many instances have now been collected where glaciers have overridden moraines, gravel-beds, or other soft material, and have moved across them for perhaps long periods without removing them. It is obvious that

[245] See the remarks already made (p. 596) on the possibility of the rotting out of basin-shaped receptacles in solid rock through the operations of superficial weathering—a process which may account for many rock-basins that have subsequently had their decomposed rock swept out of them by ice.

in these places the ice can have no marked or at least rapid erosive power. The preservation of detritus below the ice seems generally to arise from flatness of the ground, thinning away of the ice, or some other local cause sufficient to indicate that the glacier cannot there act with erosive effect.[246]

Hardly anything has yet been done in the way of actual measurement of the rate of erosion by different glaciers. An approximation to the truth might be obtained from the abundant fine sediment which, giving the characteristic milky turbidity to all streams that escape from the melting ends of glaciers, is an index of the amount of this erosion. The average quantity of sediment discharged from the melting end of a glacier during a year having been estimated, it would be easy to determine its equivalent in the precise fraction of a foot of rock annually removed from the area drained by the glacier.

From the end of the Aar glacier (which with its affluents is computed to have an area of 60 square kilometres, and is therefore by no means one of the largest in Switzerland) it has been estimated that there escape every day in the month of August two million cubic metres (440 million gallons) of water, containing 284,374 kilogrammes (280 tons) of sand. The amount of fine sand discharged from the melting glacier into the fjord of Isortok, Greenland, is estimated at 4062 million kilogrammes per day.[247] Mr. A. Helland has computed that from the Justedal glacier, Norway, one million kilogrammes of sediment are discharged in a July day, and that the total annual discharge from the ice-field, 830 square miles in area, amounts to 180 millions of kilogrammes, besides 13 million kilogrammes of mineral matter in solution. Taking the specific gravity of the suspended matter at 2·6, he finds that the basin of the glacier

---

[246] For a striking example of the way in which a glacier may spread over deposits of gravel, see the plate accompanying Mr. H. P. Cushing's paper on the Muir Glacier of Alaska, American Geologist, 1891.

[247] Meddelelser om Grönland, vol. ii.

loses 69,000 cubic metres of solid rock every year, or a cubic mass measuring 41 metres on the side.[248] There is some difficulty, however, in determining what proportion of the sediment may have been washed in below the ice by streams issuing from springs and melted snows. Estimates of the work done by glaciers, so far as based upon the amount of sediment discharged by them, may consequently be rather over the truth.

§ 6. Oceanic Waters

The area, depth, temperature, density, and composition of the sea having been already treated of (Book II.), we have now to consider its place among the dynamical agents in geology. In this relation it may be studied under two aspects: 1st, its movements, and 2d, its geological work.

I. **Movements.**—(1) *Tides.*—These oscillations of the mass of the oceanic waters, caused by the attraction of the sun and moon, require notice here only as regards their geological bearings. They are scarcely perceptible in inclosed seas, such as the Mediterranean and Black Seas, which are commonly spoken of as tideless. In strictness, however, a feeble but quite recognizable tide may be observed in the Mediterranean. On the coast of the Alpes Maritimes it has a mean rise of 6 to 8 inches, the least rise being 4 and the highest not exceeding 10 inches. The Mediterranean tides are most strongly developed in the Bay of Gibraltar (where they rise from 5 feet to 6 feet 6 inches), the upper Adriatic, and the Gulf of Gabes. At Brindisi the rise is 8 inches, at Ancona 1 foot 4 inches, at Venice 1 foot 8 inches, and at Trieste 2 feet 4 inches. With a rise of the barometer the level of the water falls sometimes a fourth lower than the limit of the normal ebb. Observations at Nice, Monaco, Cannes,

[248] Geol. Fören. Stockholm Förhandl. 1874, No. 21, Band ii. No. 7.

and other places show that from atmospheric disturbances the level of the sea may be lowered as much as 1 foot 8 inches.[249]

In a wide deep ocean, 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 littoral space between being termed the *beach* (Fig. 161). If the coast is precipitous, a beach can only occur in shelving bays and creeks, since elsewhere the tides will rise and fall against a face of rock, as they do on the piers of a port.

Fig. 161.—Section of a Beach defined by High- and Low-water Mark.

249 Haschert, Deutsche Rundschau für Geographie, July, 1887. Bull. Amer. Geograph. Soc. xix. 1887, p. 314. J. de Pulligny, Assoc. Franç. 1891, ii. p. 287.

On such rocky coasts, the line of high-water is sometimes admirably defined by the gray crust of barnacles adhering to the rocks. Where the beach is flat, and the rise and fall of the tide great, many 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 at Chepstow amounts to a maximum of 50 feet. In like manner, the tides which enter the Bay of Fundy, between Nova Scotia and New Brunswick, are more and more cooped up and rise higher as they ascend that strait, till they reach a height of 70 feet. The bore on the Tsien-Tang Kiang, 70 miles from Shanghai, rushes up the estuary as a huge breaker 20 feet or more in height, with a loud roar and a speed of sometimes eight knots an hour.[250]

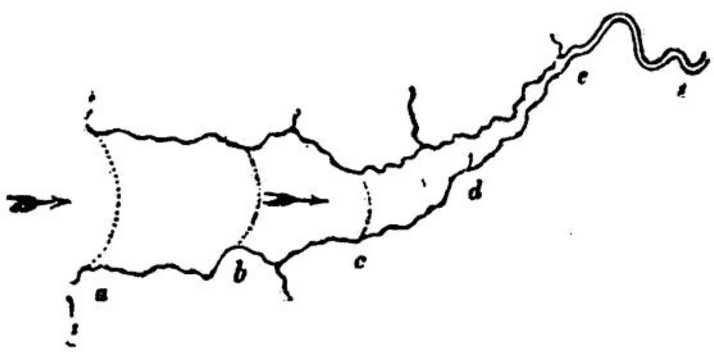


Fig. 162.—Effect of converging shores upon the Tidal Wave.
The tidal wave, running up in the direction of the arrows, rises successively higher at *a*, *b*, and *c* to *d*, after which it slackens and dies away at the upper limit of tides, *f*.

While the tidal swelling is increased in height by the

[250] Report to the Admiralty by Commander Moore, R.N., 1888.

shallowness and convergence of the shores between which it moves, 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 streams 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 whirlpool of Corryvreckan, the lurking eddies in the Kyles of Skye, the breakers at the Bore of Duncansby, 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 or "race" at its strongest runs at the rate of 10 miles an hour, which is fully three times the speed of most of our large 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.[251] 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 that 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°) rises likewise to about 300

---

[251] See, in particular, memoirs by Carpenter and Wyville Thomson, Proc. Roy. Soc. xvii. 1868; Brit. Assoc. xli. *et seq.*; Proc. Roy. Geograph. Soc. xv. Reports to the Admiralty of the "Challenger" Exploring Expedition. Wyville Thomson's "Depths of the Sea," 1873, and "Atlantic," 1877. Narrative volume of "Challenger" Report. Prince of Monaco, Brit. Assoc. 1892.

fathoms from the surface. This distribution of temperature proves that there must be a transference of cold polar water toward 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 much 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 toward 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 toward the northeast. 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 abysmal 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 currents. The tidal wave only becomes one of translation as it passes into shallow water, and is thus of merely 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 deflections. Thus, that portion which crosses the Atlantic from the African side strikes against the mass of South America, and divides, one portion turning toward the south and skirting the shores of Brazil; the other bending northwestward 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 toward the equator, sometimes in surface-currents like those which skirt the eastern and western shores of Greenland, but more generally as a cold undercurrent which creeps over the floor of the ocean even as far as the equator.

A large body of information has now been gathered as to the great marine currents which traverse the upper parts of the ocean, but comparatively little is yet known of the velocity of the movement of the water at great depths. Where the bottom is covered with a deep fine ooze we may infer that the rate of movement must be so feeble as not to disturb the deposition of the finest sediment. Where, on the other hand, "hard-bottom" is found, we may probably conclude that a sufficiently strong current flows there to prevent the accumulation of sediment, for all over the ocean there is enough of organic and inorganic particles diffused through the water to form a deposit on the floor if the conditions are favorable. A few observations have been made showing that at considerable depths among submarine ridges or islands strong currents exist. At a depth of 3000 feet near Gibraltar the telegraph cable from Falmouth was ground like the edge of a razor, and the scouring effects of strong currents have been noted at depths of 6000 feet between the Canary Islands.[252]

Much discussion has arisen in recent years as to the

[252] T. M. Reade, Phil. Mag. xxv. 1888, p. 342.

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 northeast and southeast 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, an equivalent bulk of polar water requires to move toward 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 stands at a higher level than the colder and heavier polar water; the former, therefore, flows down as it were poleward, while the latter moves as a bottom-inflow toward the equator; the cold bottom-water under the tropics slowly ascends to the warmer upper layers, and rises in temperature toward the surface, whence it drifts away as warm water toward 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 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.[253]

Apart from disputed questions in physics, the main facts for the geological reader to grasp are—that a system of cir-

---

[253] The student 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 the Royal Geographical Society for 1871–77, on the side of temperature; and Herschel's "Physical Geography," and Croll's "Climate and Time," on the side of the winds.

culation 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 around which they sweep; that cold currents set in from poles to equator; and that, apart from actual currents, there is an extremely slow "creep" of the polar water, under the warmer upper layers, to 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 undulation termed *Ground-swell.* Waves which break upon the land or sunken rocks are called *Breakers*, and the same name is applied to the ground-swell as it bursts into foam and spray upon submarine reefs and shoals. The concussion of earthquakes sometimes gives rise to very disastrous ocean-waves (pp. 461, 472).

The height and force of waves depend upon the strength and continuance of the wind, the breadth and depth of sea, 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 neighboring shore which presents itself at an angle to the 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 Scoresby among the Atlantic waves was 43 feet.[254]

---

[254] Brit. Assoc. Rep. 1850, p. 26. A table of the observed heights of waves round Great Britain is given in Mr. T. Stevenson's treatise on "Harbors," p. 20.

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 where the water shallows, the superficial part of the swell, travelling faster than the lower, which encounters the friction of the bottom, begins to curl and crest as a huge billow or wall of water, that finally bursts 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. During northwesterly gales, the windows of the Dunnet Head lighthouse, at a height of upward 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 lb. per square foot, while in the winter it was 2086 lb., or more than three times as great. 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.[255] Besides the waves produced by ordinary wind action, others of an extraordinary size and destructive power are occasionally caused by local atmospheric disturbances. Such are proba-

---

[255] T. Stevenson, Trans. Roy. Soc. Edin. xvi. p. 25; treatise on "Harbors," p. 42.

bly the *raz de marée* of the French coast, which occasionally rise to a height of several feet, and, where the shores converge inland, do considerable damage. Still more serious are the effects of 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 inrushing of the air toward 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 upward of 48,000 people.

Besides the height and force of waves it is important to know the depth to which the sea is affected by such superficial movements. Sir G. Airy states that ground-swell may break in 100 fathoms water.[256] It is common to find bowlders 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 to 8 fathoms in depth.[257] In the English Channel coarse sediment is disturbed at depths of 30 or more fathoms.[258] It is stated by Delesse that engineering operations have shown submarine constructions to be scarcely disturbed at a greater depth than 5 metres (16·4 feet) in the Mediterranean and 8 metres (26·24 feet) in the Atlantic.[259] In the Bay of Gas-

---

[256] Encyclopedia Metropolitana, art. "Waves." 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.

[257] T. Stevenson's "Harbors," p. 15.

[258] A. R. Hunt, Proc. Roy. Dublin Soc. iv. 1884, p. 285. For further information on this subject see *postea*, pp. 451, 455.

[259] "Lithologie des Mers de France," 1872, p. 110.

cony, the depth at which the sea breaks and is effective in the transport of sand along the bottom is said to vary from scarcely 3 metres in ordinary weather to 5 metres in stormy weather, and only exceeds 10 metres (32·8 feet) in great hurricanes. According to Commander Cialdi, the movement of waves may disturb fine sand on the bottom at a depth of 40 metres (131 feet) in the English Channel, 50 metres (164 feet) in the Mediterranean, and 200 metres (656 feet) in the ocean.[960] Off the Florida coast the disturbing action of the waves is believed to cease below 100 fathoms.[961] As above remarked, the influence of currents has been detected at much greater depths.

(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—*a*, the freezing of the sea itself, and *β*, the seaward prolongation of land-ice.[962]

a. 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 to 30 feet high. This shelf, known as the Ice-foot, serves as a platform on which the abundant débris, loosened by the severe

---

960 Quoted by Delesse, op. cit. p. 111.

961 A. Agassiz, Amer. Acad. xii. 1882, p. 108.

962 Consult on the whole of this subject K. Weyprecht's "Die Metamorphosen des Polareises," Vienna, 1879; Payer's "New Lands within the Arctic Circle," 1876, chap. i. The physics of sea-ice are discussed by O. Pettersson ("Vega-Expeditionens Vetenskapliga Iakttagelser," ii. p. 299, Stockholm, 1883), who concludes that instead of being contracted by cold, the volume of the frozen sea increases to an extraordinary degree, and that the rupture of the ice is thus due to expansion instead of contraction.

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, when undisturbed, becomes in the Arctic regions about eight feet thick, but which in summer breaks up into separate masses, sometimes of large

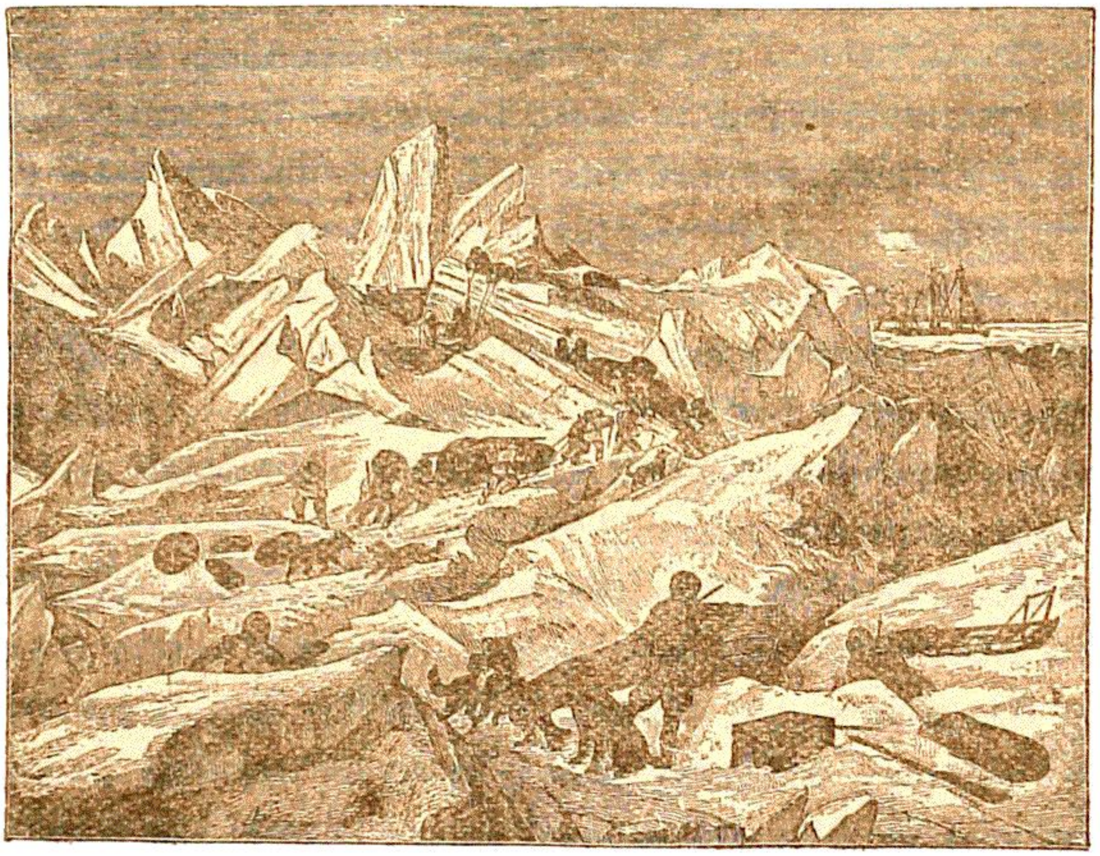


Fig. 163.—Disrupted Floe-ice of Arctic Seas.

extent, and is apt to be piled up into huge, irregular heaps (Fig. 163). 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 said to be brought up sometimes solidly frozen.[263]

β. In the Arctic regions, vast glaciers drain the snow-fields, and, descending to the sea, extend for some distance from shore until large fragments break off and float away seaward (Fig. 164). These detached masses are Icebergs. Their shape and size greatly vary, but lofty peaked forms are common (Fig. 165), and they sometimes rise from 200 to 300 feet above the level of the sea. As the part that

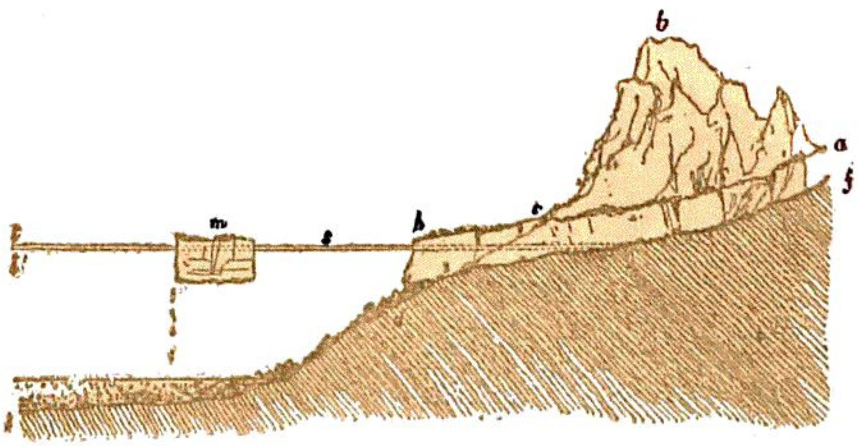


Fig. 164.—Formation of Icebergs (*B.*).

The glacier (*a*, *h*) descends from mountainous ground (*b*) to the sea-level (*s*), bearing moraine stuff on the surface, pushing on detritus below (*d*), and sending off icebergs (*m*), which may carry detritus and drop it over the sea-bottom; *t*, *t'*, *g*, lines of high and low water.

appears above water is only about one-ninth of the whole mass of ice, these larger bergs may sometimes be from 1800 to 2700 feet thick from base to top, though the submarine part of the ice may be as irregular in form and thickness as the portion above water.[264] Icebergs of the largest size consequently require water of some depth to float them, but are sometimes seen aground. In the Antarctic regions, where one vast sheet of ice envelops the land and protrudes into the sea as a long, lofty rampart of ice, the

[263] See H. Y. Hind, Canadian Naturalist, viii. 1878, pp. 227, 262.

[264] On flotation of icebergs, see Geol. Mag. (2d sec.), iii. pp. 303, 379; iv. 65, p. 135.

detached icebergs often reach a great size, and are characterized by the frequency of a flat tabular form (Fig. 166).

II. **Geological Work.**—(1) 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. A chart of the globe, with the isothermal lines drawn across it, shows that their divergences from

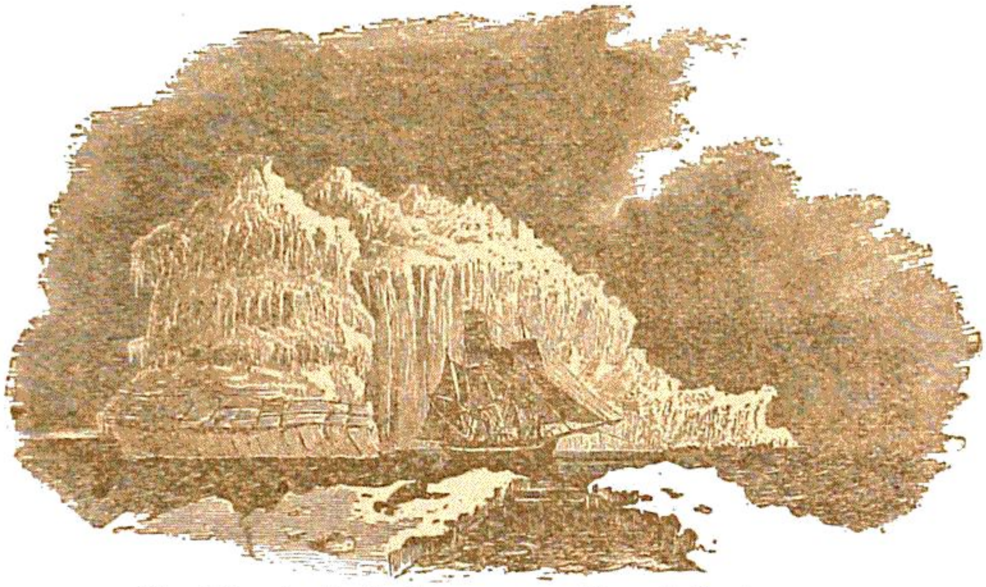


Fig. 165.—Arctic Iceberg seen on Parry's first voyage.

the parallels are striking, and most so where they approach and cross the ocean. Currents from warm regions raise the temperature of the tracts into which they flow; those from cold regions lower it. The ocean, in short, is the great distributer of temperature over the globe.

As an illustration, the two opposite sides of the North Atlantic may be taken. The cold Arctic current, flowing southward along the northeast coast of America, reduces the mean annual temperature of that region. On the other hand, the Gulf Stream brings to the shores of the northwest of Europe a temperature much above what they would otherwise enjoy. Dublin and the southeastern headlands of Labrador lie on 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.[265]

(2) Erosion. A. *Chemical.*—The chemical action of the sea upon the rocks of its bed and shores has not yet been properly studied.[266] It is evident, however, that changes analogous to those effected by fresh water on the land must be in progress. Oxidation solution, and the

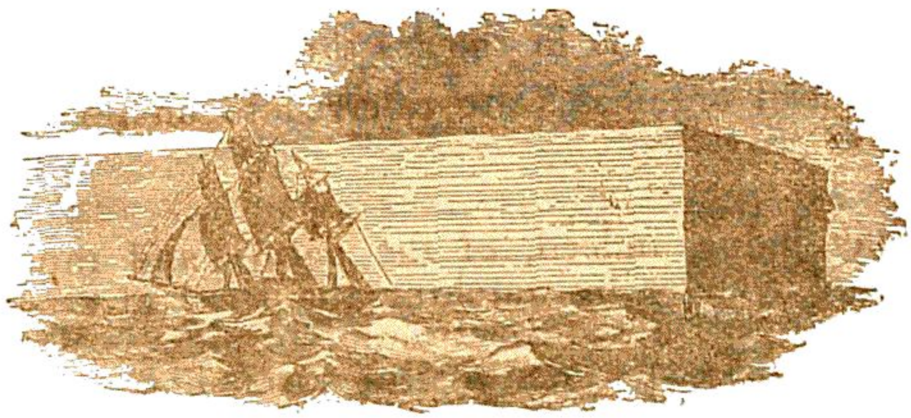


Fig. 166.—Tabular Iceberg detached from the great Antarctic Ice-barrier. (Wilkes.)

formation of carbonates, no doubt continually take place. The solvent action of sea-water on calcareous organisms, already referred to (p. 73), has in recent years been made the subject of discussion and experiment. Dr. Murray, in calling attention to the gradual disappearance of such organisms, as the deposits of the sea-bottom are traced down into the abysses, explained it by the solvent influence of the

[265] See a series of papers by him on the "Gulf Stream and Ocean Currents," in Geol. Mag. and Phil. Mag. for 1869, 1870–74, and his work "Climate and Time"; likewise a series of controversial papers on this subject by him and Prof. Newcombe, Phil. Mag. 1883–84. Prof. Haughton has offered some calculations of the actual amount of influence exercised by ocean-currents upon climate, and of the effect of a current between the Indian and Arctic Oceans across Mesopotamia and the Aralo-Caspian depression. Brit. Assoc. 1881, Reports, pp. 451–463.

[266] See Bischof's "Chemical Geology," vol. i. chap. vii.

water containing carbonic acid in solution, and he has more recently conducted a series of experiments to demonstrate the truth of this view. Ten specimens of coral of different species were immersed in sea-water and allowed to remain for periods varying from 20 to 60 days. In each case a perceptible loss of material took place, varying from 0·0725 to 0·1707 of their weight, which he estimated to be equal to a rate of loss amounting to from 0·453 to 0·1860 from one square inch of surface in a year. The more areolar or amorphous corals were attacked more rapidly than the harder crystalline varieties.[267] The complex chemical changes that take place in the sea through the operation of living and dead organisms are referred to on pp. 808, 812, 824, 825.

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. Mr. Mallet—as the result of experiments with specimens sunk in the sea—concluded that from $\frac{2}{10}$ to $\frac{4}{10}$ of an inch in depth in iron castings 1 inch thick, and about $\frac{6}{10}$ 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 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. In some of these castings, 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 lb. to 4797 lb., and yet presented no external appearance of decay. Another apparently sound specimen was reduced in strength from 4068 lb. to 2352 lb., having lost nearly half its strength in fifty years."[268] Similar results were observed by Mr. Grothe, resident engineer at the construction of the ill-fated railway bridge across the Firth of

---

[267] Proc. Roy. Soc. Edin. xvii. 1889, p. 109. See also R. Irvine, Nature, 1888, p. 461; J. G. Ross, ibid. p. 462. Compare A. Agassiz, Bull. Mus. Comp. Zool. Harvard, xvii. No. 3, 1889, p. 125.

[268] T. Stevenson on "Harbors," p. 47.

Tay. A cast-iron cylinder (such as was employed in constructing the concrete basements for the piers), 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 wave-washed rocks. Basalt, for instance, has its felspar decomposed, and shows the presence of carbonates by effervescing briskly with acid. The augite is occasionally replaced by ferrous carbonate. The solvent action of sea-water on calcareous organisms is referred to on pp. 73, 823.

B. *Mechanical.*—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 is probably the slow creeping of the polar water. But where the currents are powerful enough to move grains of sand and gravel, a slow erosion may take place even at considerable depths. It is in the upper portions of the sea, however—the region of currents, tides, and waves—that mechanical erosion is chiefly performed. The depth to which the influence of waves and ground-swell may extend seems to vary greatly according to the situation (ante, p. 736). 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.[269] From the superior limit of the accumulation of mud up to high-water mark,

[269] T. Stevenson on "Harbors," p. 15.

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 six ways.

(i.) The enormous force of the breakers suffices to tear off fragments of the solid rocks.

Abundant examples 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, the most northerly point of Shetland, walls were overthrown and a door was broken open at a height of 196 feet above the sea. At the Bishop Rock lighthouse, on the west of England, a bell weighing 3 cwt. was wrenched off at a level of 100 feet above high-water mark.[270] Some of the most remarkable instances of the power of breakers have been observed by Mr. Stevenson among the islands of the Shetland group. On the Bound Skerry he found that blocks of rock, up to 9½ tons in weight, had been washed together at a height of nearly 60 feet above the sea; that blocks weighing from 6 to 13½ tons had been actually quarried out of their original bed, at a height of from 70 to 75 feet; and that a 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. He likewise records the moving of a 50-ton block by the waves at Barrahead, in the Hebrides.[271] At Plymouth, also, blocks of several tons in weight have been known to be washed about the breakwater like pebbles.[272]

---

[270] T. Stevenson, op. cit. p. 31. D. A. Stevenson, Min. Proc. Inst. Civ. Engin. xlvi. 1876, p. 7.

[271] T. Stevenson, op. cit. pp. 21–37.

[272] The student will bear in mind that the relative weight of bodies is greatly

(ii.) The alternate compression and expansion of air in crevices of rocks exposed to heavy breakers dislocates large masses of stone, even above the direct reach of the waves. 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.[273] 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

---

reduced when in water, and still more in sea-water. The following examples will illustrate this fact (T. Stevenson's "Harbors," p. 107):

—	Specific Gravity	No. of cubic feet to a ton in air	No. of feet to a ton in sea-water of specific gravity 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

[273] Walker, Proc. Inst. Civ. Engin. i. p. 15; Stevenson's "Harbors," p. 10.

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 a cleft or cavern. 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, and on the north coast of Cornwall, 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.

(iii.) The hydraulic pressure of those portions of large waves that enter fissures and passages tends to force asunder masses of rock. 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.

(iv.) The waves make use of the **loose detritus** within their reach to break down cliffs exposed to their fury. Probably by far the largest amount of erosion is thus accomplished. The blows dealt against shore-cliffs by bowlders, gravel, and sand swung forward by breakers, were aptly compared by Playfair to a kind of artillery.[274] During a storm upon a shingly coast we may hear, at a distance of several miles, the grind of the stones upon each other, as they are dragged back by the recoil of the waves which had launched them forward.[275] 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 cliffs against which they are driven. A rock, much jointed, or from any cause presenting less resistance to attack, 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 (Fig. 167). The surface of the beach is likewise ground down. The reality of this erosion and consequent lowering of level is sometimes instructively displayed where a block of harder rock serves for a time to protect the portion of rocky beach lying beneath it. The block by degrees comes to rest on a growing pedestal, which is eventually cut round by the waves, until the overlying mass,

---

274 "Illustrations of the Huttonian Theory," sec. 97.

275 For a graphic account of the heavy roll of the bowlders and thundering of the billows as heard in a mine under the sea during a storm, see J. W. Henwood, Trans. Roy. Geol. Soc. Cornwall, v. p. 11.

losing its support, rolls down upon the beach. Thereafter the same process is renewed, and the bowlder continually diminishes in size (Fig. 168).[276]

Of the progress of marine erosion, the more exposed parts of the British coast-line furnish many admirable examples. The sea-board of Cornwall presents a most impressive range of cliffs, sea-stacks, caves, gullies, tunnels, reefs, and skerries, showing every stage in the process of demolition (Fig. 167). The west coast of Ireland, exposed to the full swell of the Atlantic, is in innumerable localities completely

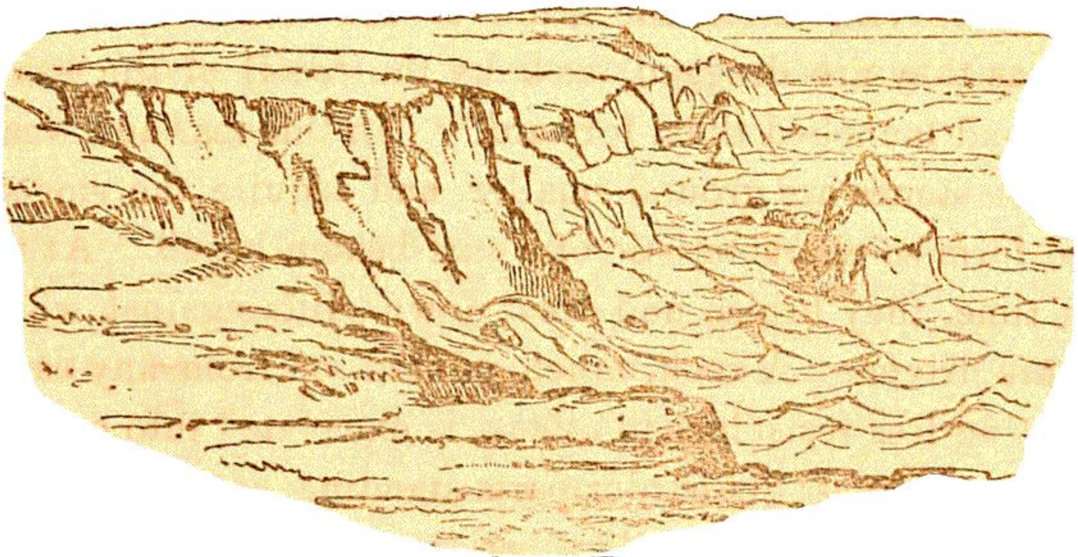


Fig. 167.—Coast of Cornwall, at Bedruthan (Devonian Rocks), cut by the sea into cliffs, bays, and stacks (*B.*).

undermined by caverns, into which the sea enters from both sides. The precipitous coasts of Skye, Sutherland, Caithness, Aberdeen, Kincardine, and Forfar 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 still more 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

[276] See on the action of waves on sea-beaches and sea-bottoms, A. R. Hunt. Proc. Roy. Dublin Soc. 1884, p. 241.

himself many illustrations of this kind of destruction around the shores of these islands. Within the last few hundred years entire parishes with their farms 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 between Spurn Point and

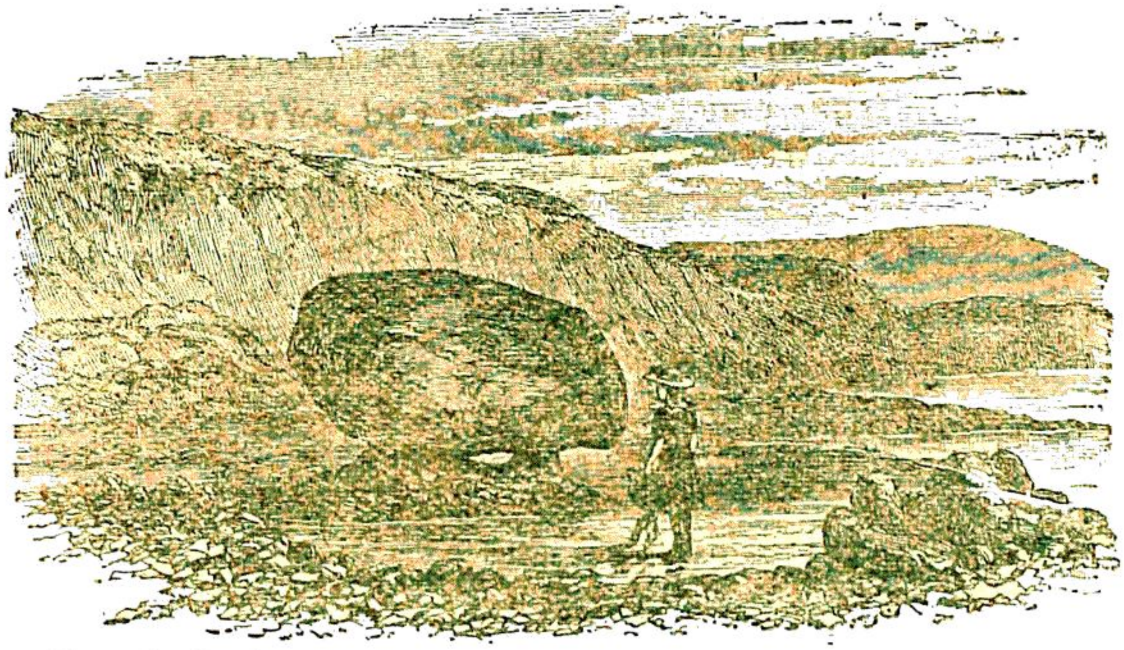


Fig. 168.—Bowlder of basalt protecting the portion of beach underneath it; Largo, Fife.

Flamborough Head this loss is said to amount to five yards per annum.[277]

Other parts of the European seaboard likewise furnish instructive lessons as to the progress of marine erosion. The destruction of Heligoland, in the North Sea, has been continuous for centuries, the stages in the disappearance of this island being easily followed on the charts of successive periods.[278] Even the hard crystalline rocks of Scandinavia are unable wholly to withstand the assaults of the Atlantic breakers.[279]

[277] R. Pickwell, Proc. Inst. Civ. Engin. li. p. 191. On the waste of the coast between the Thames and Wash, see J. B. Redman, op. cit. xxiii. 1864, p. 186; C. Reid, Geol. Mag. 2d dec. iv. p. 136. "Geology of Holderness," Mem. Geol. Surv. 1885. The Reports of the Brit. Assoc. Comm. on the erosion of the sea-coasts of England, 1885–86, give much interesting information on this subject.

[278] K. W. M. Wiebel's "Die Insel Helgoland," 4to, Hamburg, 1848.

[279] H. Reusch, Neues Jahrb. 1879, p. 244.

While investigating the progress of waste along a coast-line, the geologist has to consider the varying powers of resistance possessed by rocks, and the extent to which the action of the waves is assisted by that of the subaerial agents. Rocks of little tenacity, and readily susceptible of disintegration, obviously present least resistance to the advance of the waves. A clay, for example, is readily eaten away. If, however, it should contain numerous hard nodules or imbedded bowlders, these, as they drop out, may accumulate in front beneath the cliff, and serve as a partial breakwater against the waves (Fig. 169). On the other hand,

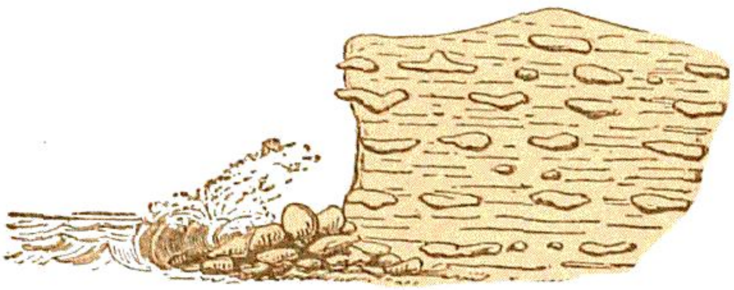


Fig. 169.—Cliffs of clay full of septarian nodules, the accumulation of which serves to arrest the progress of the waves.

a hard band or boss of rock may withstand the destruction which overtakes the softer or more jointed surrounding portions, and may consequently be left projecting into the sea, as a line of headland or promontory, or rising as an isolated stack (Fig. 167). But, besides mere hardness or softness, the geological structure of the rocks powerfully influences the nature and rate of the encroachment of the sea. Where, owing to the inclination of bedding, joints, or other divisional planes, sheets of rock slope down into the water, they serve as a kind of natural breakwater, up and down which the surges rise and fall during calms, or rush in crested billows during gales, the abrasion being here reduced to the smallest proportions. In no part of the degradation of the land can the dominant influence of rock-structure be more conspicuously observed and instructively studied than along marine cliffs. Where the lines of precipice are abrupt, with numerous projecting and retiring vertical walls, it will almost invariably be found that these perpendicular faces have been cut open along lines of intersecting joint. The existence of such lines of division permits a steep or vertical front to be presented by the land to the sea, because, as slice

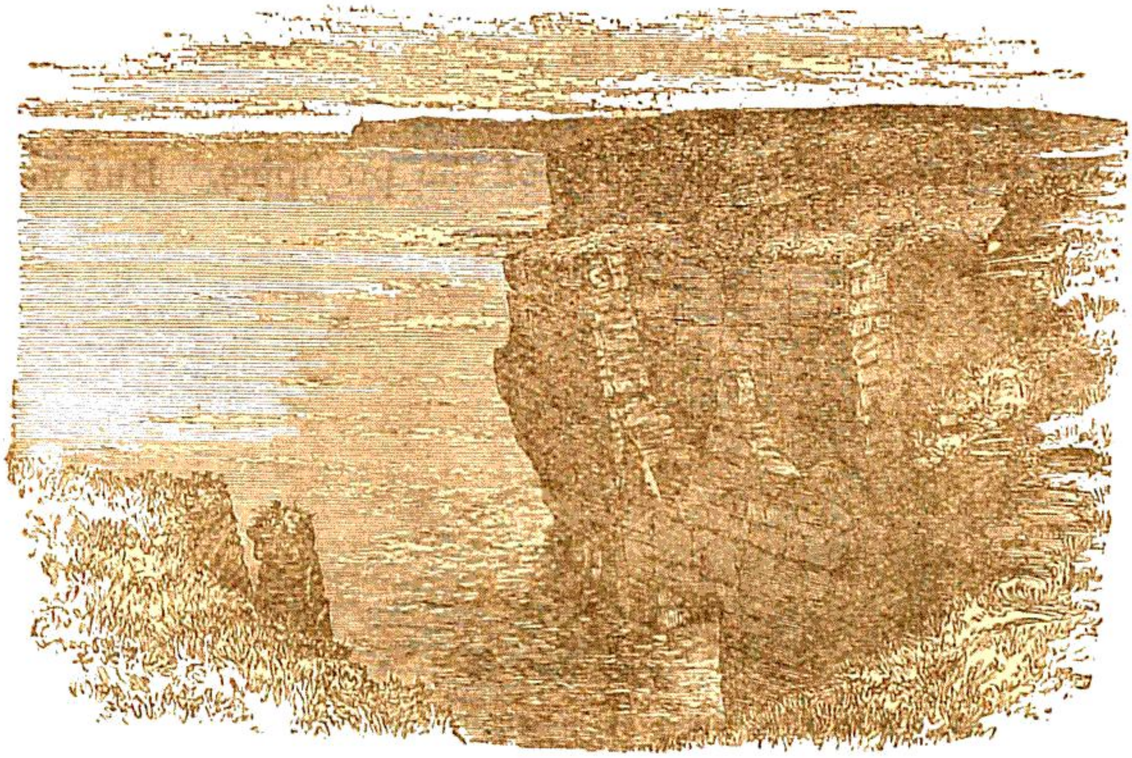


Fig. 170.—Vertical sea-cliffs of flagstone, near Holburn Head, Caithness.

after slice is removed, each freshly bared surface is still defined by a joint-plane (see Fig. 225).

During the study of any rocky coast where these features are exhibited, the observer will soon perceive that the encroachment of the sea upon the land is not due merely to the action of the waves, but that, even on shores where the gales are fiercest and the breakers most vigorous, the demolition of the cliffs depends largely upon the sapping influence of rain, springs, frosts, and general atmospheric disintegration. In Fig. 170, for example, which gives a view of a portion of the northern Caithness coast, exposed to the full fury of the gales and rapid tidal currents which rush from the Atlantic through the Pentland Firth, we see at once that though the base of the cliff is scooped out by the restless surge into long twilight caves, nevertheless the recession of the precipice is caused by the wedging off of slice after slice, along lines of vertical joint, and that this process begins at the top, where the subaerial forces and not the waves are the sculptors. Undoubtedly the sea plays its part by removing the materials dislodged, and preventing them from accumulating against and protecting the face of the precipice. But were

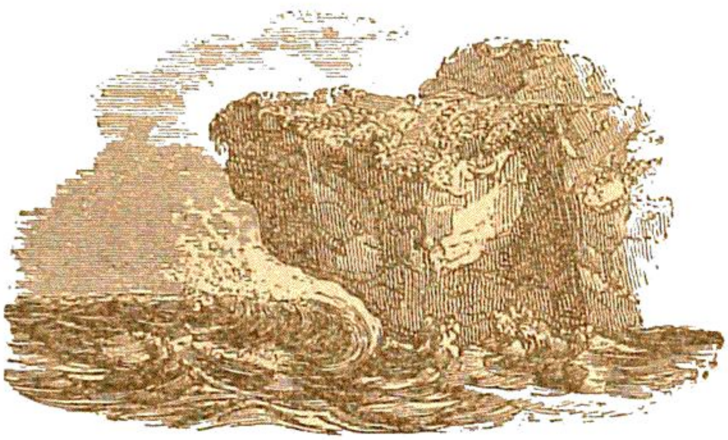


Fig. 171.—Marine erosion, where exceptionally the base of a cliff recedes faster than the upper part.

it not for the potent influence of subaerial decay, the progress of the sea would be comparatively feeble. The very blocks of stone which give the waves so much of their efficacy as abrading agents, are in great measure furnished to them by the action of the meteoric agents. If sea-cliffs were mainly due to the destructive effects of the waves, they ought to overhang their base, for only at or near their base does the sea act (Fig. 171). 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 (Fig. 167), shows that the waste from subaerial action is really greater than that from the action of the breakers.[280] Even when a cliff actually overhangs, however, it may often be shown that the apparent greater recession of its base, and inferentially the more powerful denuding action of the sea, are deceptive. In Fig. 172, one of innumerable examples from the Old Red Sandstone cliffs of Caithness and the Orkney and Shetland Islands, we at once perceive that the process

Fig. 172.—Overhanging cliff, Brough of Birsa, Orkney, due to landward inclination of joints.

of demolition is precisely similar to that already cited in Fig. 170. The cliff recedes by the loss of successive slices from its sea-front, which are wedged off not by the waves below, but by the subaerial agents above, along lines of parallel joint. To the inclination of these divisional planes at a high angle from the sea, the precipice owes its slope toward the land.

(v.) *Tidal Erosion.*—Reference has already been made (pp. 733, 736) to existence of currents at considerable depths

[280] Whitaker, Geol. Mag. iv. p. 447.

in the ocean, though not in the profounder abysses. These movements have been observed in straits between islands or submarine ridges, and they are doubtless connected with the tidal wave. They seem to possess sufficient scour to prevent the accumulation of sediment, but whether they are effective in eroding hollows on the sea-floor, as has been claimed for them, may be doubted. Their power to dig out hollows or to deepen and widen channels must depend not merely on their velocity but upon the presence of detritus which they can use in abrasion, for without this detritus they could not remove the surface of hard rocks.[281]

(vi.) *Ice-Erosion.*—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, both in abrasion and in deposit. Cakes of ice, driven ashore by storms, tear up and redistribute 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 may grind down any submarine rock on which they grate as they are driven along. The geological operations of floating ice were formerly invoked by geologists to explain much that is now believed to have been entirely the work of ice on land.[282]

(3) T r a n s p o r t.—By means of its currents, the sea transports mechanically-suspended sediment to varying dis-

---

[281] The potency of tidal action has long been maintained by Mr. T. Mellard Reade, Proc. Geol. Soc. Liverpool, 1873; Phil. Mag. xxv. 1888, p. 338.

[282] For an account of the work of floating ice ("pan-ice") see H. Y. Hind, Canadian Naturalist, viii. 1878, p. 229.

tances from the land. The distance will depend on the size, form, and specific gravity of the sediment on the one hand, and on the velocity and transporting power of the marine current on the other. Babbage estimated that if, from the mouth of a river 100 feet deep, suspended limestone mud, of different degrees of fineness, were discharged into a sea having a uniform depth of 1000 feet over a great extent, four varieties of silt, falling respectively through 10, 8, 5, and 4 feet of water per hour, would be distributed as in the following table:[283]

No.	Velocity of fall per hour	Nearest distance of deposit to river	Length of deposit	Greatest distance of deposit from river
	feet	miles	miles	miles
1.	10	180	20	200
2.	8	225	25	250
3.	5	360	40	400
4.	4	450	50	500

It must be borne in mind, however, that mechanical sediment sinks faster in salt than in fresh water.[284] The chief part of the fine mud in the layer of river-water, which floats for a time on the salter and heavier sea-water, sinks to the bottom as soon as the two waters commingle. It has been ascertained, nevertheless, by direct observation that an appreciable amount of extremely fine clay is present in ocean-water even far away from land, the proportion so transported depending not only on the size and weight of the particles, but on the temperature and to a less extent on the salinity, being greater the lower the temperature and salinity. In specimens of surface-water taken from various oceans the

[283] Q. J. Geol. Soc. xii. 368.

[284] See ante, pp. 646, 673, and authorities there cited.

amount of mechanically suspended silicates (clay) was found to be as follows:[285]

	In 14 litres of water		Per cubic mile of water
Atlantic Ocean, lat. 51° 20′, long. 31° W......	0·0052 grm.	=	1604 tons
German Ocean, 30 miles E. of May Island....	0·0063 "	=	1946 "
Mediterranean, centre of Eastern basin.........	0·0065 "	=	2031 "
Baltic Sea, salinity 1005·5..........................	0·0105 "	=	3200 "
Red Sea, off Brothers Island......................	0·0006 "	=	264 "
Indian Ocean, lat. 15° 46′ N., long. 58° 51′ E.	0·0006 "	=	264 "

Near the land, where the movements of the water are active, much coarse detritus is transported along shore or swept further out to sea. A prevalent wind, by creating a current in a given direction, or a strong tidal current setting 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 source. The Chesil Bank, which runs as a natural breakwater 16 miles long, connecting the Isle of Portland with the mainland of Dorsetshire, consists of drifted rounded shingle.[286] On the Moray Firth, the reefs of quartz-rock about Cullen furnish abundance of shingle, which, urged by successive easterly gales, moves westward along the coast for more than 15 miles. The coarser sediment probably seldom goes much beyond the littoral zone. Returning to the subject of the depth to which wave-action extends (ante, p. 736) we may take note that it has been observed by the fishermen at Land's End

---

[285] Murray and Irvine, Proc. Roy. Soc. Edin. xviii. 1891, p. 243. These authors regard the silica thus mechanically suspended in sea-water as the probable source of most of this substance secreted by marine plants and animals.

[286] On the Chesil Bank, see J. Coode, Min. Proc. Inst. Civ. Engin. xii. p. 520. J. B. Redman, op. cit. xi. p. 201; xxiii. p. 226; Nature, xxvi. pp. 30, 104, 150; J. Prestwich, Min. Proc. Inst. Civ. Engin. xl. p. 115; H. W. Bristow and W. Whitaker, Geol. Mag. vi. 1869, p. 433; O. Fisher, op. cit. 1874, p. 285; G. H. Kinahan, op. cit. 1874. A. R. Hunt, Proc. Roy. Dublin Soc. iv. 1884, p. 241. The general transport of littoral detritus in the English Channel is from west to east; Prof. Prestwich, however, thinks that at the Chesil Bank this direction is locally reversed.

that their lobster-pots are often filled with coarse sand and shingle in depths up to 30 fathoms during heavy ground-swells, and that some of the stones weigh as much as one pound.[287] From a depth of even 600 fathoms in the North Atlantic, between the Faroe Islands and Scotland, small pebbles of volcanic and other rocks are dredged up which may have been carried by an Arctic undercurrent from the north. Mr. Murray and Captain Tizzard, however, have brought up large blocks of rounded shingle from that bank at a depth of 300 fathoms. Such detritus can hardly be due to any present action of the sea, for at these depths the force of currents at the bottom is probably too feeble to push along coarse shingle. It may be moraine-stuff dating back to the ice-sheets of the Glacial Period, its finer particles having been swept away while it is prevented from being buried under submarine mud by the scour of the currents over the bank. Blocks of stone brought up from depths of more than 2000 fathoms in the Atlantic (Lat. 49° N., Long. 43°–44° W.) have probably been dropped by icebergs from the north.[288]

Much fine sediment is visibly carried in suspension by the sea for long distances from land. The Amazon pours so much silt into the sea as to discolor it for several hundred miles. After wet weather, the sea around the shores of the British Islands is sometimes made turbid by the quantity of mud washed by rain and streams from the land. Dr. Carpenter found the bottom-waters of the Mediterranean to be everywhere permeated by an extremely fine mud, derived

---

287 J. N. Douglas, Min. Proc. Inst. Civ. Engin. xl. 1875, p. 103.

288 See charts of part of North Atlantic by Messrs. Siemens Brothers & Co., London, 1882. Some specimens shown to me by Messrs. Siemens are pieces of basalt which may have come from Greenland.

no doubt from the rivers and shores of that sea. He remarks that the characteristic blueness of the Mediterranean, like that of the Lake of Geneva, may be due to the diffusion of exceedingly minute sedimentary particles through the water.

The great oceanic currents are probably powerful agents in the transport of fine detritus and of living and dead organisms. Coral-reefs appear to flourish best where these currents bring a continuous and abundant supply of food to the reef-builders. The reefs, in turn, furnish an enormous quantity of fine silt, produced by the pounding action of breakers upon them. Before the silt can sink to the bottom, it may be transported to vast distances. The lower portion of the Gulf Stream, from its exit in the Florida Channel northward to Cape Hatteras, a distance of 700 miles, has been compared to a huge muddy river, carrying its silt to the steep slope south of that cape, and depositing here and there patches of green sand along the sides of its course, while the upper waters remain perfectly clear and of the deepest blue. The silt is partly derived from the abrasion of coral-reefs, partly from the decay of the abundant pelagic fauna swept onward by the current. Prof. A. Agassiz has recently called attention to the important part which the great oceanic currents, in ancient as in modern times, may have played in the accumulation of limestones, not only by transporting calcareous organisms, but by bringing an abundant food-supply and thereby nourishing a prolific fauna along their track.[289]

During the voyage of the "Challenger," from the abysses of the Pacific Ocean, at remote distances from land, the dredge brought up bushels of rounded pieces of pumice of

---

289 Amer. Acad. xi. 1882, p. 126.

all sizes up to blocks a foot in diameter. These fragments were all evidently water-worn, as if derived from land, though we are still ignorant of the extent to which they may have been supplied by submarine volcanic eruptions. Some small pieces were taken on the surface of the ocean 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 may drift away for hundreds or even thousands of miles until, becoming water-logged, they sink to the bottom. The universal distribution of pumice 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, contains only volcanic minerals, and appears to be due to the trituration of volcanic detritus. In approaching the continents, at a distance of several hundred miles from shore, traces of the minerals of the crystalline rocks of the land begin to make their appearance.[290]

Another not unimportant process of marine transport is that performed by floating ice. Among the Arctic glaciers, moraine stuff is not abundant; 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 débris may sometimes 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 may be plentifully strewn with this kind of detritus. By means

---

[290] Murray, Proc. Roy. Soc. Edin. 1876–77, p. 247.

of the ice-foot also, an enormous quantity of earth and stones is every year borne away from the shore on the disrupted ice, and is strewn over the floor of the sounds, bays, and channels.

(4) 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 (see pp. 800, 807 *et seq.*). The inorganic deposits of the sea-floor are (i.) chemical and (ii.) mechanical.

(i.) Of Chemical deposits now forming on the sea-floor we know as yet very little. At the mouth of the Rhone a crystalline calcareous deposit accumulates, in which the débris of the sea-floor is enveloped. Bischof estimated that no precipitation of carbonate of lime could take place from sea-water until after $\frac{17}{18}$ of the water had evaporated.[291] No deposit of lime in the open sea is possible from concentration of sea-water. But the calcareous formation on the sea-bottom opposite rivers like the Rhone, if not the result of the precipitation of lime by plants or animals, may perhaps be explained by supposing that as the layer of river-water floats and thins out over the surface of the sea in warm weather with rapid evaporation, its comparatively large proportion of carbonate of lime may be partially precipitated. It has been observed near Nice, as well

[291] "Chem. Geol." i. p. 178.

as on the African coasts and other parts of the Mediterranean shores, that on shore-rocks within reach of the water a hard varnish-like crust is deposited. This substance consists essentially of carbonate of lime. As it extends over rocks of the most various composition, it has been regarded as a deposit of lime held in solution in the shore sea-water, and rapidly evaporated in pools or while bathing the surface of rocks exposed to strong sun-heat.[292] But it may possibly be due to organic agency like the amorphous crust of limestone formed by nullipores (see postea, p. 801). During the researches of the "Challenger" expedition, important facts in the history of marine chemistry have been obtained from the abysses of the Atlantic and Pacific Oceans (see pp. 763, 767, 829).

(ii.) The Mechanical deposits of the sea may be grouped into subdivisions according as they are directly connected with the waste of the land, or have originated at great depths and remote from land, when their source is not so obvious.[293]

A. *Land-derived or Terrigenous.*—These may be conveniently grouped according to their relative places on the sea-bed.[294]

a. Shore Deposits.—The most conspicuous and familiar are the layers of gravel and sand which accumulate between

---

[292] Bull. Soc. Geol. France (3), ii. p. 219, iii. p. 46, vi. p. 84. See postea, p. 823, where the evaporation in the coral-seas is referred to.

[293] See on this subject an important memoir by Messrs. Murray and Renard, Proc. Roy. Soc. Edin. 1884, and Nature, xxx. 1884; also Murray, Proc. Roy. Soc. 1876; Proc. Roy. Soc. Edin. ix.; Murray and Renard, Brit. Assoc. 1879, sects. p. 340; also for the North Atlantic, "Den Norske Nordhavs-Expedition," part ix. (on Oceanic Deposits), 1882. J. Y. Buchanan, Proc. Roy. Soc. Edin. xviii. 1891, p. 131. But the chief source of information is now the great Memoir on "Deep Sea Deposits" by Messrs. Murray and Renard in the Reports of the "Challenger" Expedition, 1891.

[294] On this subject consult the "Deep Sea Deposits" of the "Challenger" Report, chap. v.

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 though the bank or bar of shingle retains its place, its component pebbles are being constantly moved. During gales coincident with high tides, coarse gravel may be piled up considerably above the ordinary limit of the waves in the form of what are termed *storm-beaches.*[295] Below the limit of coarse shingle upon the beach lies the zone of fine gravel, and then that of sand, the sediment, though liable to irregular distribution, yet tending to arrange itself according to coarseness and specific gravity, the rougher and heavier detritus lying at the upper, and the finer and lighter toward the lower edge of the shore. The nature of the littoral accumulations on any 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 finer sediment, such as sand and mud. Estuaries and inlets, into which rivers enter, frequently show wide muddy flats at low water (p. 672). Deposits of comminuted shells, coral-sand, or calcareous organic remains thrown up on shore, may be cemented into compact rock by the solution and redeposit of carbonate of lime (p. 825). Where tidal

[295] See Kinahan on Sea-beaches, Proc. Roy. Irish Acad. (2d ser.), iii. p. 101.

currents sweep along a coast yielding much detritus, long bars or shoals may form parallel with the shore. On these the shingle and sand are driven coastwise in the direction of the prevalent current.[296] They not infrequently accumulate as long barriers, completely protecting the shores from which they are separated by a channel or lagoon of fresh or brackish water (p. 675). Into this lagoon sediment is washed from the land and aquatic vegetation takes root there, until not infrequently a salt marsh or swamp is formed. Extensive accumulations of this kind are to be found along the eastern coast of the United States.[297]

Among the deposits cast ashore by the sea, not the least interesting are the masses of driftwood which, carried down by rivers, are borne by marine currents, sometimes for hundreds of miles, and thrown down in huge accumulations in protected bays. It is in the Arctic seas that this phenomenon obtains its greatest development. Prodigious quantities of terrestrial vegetation are swept by the Siberian rivers into these waters and are carried westward until stranded in sheltered bays of the coast and of the islands. Every shoal-coast of Spitzbergen presents examples of these heaps of driftwood.[298]

β. 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

---

[296] See the authorities cited on p. 756, regarding the Chesil Bank.

[297] N. S. Shaler on sea-coast swamps, 6th Ann. Rep. U. S. Geol. Surv. 1884–85, p. 353. F. J. H. Merill on barrier beaches of Atlantic coast, Popular Science Monthly, Oct. 1890.

[298] Nordenskiöld's "'Vega' Expedition." Petermann, Geograph. Mittheil. Ergansungsheft, No. 16, where a map of these accumulations on the Arctic coasts is given.

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, inclosing 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.[299] 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 tracts or junctions 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. The more prominent features on the floor of the North Sea, however, are probably of much older date than the deposits now accumulating there. Some of them are doubtless relics of the time when the floor of that sea was a broad terrestrial plain. The Dogger Bank, for instance, is probably a prolongation of the Jurassic escarpment of the Yorkshire coast. Other minor submarine features may be partly due to irregular deposition of glacial drift.

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. The deposits were found to consist of blue and green muds derived from the degradation of older crystal-

[299] For information as to the English Channel and other parts of the British seas, see J. T. Harrison, Min. Proc. Inst. Civ. Engin. vii. 1848, p. 327 (where a map of the submarine deposits will be found); R. A. C. Godwin-Austen, Quart. Journ. Geol. Soc. vi. 1849, p. 69—a paper of singular interest and importance; Lebour, Proc. Geol. Assoc. iv. p. 158; John Murray, Min. Proc. Inst. Civ. Engin. xx. 1860–61, where a map of the North Sea floor is given.

line rocks. The blue or dark slate-colored mud takes its color from decomposing organic matter and sulphide of iron, frequently giving off the odor of sulphuretted hydrogen, and assuming a brown or red hue at the surface, owing to oxidation. Besides occurring in deposits of deep water, iron disulphide is met with on some coasts, cementing sand, gravel, and shells into a coherent mass.[300] The chemical changes that result in the elimination of sulphides from sea-water may be explained by supposing that the decomposing animal and vegetable matter of the sea-floor reduces the sulphates to sulphides, which in turn react on the iron and manganese minerals (principally silicates) in the mud, forming sulphides of those metals. Subsequently the oxygen of the water converts the sulphides to oxides, which gather into concretionary forms.[301] The green muds found at depths of 100 to 700 fathoms are characterized by the presence of a considerable quantity of glauconite grains, either isolated or united into concretions, and frequently filling the chambers of *Foraminifera* or other organisms. Round volcanic islands, the bottom is covered with gray volcanic mud and sand derived from the degradation of volcanic rocks. These deposits can be traced to great distances;

---

300 H. Reusch, Neues Jahrb. 1879, p. 255.

301 J. Y. Buchanan, Brit. Assoc. 1881, p. 584. Mr. Buchanan, in renewing this investigation and obtaining many illustrations from the seas around Scotland, has shown that the mud on many parts of the sea-bottom is being continually passed and repassed through the bodies of animals which live upon it. The mineral matter is thus brought in contact with the organic secretions of the animals and is ground up with these in their milling organs. The reducing action of the secretions produces, Mr. Buchanan believes, sulphides from the sulphates of sea-water, and these sulphides, acting on the ochreous matter of the bottom, give rise to sulphides of iron and manganese, which being very unstable in presence of water and oxygen are, where they lie on the surface, soon transformed into oxides. Proc. Roy. Soc. Edin. xviii. 1890, p. 17, "On the occurrence of sulphur in marine muds." Another view of the decomposition of the sulphates of sea-water is proposed by Dr. Murray and Mr. Irvine. See papers quoted at notes 364 and 366.

from Hawaii they extend for 200 miles or more. Pieces of pumice, scoriæ, etc., occur in them, mingled with marine organisms, and more particularly with abundant grains, incrustations, and nodules of an earthy peroxide of manganese (Fig. 175). Near coral-reefs the sea-floor is covered with a white calcareous mud derived from the abrasion of coral, and frequently containing 95 per cent of carbonate of lime. Beyond a depth of 1000 fathoms, coral mud gives place to a Globigerina ooze or red clay. 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.

Throughout these land-derived sediments are found minute particles of recognizable minerals. Of these, quartz, often in rounded grains, plays the chief part. Next come mica, felspar, augite, hornblende, and other less abundant constituents of terrestrial rocks, the materials becoming coarser toward land. Occasional pieces of wood, portions of fruits, and leaves of trees in the same deposits 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.[802]

In some regions vast quantities of terrestrial vegetation are strewn over the sea-bottom, even at depths of 2000 fathoms, and at distances of several hundred miles from land. This fact has been observed by Prof. Agassiz off

---

[802] See papers by Messrs. Murray and Renard, quoted on p. 761, and vol. of "Challenger" Report on "Deep-Sea Deposits," p. 190.

Central America, both in the Atlantic and Pacific Oceans, hardly a single haul of the dredge failing to bring up much vegetable matter, and frequently logs, branches, twigs, seeds, leaves, and fruits.[303]

B. *Abysmal* or *Pelagic.*[304]—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 gray clays found at depths of more than 2000 fathoms, down to the bottoms of the deepest abysses. These, by far the most widespread of oceanic deposits,[305] consist of exceedingly fine clay, colored sometimes red by iron-oxide, sometimes of a chocolate tint from manganese oxide, with grains of augite, felspar, and other volcanic minerals, pieces of palagonite and pumice, nodules of peroxide of manganese, and other mineral substances, together with *Foraminifera*, and in some regions a large proportion of siliceous *Radiolaria*. These clays result from the decomposition of pumice and fine volcanic dust, transported from volcanic islands into mid-ocean, or from the accumulation of the detritus of submarine eruptions. The extreme slowness of deposit is strikingly brought out in the tracts of sea-floor furthest 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

---

303 "Three Cruises of the 'Blake,'" and Bull. Mus. Comp. Zool. xxiii. No. 1, 1892, p. 11.

304 For information regarding the fauna and deposits of the ocean-abysses, besides the works quoted on page 761, note 293, consult the various writings of Prof. A. Agassiz, especially his "Three Cruises of the 'Blake,'" and papers in Bull. Mus. Comp. Zool. xxi. No. 4, and xxxiii. No. 1; also Haeckel's "Plankton-Studien," 1890.

305 They are estimated to cover upward of 50,000,000 square miles of the sea-floor. Murray and Irvine, Proc. Roy. Soc. Edin. xvii. 1889, p. 82.

them quite fresh, others partially crusted with peroxide of manganese, and some wholly and thickly surrounded with that substance. We cannot suppose that sharks and whales so abounded in the sea at one time 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

a b

Fig. 173.—Magnetic Spherules (Cosmic Dust) of the ocean-bottom (Murray and Renard).

a, Black spherule with metallic centre (magnified 60 diameters) from a depth of 2375 fathoms in South Pacific. This represents the common form of these particles, and shows the usual depression on one part of the surface. There is a lustrous crust of magnetite outside.

b, Similar spherule (60 diam.) from which the crust of magnetic oxide has been broken off to show the inner metallic nucleus, here represented by the central lighter part. 3150 fathoms in the Atlantic.

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, occur numerous minute spherular particles of metallic iron and "chondres," or spherical internally radiated particles referred to bronzite, which are in all probability of cosmic origin—portions of the dust of meteorites which in the course of ages have fallen upon the sea-bottom (Figs. 173, 174). Such particles, no doubt, fall all over the ocean; but it is only on those parts of the bottom which, by reason of 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 may be expected to be possible to detect them.[306]

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 (Fig. 175). 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 abysmal organisms, and inclosing more or less of the surrounding bottom, whatever its nature might happen to be. More recently Mr. J. Y. Buchanan dredged similar small manganese concretions from some of the deeper parts of Loch Fyne,[307] and subsequently Dr. John Murray found them abundantly at 10 fathoms in the Firth of Clyde. The formation of such concretions may be analogous to the solution and deposition of oxides of iron and manganese by organic acids, as on lake-floors, bogs, etc. (p. 810).[308] In connection with the chemical

Fig. 174.—Chondre (Cosmic Dust) of the ocean-bottom (Murray and Renard).
Spherule of bronzite (mag. 25 diam.) showing the aspect of the chondres found in the abysmal deposits. From a depth of 3500 fathoms, Pacific.

[306] Murray and Renard on Cosmic Dust, Proc. Roy. Soc. Edin. 1884; Nature, xxix. "Challenger" Expedition Report, vol. on "Deep-Sea Deposits," p. 327 *et seq.*

[307] Nature, xviii. 1878, p. 628. Brit. Assoc. 1881, p. 583. Proc. Roy. Soc. Edin. ix. p. 287. Trans. R. S. Edin. xxxvi. 1891, p. 459. Dieulafait, Comptes Rend. 1884, p. 589.

[308] Different views have been expressed by Dr. John Murray and Mr. J. Y.

reactions indicated by these nodules as taking place on the sea-bottom, reference may be made to a still more remarkable discovery made by Messrs. Murray and Renard in the course of their examinations of the materials brought up from the same abysmal deposits. Minute crystals, simple, twinned, or in spheroidal groups, which occur abundantly in the typical **red clay of** the central Pacific, have

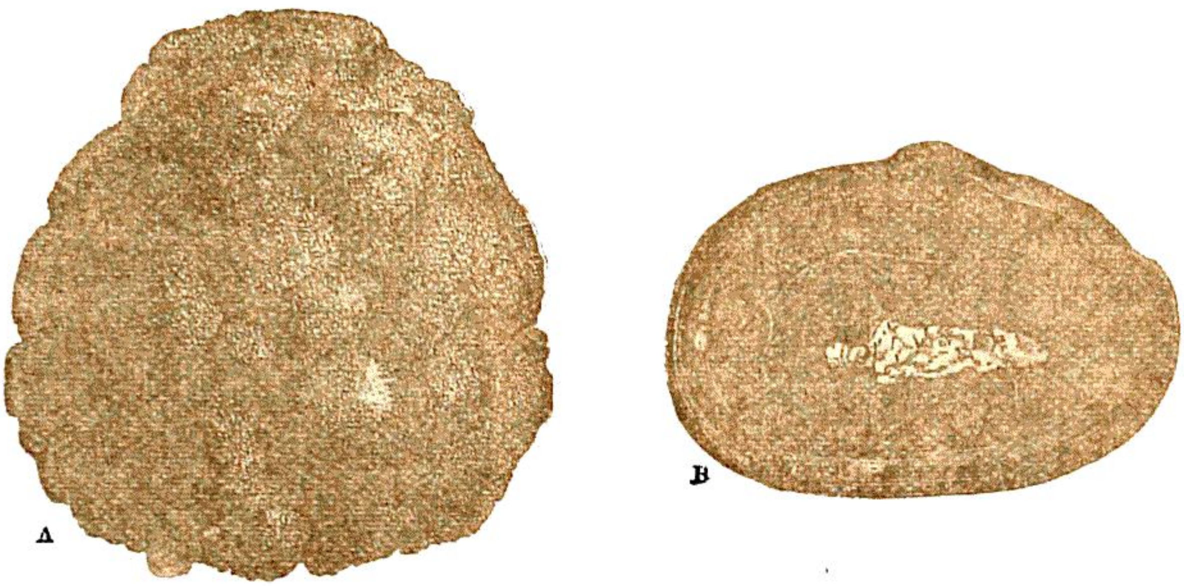


Fig. 175.—Manganese Nodules; floor of the North Pacific. Two-thirds natural size.[309]
A, Nodule from 2900 fathoms showing external form. B, Section of nodule from 2740 fathoms, showing internal concentric deposit round a fragment of pumice.

been identified with the zeolite known as christianite. These crystals have certainly been formed directly on the sea-bottom, for they are found gathered round abysmal organisms, and their production has been effected at about the temperature of 32° Fahr. The importance of this fact in reference to the chemistry of marine deposits is at once obvious.

Buchanan as to the mode of origin of the marine manganese deposits. See R. Irvine and J. Gibson, Proc. Roy. Soc. Edin. xviii. 1891, p. 54.

309 These and Fig. 174 are taken from plate xxxiii. of the vol. on "Deep-Sea Deposits" in the Reports of the "Challenger" Expedition. The detailed investigation by Messrs. Murray and Renard of the deep-sea deposits obtained by this expedition forms the most important contribution yet made to our knowledge of the oceanic abysses.

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 little in the character of the deep-sea deposits which finds a parallel among the marine geological formations visible to us on land. It is only among the comparatively shallow-water accumulations of the existing sea that we encounter obvious analogies to the older formations. And thus we reach, by another and a new approach, the conclusion which on other and very different grounds has been arrived at, viz. that the present continental axes have existed from the remotest times, and that the marine strata which constitute so large a portion of their present mass have been accumulated not as deep-water deposits, but in comparatively shallow water along their flanks or over their submerged ridges.[310]

§ 7. Denudation and Deposition.—The results of the action of Air and Water upon Land[311]

It may be of advantage, before passing from the subject of the geological work of water, to consider the broad results achieved by the co-operation of all the forces by which the surface of the land is worn down. These results naturally group themselves under the two heads of Denudation and Deposition.

1. *Subaerial Denudation—the general lowering of land*

The true measure of denudation is to be sought in the amount of mineral matter removed from the surface of

---

[310] Proc. Roy. Geograph. Soc. July, 1879.

[311] This section is mainly taken from an essay by the author, Trans. Geol. Soc. Glasgow, iii. p. 153. The subject has been discussed anew on the basis of more exact knowledge of the interior of the continents and the depths of the sea by Dr. John Murray, Scottish Geograph. Mag. 1887. See also a note by Mr. C. Davison, Geol. Mag. 1889, p. 409. A. De Lapparent, Bull. Soc. Geol. France, xviii. 1890, p. 351.

the land and carried into the sea. This is an appreciable and measurable quantity. There may be room for discussion as to the way in which the waste is to be apportioned to the different forces that have produced it, but the total amount of sea-borne detritus must be accepted as a fact about which, when properly verified, no further question can possibly arise. In this manner the subject is at once disencumbered of difficulty in fixing the relative importance of rain, rivers, frost, glaciers, etc., considered as denuding agents. We have simply to deal with the sum-total of results achieved by all these forces acting severally and conjointly. Thus considered, this subject casts a new light on the origin of existing land-surfaces, and affords some fresh data for approximating to a measure of past geological time.

Of the mineral substances received by the sea from the land, by much the larger portion is brought down by streams; a relatively small amount is washed off by the waves of the sea itself. It is the former, or stream-borne part, which is at present to be considered. The quantity of mineral matter carried every year into the ocean by the rivers of a continent represents the amount by which the general surface of that continent is annually lowered. Much has been written of the vastness of the yearly tribute of silt borne to the ocean by such streams as the Ganges and Mississippi; but "the mere consideration of the number of cubic feet of detritus annually removed from any tract of land by its rivers does not produce so striking an impression upon the mind as the statement of how much the mean surface-level of the district in question would be reduced by such a removal."[812] This method of inquiry is so obvious and instructive that it probably received attention from early

[812] Tylor, Phil. Mag. 4th series, v. p.268, 1850.

geologists, though data were still wanting for its proper application. Playfair, for instance, in speaking of the transference of material from the surface of the land to the bottom of the sea, remarks that "the time requisite for taking away by waste and erosion 2 feet from the surface of all our continents and depositing it at the bottom of the sea cannot be reckoned less than two hundred years."[313] This estimate does not appear to have been based on any actual measurements, and must greatly exceed the truth; but it serves to indicate how broad was the view that Playfair held of the theory which he undertook to illustrate. The first geologist who appears to have attempted to form any estimate on this subject, from actually ascertained data, was Mr. Alfred Tylor, who in the year 1850 published a paper in which he estimated the probable amount of solid matter annually brought into the ocean by rivers and other agents. He inferred that the quantity of detritus now distributed over the sea-bottom every year would, at the end of 10,000 years, cause an elevation of the ocean-level to the extent of at least 3 inches.[314] The subject was afterward taken up by Dr. Croll, who specially drew attention to the Mississippi as a measure of denudation and thereby of geological time.[315]

When the annual discharge of mineral matter carried seaward by a river, and the area of country drained by that river, are both known, the one sum divided by the other gives the amount by which the drainage-area has its mean

---

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

[314] Phil. Mag. loc. cit.

[315] Phil. Mag. for February, 1867 and May, 1868; and his "Climate and Time." See also Geol. Mag. June, 1868; Trans. Geol. Soc. Glasgow, iii. p. 153.

general level reduced in one year. For it is clear that if a river carries so many millions of cubic feet of sediment every year into the sea, the area drained by it must have lost that quantity of solid material, and if we could restore the sediment so as to spread it over the basin, the layer so laid down would represent the fraction of a foot by which the surface of the basin had been lowered during a year.

It has been already shown that the material removed from the land by streams is twofold—one portion is chemically dissolved, the other is mechanically suspended in the water or pushed along the bottom. Properly to estimate the loss sustained by the surface of a drainage-basin, we ought to know the amount of mineral matter removed in each of these conditions, and also the volume of water discharged, from measurements and estimates made at different seasons and extending over a succession of years. These data have not yet been fully collected from any river, though some of them have been ascertained with approximate accuracy, as in the Mississippi Survey of Messrs. Humphreys and Abbot, and the Danube Survey of the International Commission. As a rule, more attention has been shown to the amount of mechanically suspended matter than to that of the other ingredients. It will be borne in mind, therefore, that the following estimates, in so far as they are based upon only one portion of the waste of the land—that carried in mechanical suspension—are understatements of the truth.[316]

---

[316] Geologists are largely indebted to Mr. Mellard Reade for the attention which he has given to the important part played by chemical solution in the general denudation of the land. From the data collected by him he infers, as the proportion of solids in solution in the water of the Mississippi is $\frac{1}{3615}$ by weight, about 150 millions of tons of dissolved mineral must be carried by this river annually into the sea. In the River Plate the proportion is $\frac{1}{6448}$, in the St. Lawrence $\frac{1}{6280}$, in the Amazon $\frac{1}{16890}$. Presidential Address, Liverpool Geol. Soc. 1884.

The proportion of mineral substances held in suspension in the water of rivers has been already (p. 643) discussed. It is most advantageous to determine the amount of mineral matter by weight, and then from its average specific gravity to estimate its bulk as an ingredient in river-water. The proportion by weight is probably, on an average, about half that by bulk.

It may seem superfluous to insist that the earthy matter borne into the sea from any given area represents so much actual loss from the surface of that area. Yet this self-evident statement is probably not realized by many geologists to the extent which it deserves. If a stream removes in one year one million of cubic yards of earth from its drainage-basin, that basin must have lost one million of cubic yards from its surface. From the data and authorities which have already been adduced (p. 649), the subjoined table has been constructed, in which are given the results of the measurement of the proportion of sediment in a few rivers. The last column shows the fraction of a foot of rock (reckoning the specific gravity of the silt at 1·9 and that of rock at 2·5) which each river must remove from the general surface of its drainage-basin in one year.

Name of River	Area of basin in square miles	Annual discharge of sediment in cubic feet	Fraction of foot of rock by which the area of drainage is lowered in one year
Mississippi . .	1,147,000	7,468,694,400	$\frac{1}{6000}$
Ganges (Upper) .	143,000	6,368,077,440	$\frac{1}{823}$
Hoang Ho . .	700,000	17,520,000,000(?)	$\frac{1}{1464}$
Rhone	25,000	600,381,800	$\frac{1}{1528}$
Danube . . .	234,000	1,253,738,600	$\frac{1}{6846}$
Po	30,000	1,510,137,000	$\frac{1}{729}$

At the present rate of erosion, the rivers named in this table remove one foot of rock from the general surface of their basins in the following ratio: The Mississippi removes one foot in 6000 years; the Ganges above Ghazipûr does the same in 823 years;[317] the Hoang Ho in 1464 years; the Rhone in 1528 years; the Danube in 6846 years; the Po in 729 years. If these rates should continue, the Mississippi basin will be lowered 10 feet in 60,000 years, 100 feet in 600,000 years, 1000 feet in 6,000,000. Assuming Humboldt's estimate of the mean height of the North American continent, 748 feet,[318] we find that at the Mississippi's rate of denudation, this continent would be worn away in about four and a half million years. The Ganges works still more rapidly. It removes one foot of rock in 823 years, and if Humboldt's estimate of the average height of the Asiatic continent be accepted, viz. 1132 English feet, that mass of land, worn down at the rate at which the Ganges destroys it, would be reduced to the sea-level in little more than 930,000 years. Still more remarkable is the extent to which the River Po denudes its area of drainage. Even though measurements had not been made of the ratio of sediment contained in its water, we should be prepared to find that proportion a remarkably large one, if we look at the enormous changes which, within historic times, have been made by the alluvial accumulations of this river (p. 667). If the Po removes one foot of rock from its drainage basin in 729 years, it will lower that basin 10 feet in 7290 years, 100 feet

[317] In my original paper the area of drainage of the Ganges was given as 432,480 square miles. But the area from which the annual discharge of silt was there given was only that part of the Gangetic basin above Ghazipûr, which Dr. Haughton estimates at 143,000 square miles (Proc. Roy. Dublin Soc. 1879, No. xxxix.). Hence, as he has pointed out, the rate of erosion is really much greater than I had made it. I have recalculated the rate from the altered data, and the result is as given above.

[318] Ante, pp. 76, 77, where other and more probable estimates of the height of the land are given. But as the numbers do not affect the argument, those originally assumed are here retained.

in 72,900 years. If the whole of Europe (taken at a mean height of 671 feet) were denuded at the same rate, it would be levelled in rather less than half a million of years.

It is not pretended that these results are strictly accurate. On the other hand, they are not mere guesses. The amount of water flowing into the sea, and the annual discharge of sediment, have been in each case measured with greater or less precision. The areas of drainage may perhaps require to be increased or lessened. But though some change may be made upon the ultimate results just given, it is hardly possible to consider them attentively without being forced to ask whether those enormous periods which geologists have been in the habit of demanding for the accomplishment of geological phenomena, and more especially for the very phenomena of denudation, are not in reality far too vast. If the Mississippi is carrying on the process of denudation so rapidly that at the same rate the whole of North America might be levelled in four and a half millions of years, surely it is most unphilosophical to demand unlimited ages for similar but often much less extensive denudations in the geological past. Moreover, that rate of erosion appears, on the whole, to be rather below the average in point of rapidity. The Po, for instance, works more than eight times as fast. But as the physics of the Mississippi have been more carefully studied than those of perhaps any other river, and as that river drains so extensive a region, embracing so many varieties of climate, rock, and soil, we shall probably not exaggerate the result if we assume the Mississippi ratio as an average. It is, of course, obvious that as the level of the land is lowered, the rate of subaerial denudation decreases, so that on the supposition that no subterranean movements took place to aid or retard the denudation, the last stages in the demolition of a continent must be enormously slower than during earlier periods.

It must not be forgotten, however, that as already remarked, the estimates here given, inasmuch as they are based only on the material removed in mechanical suspension, are probably understatements of the truth. If we take into account also the material carried away in chemical solution, the rate of subaerial denudation will be considerably heightened. It is difficult, however, to apportion the loss of dissolved substance from the surface of the land. The salts contained in solution in river-water are derived not only from the superficial rocks, but probably to a much greater extent from springs which sometimes carry up dissolved substances from considerable depths. In the end, no doubt, as the level of the land is reduced by subaerial waste, this subterranean solution will tell, but it can hardly be said sensibly to affect the lowering of the level from century to century. Mr. Mellard Reade, from his researches into this subject, believes that the amount of solids in solution is on the whole about one-third of that of those in suspension. He finds this to be the ratio in the Nile, the Danube, and the Mississippi, the last-named being in many respects a typical river. If, as he proposes, we add this additional loss by chemical solution to the amount of material removed in mechanical suspension from the Mississippi basin, the annual lowering of the level of the basin will be raised from $\frac{1}{6000}$ to $\frac{1}{4500}$ of a foot.[319] It is quite true that the loss of mineral matter from the whole basin would be equivalent to that sum, but there would obviously not be strictly a lowering of the level of the basin to that amount. It is difficult

[319] T. Mellard Reade, Presidential Address, Liverpool Geol. Soc. 1884–85.

to see how we are to discriminate between superficial and subterranean solution; and until some separation of this kind is made, it seems hardly legitimate to class the whole of the dissolved matter with that carried in mechanical suspension as a measure of the annual loss from the surface of the land.

There is another point of view from which a geologist may advantageously contemplate the active denudation of a country. He may estimate the annual rainfall and the proportion of water which returns to the sea. If he can obtain a probable average ratio for the earthy substances contained in the river-water which enters the sea, he will be able to estimate the mean amount of loss sustained by the whole country. Thus, taking the average rainfall of the British Islands at 36 inches annually, and the superficial area over which this rain is discharged at 120,000 square miles, then it will be found that the total quantity of rain received in one year by the British Isles is equal to about 68 cubic miles of water. If the proportion of rainfall returned to the sea by streams be taken at a third, there are 23 cubic miles; if at a fourth, there are 17 cubic miles of fresh water sent off the surface of the British Islands into the sea in one year. Assuming, in the next place, that the average ratio of mechanical impurities is only $\frac{1}{5000}$ by volume of the water, the proportion of the rainfall returned to the sea being $\frac{1}{4}$, then it will follow that $\frac{1}{8800}$ of a foot of rock is removed from the general surface of Britain every year. One foot will be planed away in 8800 years. If the mean height of the British Islands be taken at 650 feet, then, if the ratio now assumed were to continue, these islands might be levelled in about five and a half millions of years. Much more detailed observation is needed before any estimate of this kind can be based upon accurate and reliable data. But it illustrates a method of vividly bringing before the mind the reality and extent of the denudation now in progress.

2. *Subaerial Denudation—the unequal erosion of land*

It is obvious that the earthy matter annually removed from the surface of the land does not come equally from the whole surface. The determination of its total quantity furnishes no aid in apportioning the loss, or in ascertaining how much each part of the surface has contributed to the total amount of sediment. On plains, watersheds, and more or less level ground, the proportion of loss may be small, while on slopes and in valleys it may be great, and it may not be easy to fix the true ratios in these cases. But it must be borne in mind that estimates and measurements of the sum-total of denudation are not thereby affected. If we allow too little for the loss from the surface of the table-lands, we increase the proportion of the loss sustained by the sides and bottoms of the valleys, and *vice versâ*.

While these proportions vary indefinitely with the form of the surface, rainfall, etc., the balance of loss must always be, on the whole, on the side of the sloping surfaces. In order to show the full import of this part of the subject, certain ratios may here be assumed which are probably understatements rather than exaggerations. Let us take the proportion between the extent of the plains and table-lands of a country, and the area of its valleys, to be as nine to one; in other words, that, of the whole surface of the country, nine-tenths consists of broad undulating plains, or other comparatively level ground, and one-tenth of steeper slopes. Let it be further assumed that the erosion of the surface is nine times greater over the latter than over the former area, so that while the more level parts of the country have been lowered one foot, the valleys have lost nine feet. If, following the measurements and calculations already given, we admit that the mean annual quantity of detritus carried to the sea may, with some probability, be regarded as equal to the yearly loss of $\frac{1}{6000}$ of a foot of rock from the general surface of the country, then, apportioning this loss over the surface in the ratio just given, we find that it amounts to $\frac{5}{9}$ of a foot from the more level grounds in 6000 years, and 5 feet from the valleys in the same space of time. Now, if $\frac{5}{9}$ of a foot be removed from the level grounds in 6000 years, 1 foot will be removed in 10,800 years; and if 5 feet be worn out of the valleys in 6000 years, 1 foot will be worn out in 1200 years. This is equal to a loss of only $\frac{1}{12}$ of an inch from the table-lands in 75 years, while the same amount is excavated from the valleys in $8\frac{1}{2}$ years.

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

Objection may be taken to the ratios from which this average rate of denudation is computed. Without attempting to decide what this average rate actually is—a question which must be determined for each region upon much fuller data than are at present available—the geologist will find advantage in considering, from the point of view now indicated, what, according to the most probable estimates, is actually in progress around him. Let him assume any other apportioning of the total amount of denudation, he does not thereby lessen the measurement of that amount, which can be and has been ascertained in the annual discharge of rivers. A certain determined quantity of rock is annually worn off the surface of the land. If, as already remarked, we represent too large a proportion to be derived from the valleys and water-courses, we diminish the loss from the open country; or, if we make the contingent derived from the latter too great we lessen that from the former. Under any ascertained or assumed proportion, the facts remain, that the land loses a certain ascertainable fraction of a foot from its general surface per annum, and that the loss from the valleys and water-courses is larger than that fraction, while the loss from the level ground is less.

3. *Marine Denudation—its comparative rate*

From the destructive effects of occasional storms an exaggerated estimate has been formed of the relative potency of marine erosion. That the amount of waste by the sea must be inconceivably less than that effected by the subaerial agents, will be evident if we consider how small is the extent of surface exposed to the power of the waves, when contrasted with that which is under the influence of atmospheric waste. In the general degradation of the land, this is an advantage in favor of the subaerial agents which would not be counterbalanced unless the rate of waste by the sea were many thousands or millions of times greater than that of rains, frosts, and streams. But in reality no such compensation exists. In order to see this, it is only necessary to place side by side measurements of the amount of work actually performed by the two classes of agents. Let us suppose, for instance, that the sea eats away a continent at the rate of ten feet in a century—an estimate which probably attributes to the waves a much higher rate of erosion than can, as the average, be claimed for them.[320] Then a slice of about a mile in breadth will require about 52,800 years for its demolition, ten miles will be eaten away in 528,000 years, one hundred miles in 5,280,000 years. Now we have already seen that, on a moderate computation, the land loses about a foot from its general surface in 6000 years, and that, by the continuance of this rate of subaerial denudation, the continent of Europe might be worn away in about 4,000,000 years. Hence, before the sea, advancing at the rate of ten feet in a century, could pare off more than a mere marginal strip of land, between 70 and 80 miles in breadth, the whole land might be washed into the ocean by atmospheric denudation.

Some such results as these would necessarily be pro-

---

[320] It may be objected that this rate is far below that of parts of the east coast of England (ante, p. 749). But along the rocky western coast of Britain the loss is perhaps not so much as one foot in a century.

duced if no disturbance took place in the relative levels of sea and land. But in estimating the amount of influence to be attributed to each of the denuding agents in past times, we require to take into account the complicated effects that would arise from the upheaval or depression of the earth's crust. If frequent risings of the land, or elevations of the sea-floor into land, had not taken place in the geological past, there could have been no great thickness of stratified rocks formed, for the first continents must soon have been washed away. But the great depth of the stratified part of the earth's crust, and the abundant breaks and unconformabilities among the sedimentary masses, show how constantly, on the one hand, the waste of the land was compensated by elevatory movements, while, on the other, the continued upward growth of vast masses of sedimentary deposits was rendered possible by prolonged depression of the sea-bed.

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

4. *Marine Denudation—its final result*

The general result of the erosive action of the sea on the land is the production of a submarine plain. As the sea advances, the sites of successive lines of beach pass under low-water mark. Where erosion is in full operation, the littoral belt, as far down as wave-action has influence, is ground down by moving detritus. This result may often be instructively observed, on a small scale, upon rocky shores where sections like that in Fig. 176 occur. We can conceive that, should no change of level between sea and land take place, the sea might slowly eat its way far into the land, and produce a gently sloping, yet apparently 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, as may be seen even on a small scale on any rocky beach (Fig. 167). 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 valley or hollow.[821]

This tendency to the formation of a submarine plain along the margin of the land deserves special attention by

Fig. 176.—Section of rocks ground down to a plain on the beach by wave-action.

the student of denudation. The angle at which a mass of land descends to the sea-level serves roughly to indicate the depth of water near shore. A precipitous coast commonly rises out of deep water; a low coast is usually skirted with shallow water, the line of slope above sea-level being in a general way prolonged below it. The belt of beach forms a kind of terrace or notch along the maritime slope. Sometimes, where the coast-line is precipitous, this terrace is nearly or wholly wanting. In other places, it runs out a good way beyond low-water mark. On a great scale, the floor of the North Sea and that of the Atlantic Ocean, for some distance to the west of Ireland, may be regarded as a marine platform that once formed part of the European con-

[821] Mr. Whitaker, in the excellent paper on subaerial denudation cited on p. 753 has pointed out the different results which are obtained by the subaerial forces from those of sea-action in the production of lines of cliff.

tinent (Fig. 177), and has been reduced by denudation and subsidence to its present position.

So far as the present régime of nature has been explored, it would seem to be inevitable that, unless where subterra-

Fig. 177.—Map of British submarine platform.

The darker tint represents sea-bottom more than 100 fathoms deep, while the paler shading shows the area of less depths. The figures mark the depth in fathoms. The narrow channel between Norway and Denmark is 2580 feet deep.

nean movements interfere, or where volcanic rocks are poured forth at the surface, a submarine plain should be formed along the margin of the land. This final result of denudation has been achieved again and again in the geological past, as is shown by the existence of table-lands of erosion (ante, p. 83). To these table-lands the name of "plains of marine denudation" has been applied by Sir A. C. Ramsay. From what has now been said, however, it will be seen that in their actual production the sea has really had less to do than the meteoric agents. A "plain of marine denudation" is that base-level of erosion to which a mass of land had been reduced mainly by the subaerial forces—the line below which further degradation became impossible, because the land was thereafter protected by being covered by the sea. Undoubtedly the last touches in the long process of sculpturing were given by marine waves and currents, and the surface of the plain, save where it has subsided, may correspond generally with the lower limit of wave-action. Nevertheless, in the past history of our planet, the influence of the ocean has probably been far more conservative than destructive. Beneath the reach of the waves, the surface of the abraded land has escaped the demolition which sooner or later overtakes all that rises above them.

5. *Deposition—the framework of new land*

If a survey of the geological changes in daily progress upon the surface of the earth leads us to realize how momentously the land is being worn down by the various epigene agents, it ought also to impress us with the vast scale on which new formations—the foundation of future land—are being continually accumulated. Every foot of rock removed from the surface of a country is represented by a corresponding amount of sedimentary material arranged somewhere beneath the sea. Denudation and deposition are synchronous and coequal.

On land, vast accumulations of detrital origin are now in progress. Alluvial plains of every size, from those of mere brooks up to those of the largest rivers, are built up of gravel, sand, and mud derived from the disintegration of higher ground. From the level of the present streams, successive terraces of these materials can be followed up to heights of several hundred feet. Over wide regions, the daily changes of temperature, moisture and wind supply a continual dust, which, in the course of centuries, has accumulated to a depth of sometimes 1500 feet, and covers thousands of square miles of the surface of the continents. The numerous lakes that dot the surface of the land serve as receptacles in which a ceaseless deposition of sediment takes place. Already an unknown number of once existent lakes has been entirely filled up with detrital accumulations, and every stage toward extinction may be traced in those that remain.

But extensive though the terrestrial sedimentary deposits may be, they can be regarded merely as temporary accumulations of the detritus. Save where protected and concealed under the water of lakes, they are everywhere exposed to a renewal of the denudation to which they owe their origin. Only where the sediment is strewn over the sea-floor beneath the limit of breaker-action, is it permitted to accumulate undisturbed. In these quiet depths, are now growing the shales, sandstones, and limestones, which by future terrestrial revolutions will be raised into land, as those of older times have been. Between the modern deposits and those of former sea-bottoms which have been upheaved, there is the closest parallel. Deposition will obviously continue as long as denudation lasts. The secular movements of the crust seem to have been always sufficiently frequent and extensive to prevent cessation of these operations. And so we may anticipate that it will be for many geological ages yet to come. Elevation of land will repair what has been lost by superficial waste, and subsidence of sea-bottom will provide space for continued growth of sedimentary deposits.

Section iii. Life

Among the agents by which geological changes are now, and have in past time been effected upon the earth's surface, living organisms take by no means an unimportant place. They serve as a vehicle for continual transferences from the atmosphere into the mineral world, and from the mineral world back into the atmosphere. Thus they decompose atmospheric carbon-dioxide, and in this process have gradually removed from the atmosphere the vast volumes of carbon now locked up within the earth's crust in beds of solid coal. By their decomposition, organic acids are produced which partly enter into mineral combinations, and partly return to the atmosphere as carbon-dioxide. Plants abstract from the soils silica, alkalies, calcium-phosphate, and other mineral substances, which enter largely into the composition of the hard parts of animals. On the death and decomposition of animals, these substances are once more relegated to the inorganic world, thence to enter upon a new circulation through the tissues of living organisms.

From a geological point of view, the operations of organic life may be considered under three aspects—destructive, conservative, and reproductive.

§ 1. Destructive Action

Plants in several ways promote the disintegration of rocks.

1. By keeping the surfaces of rocks moist, plants pro-

vide means for the continuous solvent action of water. This influence is particularly observable among liverworts, mosses, and similar moisture-loving plants.

2. By their decay, plants supply an important series of organic acids, which exert a powerful influence upon soils, minerals, and rocks. The humus, or organic portion of vegetable soil, consists of the remains of plants and animals in all stages of decay, and contains a complex series of organic compounds still imperfectly understood. Among these are humic, ulmic, crenic and apocrenic acids.[322] The action of these organic acids is twofold. (1) From their tendency to oxidation, they exert a markedly reducing influence (ante, pp. 584, 611, 766). Thus they convert metallic sulphates into sulphides, as in the blue marine muds, and the abundant pyritous incrustations of coal-seams, shell-bearing clays, and even sometimes of mine-timbers. Metallic salts are still further reduced to the state of native metals. Native silver occurs among silver ores in fossil wood among the Permian rocks of Hesse. Native copper has been frequently noticed in the timber-props of mines; it was found hanging in stalactites from timbers of the Ducktown copper mines, Tennessee, when the mines were reopened after being shut up during the Civil War. Fossil fishes from the Kupferschiefer have been incrusted with native copper, and fish-teeth have been obtained from Liguria completely replaced by this metal. (2) They exert a remarkable power of dissolving mineral substances.[323] This phase of their activity has probably been undervalued by geologists.[324] Experi-

---

[322] See J. Roth, "Allgemeine und Chemische Geologie," 1883, p. 596.

[323] Prof. Sollas has noticed the formation of minute hemispherical pits on limestone by the solvent action of a lichen, Verrucaria rupestris (Brit. Assoc. 1880, sects. p. 586). See also J. G. Goodchild, Geol. Mag. 1890, p. 464.

[324] This has been strongly insisted upon by A. A. Julien in a memoir on the

ments have shown that many of the common minerals of rocks are attacked by organic acids. There is reason to believe that in the decomposition effected by meteoric waters, and usually attributed mainly to the operation of carbonic acid, the initial stages of attack are due to the powerful solvent capacities of the humus acids. Owing, however, to the facility with which these acids pass into higher states of oxidation, it is chiefly as carbonates that the results of their action are carried down into deeper parts of the crust or brought up to the surface. Although carbonic acid is no doubt the final condition into which these unstable organic acids pass, yet during their existence they attack not merely alkalies and alkaline earths, but even dissolve silica. The relative proportion of silica in river-waters has been referred to the greater or less abundance of humus in their hydrographical basins,[325] the presence of a large percentage of silica being a concomitant of a large proportion of organic matter. Further evidence of the important influence of organic acids upon the solution of silica is supplied by many siliceous deposits (p. 810).

Wherever a layer of humus has spread over the surface of the land, traces of its characteristic decompositions may be found in the soils, subsoils and underlying rocks. Next the surface, the normal color of the subsoils is usually changed by oxidation and hydration into tints of brown and yellow, the lower limit of the weathered zone being often sharply defined. Where the humus acids can freely

---

Geological Action of the Humus Acids. Amer. Assoc. 1879, p. 311. Prof. H. C. Bolton has experimented on the action of citric acid on 200 different mineral species, and he finds that this organic acid possesses a power of dissolving minerals only slightly less than that of hydrochloric acid; Brit. Assoc. 1880, Sects. p. 505.

[325] Sterry Hunt's "Chemical and Geological Essays," pp. 126–150.

attack the hydrated peroxide of iron, they remove it in solution, and the decomposed rock or soil is thereby bleached. This may be observed where pine-trees grow on ferruginous sand, a rootlet one-sixth of an inch in diameter being by its decay capable of whitening the sand to a distance of from one to two inches around it.[326] It has recently been proposed to ascribe mainly to the operation of the humus acids the thick layer of decomposed rock above noticed (p. 595) as observable so frequently south of the limits of the ice of the Glacial Period, and the inference has been drawn that, even where the surface is now comparatively barren, the mere existence of this thick decomposed layer affords a presumption that it once underlay an abundant vegetation, such as a heavy primeval forest-growth.[327] Nor is the chemical action confined to the superficial layers. The organic acids are carried down beneath the surface, and initiate that series of alterations which carbonic acid and the alkaline carbonates effect among subterranean rock masses (ante, p. 611).

3. Plants insert their roots or branches between the joints of rock, or penetrate beneath the soil. Two marked effects are traceable to this action. In the first place, large slices of rock may be wedged off from the sides of wooded hills or cliffs. 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. In the second place, the soil and subsoil are opened up to the decomposing influences of the air and descending water. The distance to which, under favorable

---

[326] Kindler, Poggend. Annal. xxxvii. 1836, p. 203. J. A. Phillips, "Ore Deposits," 1884, p. 14.

[327] Julien, Amer. Assoc. 1879, p. 378.

circumstances, roots may penetrate downward are much greater than might be supposed. Thus in the loess of Nebraska the buffalo-berry (*Shepherdia argophylla*) has been observed to send a root 55 feet down from the surface, and in that of Iowa the roots of grasses penetrate from 5 to 25 feet.[328]

4. By attracting rain, as thick forests, woods, and mosses, more particularly on elevated ground, are believed to do, plants accelerate 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.[329]

5. Plants promote the decay of diseased and dead plants and animals, as when fungi overspread a damp rotting tree or the carcass of a dead animal.

Animals.—The destructive influences of the animal kingdom likewise show themselves in several distinct ways.

1. The surface-soil is moved, and exposed thereby to attack by rain, wind, etc. As Darwin showed, the common earth-worm is continually engaged in bringing up the fine particles of soil to the surface. He found that in fifteen years a layer of burned marl had been buried under 3 inches of loam, which he attributed to this operation.[330] It has been already pointed out that part of the growth of soil may be due to wind-action (ante, p. 563). There can be no doubt, however, that the materials of vegetable soil are largely commingled and fertilized by the earth-worm, and in par-

---

[328] Aughey's "Physical Geography and Geology of Nebraska," 1880, p. 275.

[329] See on this disputed question the works cited by Rolleston, Journ. Roy. Geog. Soc. xlix. 1879. The destruction of forests is also alleged to increase the number and severity of hail-storms.

[330] Trans. Geol. Soc. v. p. 505. "Vegetable Mould," 1881.

ticular that, by being brought up to the surface, the fine particles are exposed to meteoric influences, notably to wind and rain. Even a grass-covered surface may thus suffer slow denudation. Lob-worms on sandy shores possibly aid transport by waves and tides, inasmuch as they bring up large quantities of fresh sand.[381]

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 and gopher have 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. The decomposition of animal remains produces chemical changes similar to those resulting from the decay of plants.

2. The flow of streams is sometimes interfered with, or even diverted, by the operations of animals. Thus the beaver, by cutting down trees (sometimes 1 foot or more in diameter) and constructing dams with the stems and branches, checks the flow of water-courses, intercepts floating materials, and sometimes even diverts the water into new channels. This action is typically displayed in Canada and in the Rocky Mountain regions of the United States. Thousands of acres in many valleys have been converted into lakes, which, intercepting the sediment carried down

---

[381] Mr. Davidson estimates the amount to be sometimes nearly 2000 tons annually over an acre. Geol. Mag. 1891.

by the streams, and being likewise invaded by marshy vegetation, have subsequently become morass and finally meadow-land. The extent to which, in these regions, the alluvial formations of valleys have been modified and extended by the operations of the beaver is almost incredible. The embankments of the Mississippi are sometimes weakened to such an extent by the burrowings of the cray-fish as to give way, and allow the river to inundate the surrounding country. Similar results have happened in Europe from the subterranean operations of rats.

3. Some mollusks (*Pholas*, *Saxicava*, *Teredo*, etc., Fig. 178) bore into stone or wood, and by the number of contiguous perforations greatly weaken the materials. Pieces of driftwood are soon riddled with long holes by the teredo; while wooden piers, and the bottoms of wooden ships, are often rapidly perforated. Saxicavous shells, by piercing stone and leaving open cavities for rain and sea-water to fill, promote its decay. A potent cause of the destruction of coral-reefs is to be found in the borings of mollusks, annelids, and echinoderms, whereby masses of coral are weakened so as to be more easily removed by breakers.

Fig. 178.—Shell-borings in limestone.

4. Many animals exercise a ruinously destructive influence upon vegetation. Of the various insect-plagues of this 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. As an illustration of this action, reference may be made to the occasionally enormous development of the protozoon genera *Peridinium* and *Glenodinium*, and the consequent killing off of the oysters and other mollusks in the waters of Port Jackson.[332]

§ 2. Conservative Action

Plants.—The protective influence of vegetation is well known.

1. The formation of a stratum of turf protects soil and rocks from being rapidly removed by rain or wind. Hence the surface of a district so protected is denuded with extreme slowness, except along the lines of its water-courses. A crust of lichens doubtless on the whole protects the rock underneath it from atmospheric agents.[333]

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 littoral sand-dunes, and give them a permanence which would at once be destroyed were the sand laid bare again to the storms. In North America, the sandy tracts of the

---

[333] But see the remark already made, ante, p. 792, note [328].

[332] An occurrence of this kind in March, 1891, led to an almost complete destruction of the oysters, mussels and other bivalves; the rest of the littoral fauna—limpets and other univalves, starfish, worms, ascidians and other lower forms of life—were so seriously affected that dead and dying were strewn about in great numbers, while the higher forms, able to move rapidly, had retired to deep water. T. Whittelegge, Records of Australian Museum, i. No. 9, 1891, p. 179.

Western Territories are in many places protected by the 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 planted with pine woods, which, while preventing the destructive inland march of the sand, also yield a large revenue in timber, and have so influenced the climate as to make these districts a resort for pulmonary invalids.[334] In tropical countries, the mangrove grows along the sea-margin, and not only protects the land, but adds to its breadth, by forming and increasing a maritime alluvial belt.

3. Some marine plants likewise afford protection to shore rocks. This is done by the hard incrustation of calcareous nullipores; likewise by the tangles and smaller fuci which, growing abundantly on the littoral zone, break the force of waves, or diminish the effects of ground-swell.

4. Forests and brushwood protect soil, especially on slopes, from being washed away by rain. This is shown by the disastrous results of the thoughtless destruction of woods. According to Reclus,[335] in the three centuries from

---

[334] De Lavergne, "Economie rurale de la France depuis 1789," p. 297. Edin. Review, Oct. 1864, article on Coniferous Trees.

[335] "La Terre," p. 410. J. C. Brown, "Reboisement en France," London, 1876. According to Dr. J. Carret, however, the deterioration of the climate of Savoy and the diminution of the population there cannot be attributed to deboisement. The cutting down of the forests dates from the First Empire, but replanting has been going on for some time, and the forest area is now a little larger than it was last century. Nevertheless the depopulation of the higher tracts, which had begun before last century, continues, notwithstanding the replanting of the slopes: Assoc. Française, 1879, p. 538.

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.[336]

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 on the whole exert an important conservative action upon the earth's surface, save in so far as they form new deposits, as will be immediately referred to. On many shores, however, by thickly incrusting rocks, they act like the marine vegetation above alluded to, and protect these to a considerable extent from abrasion by the waves. The most familiar example in Europe of this action is that of the common acorn-shell or barnacle (*Balanus balanoides*). Serpulæ often incrust considerable masses of a coral-reef, and act like nullipores, in protecting decaying and dead corals from being so rapidly broken up by the waves as they would otherwise be. But even soft-bodied animals, such as sponges and ascidians, when they spread over rocks near

[336] Recent attempts to reclothe the desiccated stone-wastes of Dalmatia with trees have been attended with success. See Mojsisovics, Jahrb. Geol. Reichsanst. 1880, p. 210.

low-water, afford protection from at least the less violent attacks of the breakers. Prof. Herdman, who has called attention to this subject, enumerates as the more important animals in protecting shore rocks: Foraminifera (such as *Planorbulina vulgaris*), calcareous and fibrous sponges, hydroid zoophytes, sea anemones, corals, annelids (serpula), polyzoa, cirripeds, mollusks (such as gregarious forms like the mussel and oyster, and gasteropods like the limpet), and simple and compound ascidians.[337]

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. The trails made by the bison, the elk, and the bighorn or mountain-sheep, are 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 winds.[338]

§ 3. Reproductive Action

Plants.—Both plants and animals contribute materials toward new geological formations, chiefly by the aggrega-

---

[337] Proc. Liverpool Geol. Soc. 1884–85.

[338] Comstock, in Captain Jones's "Reconnoissance of N. W. Wyoming," 1875, p. 175.

tion of their remains, partly from their chemical action. Their remains are likewise inclosed in deposits of sand and mud, the bulk of which they thus help to increase. Of plant-formations the following illustrative examples may be given:

1. Sea-weeds.—It was long ago shown by Forchhammer that fucoids abstract an appreciable amount of lime, magnesia, soda, and other components of sea-water, and he believed that these plants probably played an important part in the accumulation of the older Palæozoic sediments.[339] The calcareous nullipores which incrust shore rocks provide solid material which, either growing *in situ* or broken off and distributed by the waves, gives rise to a distinct geological deposit. Considerable masses of a structureless limestone are formed in the Bay of Naples mainly by calcareous algæ. By the infiltration of water into the dead parts of the material the organic structure is destroyed.[340]

2. Humus, Black Soils, etc.—Long-continued growth and decay of vegetation upon a land-surface not only promotes disintegration of the superficial rock, but produces an organic residue, the intermingling of which with mineral débris constitutes vegetable soil. Undisturbed through long ages, this process has, under favorable conditions, given rise to thick accumulations of a rich dark loam. Such are the "regur," or rich black cotton soil of India, the "tchernayzem," or black earth of Russia, containing from 6 to 10 per cent of organic matter, and the deep fertile soil of the American prairies and savannas. These formations cover plains many thousands of square miles in extent. The "tundras" of northern latitudes are frozen plains of

---

339 Brit. Assoc. 1844, p. 155.
340 J. Walther, Zeitsch. Deutsch. Geol. Gesell. xxxvii. 1885, p. 329.

which the surface is covered with arctic mosses and other plants.[341]

3. Peat-mosses and Bogs.[342]—In temperate and arctic latitudes, marshy vegetation accumulates *in situ* to a depth of sometimes 40 or 50 feet, in what are termed bogs or peat-mosses. In northern Europe and America these vegetable deposits have been largely formed by mosses, especially species of *Sphagnum*, which, growing on hilltops, slopes, and valley-bottoms as a wet spongy fibrous mass, die in their lower parts and send out new fibres above. Some peaty deposits have been formed in lakes, either by the growth of aquatic plants on the bottom, or by the precipitation of decaying vegetation from the layer of matted plant-growth which creeps from shore along the surface of the water.[343] In some cases, peat may possibly have arisen in brackish-water conditions. There are even instances cited of marine peat formed of sea-weeds (*Zostera*, *Fucus*, etc.).[344] Among the Alps, as also in the northern parts of South

---

341 See a pamphlet, "Ueber den Humus," by Dr. von Ollech, Berlin, Bodo Grundmann, 1890. It may be well to take note here again of the extensive accumulation of red loam in limestone regions which have long been exposed to atmospheric influences. To what extent vegetation may co-operate in the production of this loam has not been determined. Fuchs believes that the "terra rossa" is only present in dry climates where the amount of humus is small (ante, p. 596, and authorities there cited).

342 For a general account see T. R. Jones, Proc. Geol. Assoc. vi. 1880, p. 207. On the composition, structure and history of peat-mosses, consult Rennie's "Essays on Peat-moss," Edinburgh, 1810; Steele's "Natural and Agricultural History of Peat-moss," Edinburgh, 1826; Templeton, Trans. Geol. Soc. v. p. 608; H. Schinz-Gessner, "Der Torf," etc., Zurich, 1857; Pokorny Verhand. Geol. Reichsanst. Vienna, 1860; Senft, "Humus-, Marsch-, Torf-, und Limonit-bildungen," Leipzig, 1862; G. Thenius, "Die Torfmoore Oesterreichs," Vienna, 1874; J. Geikie, Trans. Roy. Soc. Edin. xxiv. p. 363. For a list of plants that supply material for the formation of peat, see J. Macculloch's "Western Islands," vol. i.; T. R. Jones, above quoted; J. Früh, "Kritische beiträge zur Kenntniss des Torfes," Jahrb. Geol. Reichsanst. xxxv. 1885, p. 677; and Bull. Soc. Botan. Suisse, i. 1891.

343 For accounts of matted vegetation covering lakes, see Land and Water, 1876, pp. 180, 282.

344 J. Macculloch, "System of Geology," 1831, vol. ii. p. 341. Sirodot, Compt. Rend. lxxxvii. 1878, p. 267. Bobierre, Ann. Mines, 7me ser. x. 1876, p. 469.

America, and among the Chatham Islands, east of New Zealand, various phanerogamous plants form on the surface a thick stratum of peat.

A succession can sometimes be detected in the vegetation out of which the peat has been formed. Thus in Europe, among the bottom layers traces of rush (*Juncus*), sedge (*Iris*), and fescue-grass (*Festuca*) may be observed, while not infrequently an underlying layer of fresh-water marl, full of mouldering shells of *Limnea*, *Planorbis*, and other lacustrine mollusks, shows that the area was originally a lake which has been filled up with vegetation. The next and chief layer of the peat will usually be found to consist mainly of

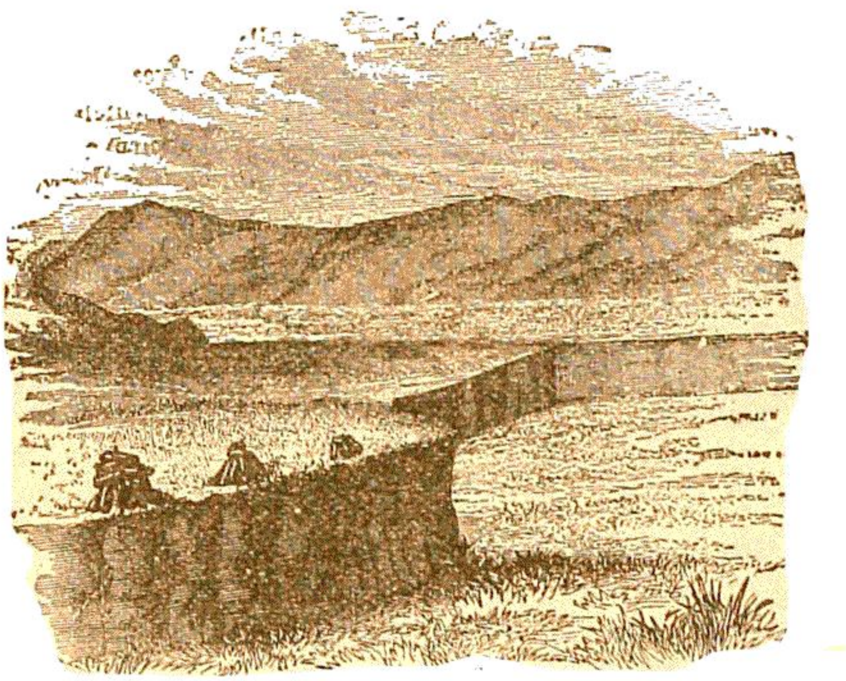


Fig. 179.—View of Scottish Peat-moss opened for digging fuel.

matted fibres of different mosses, particularly *Sphagnum*, *Polytrichum*, and *Bryum*, mingled with roots of coarse grasses and aquatic plants. The higher layers frequently abound in the remains of heaths. Every stage in the formation of peat may be observed where mosses are cut for fuel; the portions at the bottom are more or less compact, dark brown or black, with comparatively little external appearance of vegetable structure, while those at the top are loose, spongy, and fibrous, where the living and dead parts of the mosses commingle (Fig. 179).

It frequently happens that remains of trees occur in peat-mosses. Sometimes the roots are imbedded in soil underlying the moss, showing that the moss has formed since the growth of the trees (see p. 564). In other cases, the roots and trunks occur in the heart of the peat, proving that the trees grew upon the mossy surface, and were finally, on their decay, inclosed in growing peat (Fig. 180). A succession of trees has been observed among the Danish peat-mosses, the Scotch fir (*Pinus sylvestris*) and white birch (*Betula alba*) being characteristic of the lower layers; higher portions of the peat being marked by remains of the oak, while at the

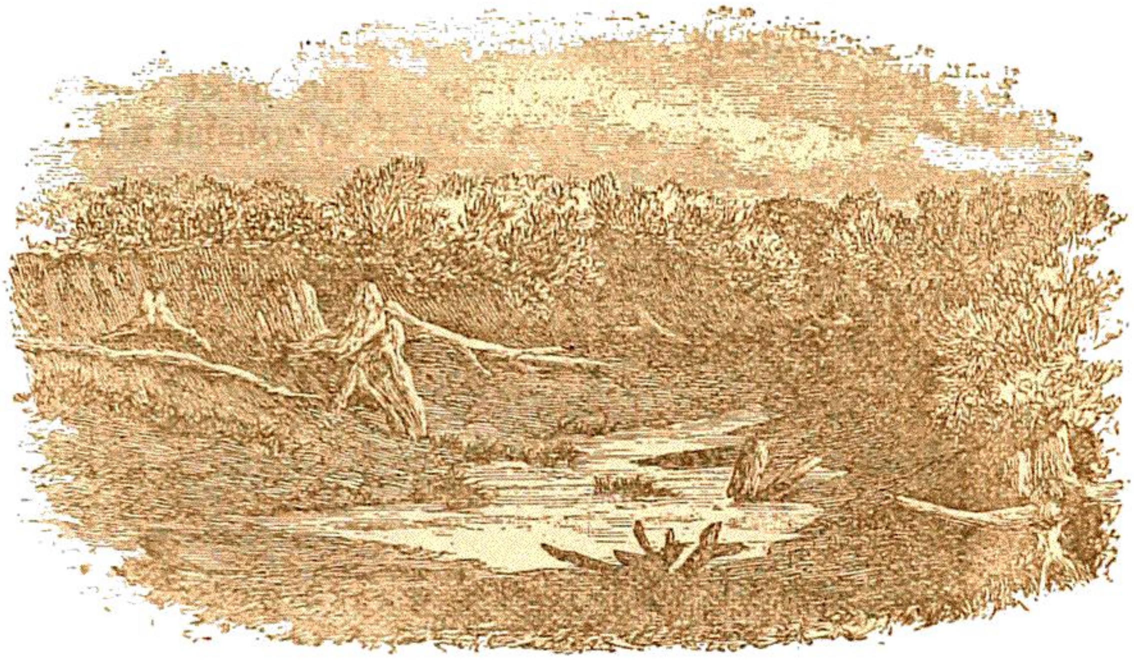


Fig. 180.—Scene in a Sutherland Peat-moss.

top comes the common beech. Remains of the same kinds of trees are abundant in the bogs of Scotland and Ireland.

The rate of growth of peat varies within wide limits. An interesting example of the formation and growth of peat-moss in the latter half of the seventeenth century is on record.[345] In the year 1651 an ancient pine-forest occupied a level tract of land among the hills in the west of Ross-shire. The trees were all dead, and in a condition to be blown down by the wind. About fifteen years later every vestige of a tree had disappeared, the site being occupied by a spongy green bog into which a man would sink up to the armpits. Before the year 1699 the tract had become firm enough to yield good peat for fuel. In the valley of the Somme, three feet of peat will grow in from 30 to 40 years.[346] On a moor in Hanover, a layer of peat from 4 to 6 feet thick

345 Earl of Cromarty, Phil. Trans. xxvii.
346 J. Kolb, Proc. Inst. Civ. Engin. xl. 1875, p. 35.

formed in about 30 years. Near the Lake of Constance, a layer of 3 to 4 feet grew in 24 years. Among the Danish mosses, a period of 250 to 300 years has been required to form a layer 10 feet thick. Much must depend upon the climate, slope, drainage, and soil. Some European peat-mosses are probably of extreme antiquity, having begun to form soon after the surface was freed from the snow and ice of the glacial period. In the lower parts of these mosses, traces of the arctic flora which then overspread so much of the continent are to be met with. In other instances, the mosses are at least as late as Roman times.[347] Change of climate and likewise of drainage may stop the formation of peat, so that shrubs and trees spring up on the firm surface. Along the Flemish coast a layer of peat containing mosses, rushes, and other fresh-water plants underlies four or five feet of clays and sands with marine shells, indicating a subsidence and re-elevation of the country.[348]

Peat-mosses cover many thousand square miles of Europe and North America.[349] About one-seventh of Ireland is covered with bogs, that of Allen alone comprising 238,500 acres, with an average depth of 25 feet. Where lakes are gradually converted into bogs, the marshy vegetation advances from the shores, and sometimes forms a matted treacherous green surface, beneath which the waters of the lake still lie. The decayed vegetable matter from the under part of this crust sinks to the bottom of the water, forming there a fine peaty mud, which slowly grows upward. Eventually, as the spongy covering spreads over the lake, a layer of brown muddy water may be left between the still growing vegetation above and the muddy deposit at the bottom. Heavy rains, by augmenting this intermediate watery layer, sometimes make the centre swell up until the matted skin of moss bursts, and a deluge of black mud pours into the surround-

---

[347] On mosses of Flanders and north of France see H. Debray, Bull. Soc. Geol. France, 3me, ser. ii. p. 46. Ann. Soc. Geol. Nord, 1870–74, p. 19. Lorié, Arch. Mus. Teyler, 2me, ser. iii. part 5, 1890, pp. 423, 439. Below the moors of Oldenburg, Roman coins, weapons and plank-roads are found at a depth of 13 feet and upward (Petermann's Mittheil. 1883, v.). On the Bohemian peat-bogs, F. Sitensky, Archiv Landesdurch-forsch. Böhmen, vi. 1891; on those lying east of the Christiania Fjord, G. E. Stangeland, "Torvmyrer," Norges Geolog. Undersög. 1892; on those of Schleswig-Holstein, R. v. Fischer-Benzon, Abh. Naturwiss. Ver. Hamburg, xi. 1891.

[348] Ann. Mines, 7me, ser. x. p. 468.

[349] For an account of the fresh-water morasses and swamps of the United States see Shaler, 10th Ann. Rep. U. S. Geol. Surv. 1890, p. 255.

ing country. The inundated ground is covered permanently with a layer of black peaty earth.

From the treacherous nature of their surface, peat-mosses have frequently been the receptacles for bodies of men and animals that ventured upon them. As peat possesses great antiseptic power, these remains are usually in a state of excellent preservation. In Ireland, the remains of the extinct large Irish elk (*Megaceros hibernicus*) have been dug up from many of the bogs. Human weapons, tools, and ornaments have been exhumed from peat-mosses; likewise crannoges, or pile-dwellings (constructed in the original lakes that preceded the mosses), and canoes hollowed out of single trees.

4. 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 twenty 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 that flows off the land is filtered of its sediment, which, retained among the vegetation, helps to turn the spongy jungle into a firm soil.[360] On the coast of Florida, the mangrove swamps stretch for long distances, as a belt from five to twenty 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 amid the sand and

[360] For an account of the growth of mangrove swamps, see N. S. Shaler, 10th Ann. Rep. U. S. Geol. Surv. 1890, p. 291.

vegetation, they form a remarkably calcareous soil (pp. 226, 574).[351]

5. Diatom-Earth or Ooze.—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. The most extensive terrestrial accumulations of this nature now in course of formation are probably those of the warm water marshes supplied by the hot springs of the Yellowstone Park, where the oozy deposits and drier meadows

Fig. 181.—Diatom ooze dredged up by the "Challenger" Expedition from a depth of 1950 fathoms in the Antarctic Ocean. Lat. 53° 85′ S.; Long. 108° 38′ E. Magnified 300 diameters.

cover many square miles, sometimes to a depth of six feet.[352] "Infusorial" earth and "tripoli powder" consist mainly of the frustules and fragmentary débris of diatoms, which have accumulated on the bottoms of lacustrine areas. the purer varieties containing 90 to 97 per cent of silica, They form beds sometimes upward of 30 feet thick. (Richmond, Virginia; Bilin, Bohemia; Aberdeenshire.) *Diatomaceæ* occur in abundance, both in the surface-waters of the ocean and on the bottom. In the Arctic

[351] See Nelson, Q. J. Geol. Soc. ix. p. 200 *et seq.*; J. J. Rein, Bericht Senckenb. Naturf. Ges. 1872–73, p. 139; Wyville Thomson's "Atlantic," i. p. 290. (See ante, pp. 226, 573.)

[352] W. H. Weed, Botanical Gazette, xiv. 1889, p. 117.

Ocean and in the seas around the Shetland Islands living diatoms sometimes form vast floating banks of a yellowish slimy mass, which impedes the prosecution of the herring fishery.[353] The frustules of these plants accumulate at depths of from 1260 to 1975 fathoms, as a pale straw-colored deposit, which when dried is white and very light (Fig. 181).[354]

6. Chemical Deposits.—But, besides giving rise to new formations by the mere accumulation of their remains, plants do so also both directly and indirectly by originating or precipitating chemical solutions. The most conspicuous example of this action is the production of calc-sinter. Some plants (several species of *Chara*, for instance) have the power of decomposing the carbonic acid dissolved in water, and precipitating calcium-carbonate within their own cell walls. Others (such as the mosses *Hypnum*, *Bryum*, etc.[355]) precipitate the carbonate as an inorganic incrustation outside their own substance. Some observers have even maintained that this is the normal mode of production of calc-sinter in large masses like those of Tivoli. It is certainly remarkable that this substance may be observed incrusting fibrous bunches of moss (*Hypnum*, etc.), when it can be found in no other part of the water-course, and this, too, at a spring containing only 0·034 of carbonate. It is evident that if the deposit of calc-sinter were due to mere evaporation, it would be more or less

---

[353] Murray and Irvine, Proc. Roy. Soc. Edin. xviii. 1891, p. 231. On the source whence marine plants and animals obtain their silica, see ante, p. 755 and postea, p. 828.

[354] Messrs. Murray and Irvine estimate the area of sea-bottom covered with diatom ooze at 10,420,600 square miles, and the mean depth of the surface of the deposit at 1477 fathoms below sea-level, Proc. Roy. Soc. Edin. xvii. 1889, p. 82.

[355] Also phanerogams, as *Ranunculus* and *Potamogeton*.

equally spread along the edges and shallow parts of the channel. It appears to arise first from the decomposition of dissolved carbonic acid by the living plants, and it proceeds along their growing stems and fibres. Subsequently, evaporation and loss of carbon-dioxide cause the carbonate to be precipitated over and through the fibrous sinter, till the substance may become a solid crystalline stone. Varieties of sinter are traceable to original differences in the plants precipitating it. Thus at Weissenbrunnen, near Schalkau, in central Germany, a cavernous but compact sinter is made by *Hypnum molluscum*, while a loose porous kind gathers upon *Didymodon capillaceus.*[356]

Some marine algæ, as above noticed, abstract calcium-carbonate from sea-water and build it up into their own substance. A nullipore (*Lithothamnium nodosum*) has been found to contain about 84 per cent of calcium-carbonate, 5½ of magnesium-carbonate, with a little phosphoric acid, alumina, and oxides of iron and manganese.[357] Vegetable life has likewise the power of precipitating silica from solution in hot springs and forming siliceous sinter. In the geyser district of the Yellowstone Park it has been ascertained that the extensive sinter deposits are largely formed by vegetation, which causes the siliceous material to be thrown down as a stiff gelatinous substance, in many varied forms. Algæ are chiefly concerned in this process. On the death of the plant the jelly-like mass, which consists of the siliceous filaments of the algæ and their slimy en-

---

[356] See V. Schauroth, Z. Deutsch. Geol. Ges. iii. 1851, p. 137. Cöhn, Neues Jahrb. 1864, p. 580, gives some interesting information as to the plants by which the sinter is formed, and their work. In Scotland *Hypnum commutatum* is a leading sinter-former.

[357] Gümbel, Abhandl. Bayerisch. Akad. Wissensch. xi. 1871.

velope, loses part of its water, becomes cheese-like in consistency, and finally hardens into stone.[858]

In the formation of extensive beds of bog iron-ore, the agency of vegetable life is of prime importance. In marshy flats and shallow lakes, where the organic acids are abundantly supplied by decomposing plants, the salts of iron are attacked and dissolved. Exposure to the air leads to the oxidation of these solutions, and the consequent precipitation of the iron in the form of hydrated ferric oxide, which, mixed with similar combinations of manganese, and also with silica, phosphoric acid, lime, alumina, and magnesia, constitutes the bog-ore so abundant on the lowlands of North Germany and other marshy tracts of northern Europe.[859] On the eastern seaboard of the United States, large tracts of salt marsh, lying behind sand-dunes and bars, form receptacles for much active chemical solution and deposit. There, as in the European bog-iron districts, ferruginous sands and rocks containing iron are bleached by the solvent action of humus acids, and the iron removed in solution is chiefly oxidized and thrown down on the bottom. In presence of the sulphates of sea-water and of organic matter, the iron of ferruginous minerals is partially changed into sulphide, which on oxidation gives rise to the precipitation of bog-iron.[860] The existence of beds of iron-ore among sedimentary formations affords strong presumption of the existence of contemporaneous organic life by which the iron was dissolved and precipitated.

---

858 W. H. Weed, Ninth Ann. Rep. U. S. Geol. Survey, 1889. Amer. Journ. Sci. xxxvii. 1889, p. 351.

859 Forchhammer, Neues Jahrb. 1841, p. 17, ante, p. 254.

860 Julien, Amer. Assoc. 1879, p. 347, and ante, p. 763.

The humus acids, which possess the power of dissolving silica, precipitate it in incrustations and concretions. Julien describes hyalite crusts at the Palisades of the Hudson, due, as he thinks, to the action of the rich humus upon the fallen débris of diabase. The frequent occurrence of nodules of flint and chert in association with organic remains, the common silicification of fossil wood, and similar close relations between silica and organic remains, point to the action of organic acids in the precipitation of this mineral. This action may consist sometimes in the neutralization, by organic acids, of alkaline solutions charged with silica;[361] sometimes in the solution and redeposit of colloid silica by albuminoid compounds, developed during the decomposition of organic matter in deposits through which silica has been disseminated, the deposit taking place preferentially round some decaying organism, or in the hollow left by its removal.[362]

Animals.—Animal formations are chiefly composed of the remains of the lower grades of the animal kingdom, especially of *Mollusca*, *Actinozoa*, and *Foraminifera*.

1. Calcareous.—Lime, chiefly in the form of carbonate, is the mineral substance of which the solid parts of invertebrate animals are mainly built up. The proportion of carbonate of lime in sea-water is so small as to have presented a difficulty in the endeavor to account for the vast quantities of this substance eliminated by marine organisms. Mr. J. Y. Buchanan, however, has suggested that the testaceous denizens of the sea assimilate their lime from the gypsum dissolved in sea-water, forming sulphide in the

---

[361] Leconte, Amer. Journ. Sci. 1880, p. 181.

[362] Julien, op. cit. 396. Sollas, Ann. Mag. Nat. Hist. Nov. Dec. 1880. J. Roth, "Allgem. Chem. Geologie," p. 576, and Dr. von Ollech's pamphlet cited ante, p. 802.

interior of the animal, which is transformed into carbonate on the outside.[363] Messrs. Murray and Irvine have experimentally proved that sea-animals can secrete carbonate of lime from sea-water from which carbonate of lime is rigidly excluded, and thus that the other lime salts, notably the sulphate, are made use of in the process. They infer that the living tissues of the lower animals and the effete secretions of higher forms, produce carbonate of ammonia, which in presence of the sulphate of lime of sea-water becomes carbonate of lime and sulphate of ammonia.[364] The great majority of the accumulations formed of animal remains are calcareous. Those organisms which secrete their lime as calcite produce much more durable skeletons or tests than those which accumulate it in the form of aragonite. Hence among geological formations aragonite shells have in large measure disappeared.[365]

In fresh water, accumulations of animal remains 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, as in oyster-banks. Under favorable conditions, extensive deposits of limestone are now being formed on the sea-floor in tropical latitudes. Mr. Murray, from observations made during the "Challenger" voyage, estimates that in a square mile of the tropical ocean down to a depth of 100 fathoms there are more than 16 tons of calcareous matter in the form of animal and vegetable organisms.[366] These surface organisms, when dead,

[363] Brit. Assoc. 1881, sects. p. 584.
[364] Proc. Roy. Soc. Edin. xvii. 1889, p. 89.
[365] Sorby, Presidential Address Geol. Soc. 1879; P. F. Kendall, Geol. Mag. 1883, p. 497; V. Cornish and P. F. Kendall, Geol. Mag. 1888, p. 60. See postea, Book V. § ii. 2.
[366] Proc. Roy. Soc. Edin. x. 1880, p. 508.

are continually falling to the bottom, where their remains accumulate as a soft ooze. On the floor of the West Indian seas, where an extraordinarily abundant fauna is supported by the plentiful supply of food brought by the great ocean currents which enter that region from the South Atlantic, a calcareous deposit is being formed out of the hard parts of the animals that live on the bottom (mollusks, echinoderms, corals, alcyonoids, annelids, crustacea, etc.), mingled with what may fall from the upper water. This deposit accumulates as a vast submarine plateau or series of broad banks, and is comparable in extent to some of the more important limestones of older geological time. Some portions of it have here and there (Barbadoes, Guadeloupe, Cuba, etc.) been elevated above the sea, so that its composition and structure can be studied. The organisms in these upraised limestones are the same as those which still live, and form a similar limestone in the surrounding seas. In Yucatan the rock is perforated with caverns, one of which is 70 fathoms deep.[867]

Here and there considerable deposits of broken shells have been produced by the accumulation of the excrement of fishes, as Verrill has pointed out on the northeastern coasts of the United States. Deposits of broken shells raised above sea-level either by breakers and winds or by subterranean movements are solidified into more or less compact shelly limestone. Extensive beds of this nature, composed mainly of species of *Arca*, *Lutraria*, *Mactra*, etc., form islands fronting the shores of Florida, and likewise underlie the soil of that State. Some of the shells still retain their colors. The whole mass is in layers 1 to 18 inches

[867] A. Agassiz, Amer. Acad. xi. 1882, p. 111; and his "Three Cruises of the 'Blake.'"

thick, quite soft before exposure to the air, but hardening thereafter, and much of it exhibiting a confused crystallization.[368] It is known locally as Coquina. The calcareous dunes of Bermuda have been already referred to (p. 573).

Coral-reefs.[369]—But the most striking calcareous formations now in progress are the reefs and islands of coral. These vast masses of rock are formed by the continuous growth of various genera and species of corals, in tracts where the mean temperature is not lower than 68° Fahr. Coral-growth is prevented by colder water, and by the fresh and muddy water discharged into the sea by large rivers. One of the essential conditions for the formation of coral-reefs is abundance of food for the reef-builders, and this seems to be best supplied by the great equatorial currents. It is observed that on the eastern coasts of Africa, Central America, and Australia, bathed by ocean currents, extensive coral-reefs flourish, while on the western coasts, in corresponding latitudes, where no such powerful currents flow, only isolated patches of coral exist.[370]

Darwin and Dana have shown that reef-building corals cannot live at depths of more than about fifteen or twenty

---

368 H. D. Rogers, Brit. Assoc. Rep. 1834, p. 11.

369 See Darwin, "The Structure and Distribution of Coral Islands," 1842; 2d edit. 1874; Dana, "Corals and Coral Islands," 1872; 2d edit. 1890; Jukes's "Narrative of Voyage of H.M.S. 'Fly,'" 1847; C. Semper, Zeitsch. Wissen. Zool. xiii. 1863, p. 558; Verhandl. Phys. Med. Gesellsch. Würzburg, Feb. 1868; "Die Philippinen und ihre Bewohner," 1869, p. 100; J. J. Rein, Senckenb. Naturf. Ges. Würzburg, 1869–70, p. 157. Murray, Proc. Roy. Soc. Edin. x. p. 505, xvii. 1889, p. 79; A. Agassiz, Mem. Amer. Acad. xi. 1882, p. 107; Bull. Mus. Compar. Zool. Harvard, 1889, No. 3. C. P. Sluiter, on the coral-reefs of the Java Sea, Natuurkund. Tijd. Nederlandsch. Indië. xlix. 1890; J. Walther, on the coral-reefs of the Sinai peninsula, Abhand. Math.-Phys. Kön. Sachs. Gesell. xiv. 1888; H. B. Guppy, Trans. Roy. Soc. Edin. xxxii. 1885, "The Solomon Islands," 1887; J. C. Bourne, Nature, 1888, pp. 414, 546; J. C. Wharton, ibid. p. 393; A. Heilprin, "The Bermuda Islands," 1889, Proc. Acad. Nat. Sci. Philadelphia, 1890, p. 303; Jukes Brown and Harrison, Barbadoes, Quart. Journ. Geol. Soc. xlvii. 1891, p. 197; Walther, Peterm. Mitth. Ergänz. No. 102, 1891.

370 A. Agassiz, Amer. Acad. xi. 1882, p. 120.

fathoms; they appear, indeed, not to thrive below a depth of six or seven fathoms. They cannot survive exposure to sun and air, and consequently are unable to grow above the level of the lowest tides. They are likewise prevented from growing by the presence of much mud in the water. Various observations and estimates have been made of the rate of growth of coral. Individual specimens of *Mœandrina* have been found to increase from half an inch to an inch in a year, and others of *Madrepora* have grown three inches in the same time.[371] Specimens of *Orbicella*, *Manicina*, and *Isophyllia*, taken from the submarine telegraph-cable between Havana and Key West, showed a growth of from one to two and a half inches in about seven years. A. Agassiz estimates that in the Florida reef the corals could build up a reef from a depth of seven fathoms to the surface in 1000 or 1200 years.[372] When coral-reefs begin to grow, either fronting a coast-line or on a submarine bank, they continue to advance outward, the living portion being on the outside, while on the inside the mass consists of dying or dead coral, which becomes a solid white compact limestone. In the coral area of the Pacific there are, according to Dana, 290 coral-islands, besides extensive reefs round other islands. The Indian Ocean contains some groups of large coral-islands; others occur in the Red Sea. Reefs of coral occur less abundantly in the tropical parts of the Atlantic, among the West Indian Islands and on the Florida coast, but they are absent from the Pacific side of Central America—a fact attributed by Prof. Agassiz not to a cold marine current, as suggested by Prof. Dana, but to the enormous amount of

---

[371] Dana, "Corals and Coral Islands," 2d edit. 1890, p. 123.

[372] Amer. Acad. xi. 1882, p. 129. See also Bull. Mus. Comp. Zool. Harvard, xx. 1890, p. 61.

mud poured into the sea on this side during the rainy season.[373] The great reef of Australia is 1250 miles long and from 10 to 90 miles broad.

Coral-rock, though formed by the continuous growth of the polyps, gradually loses any distinct organic structure, and acquires an internal crystalline character like an ancient limestone, owing to the infiltration of water through its mass, whereby calcium-carbonate is carried down and deposited in the pores and crevices, as in a growing stalactite. Great quantities of calcareous sand and mud are produced by the breakers which beat upon the outer edge of the reefs. This detritus is partly washed up upon the reefs, where, being cemented by solution and redeposit, it aids in their consolidation, sometimes acquiring an oolitic structure;[374] but much of it is swept away by the ocean currents and distributed over the sea-floor, the water becoming milky with it after a storm.[375] Around volcanic islands much lava detritus may be mixed with the coral-sand and mud. Thus at Hawaii, where great abrasion by the waves takes place on the ends of the lava-streams which have run out to sea, large quantities of olivine sand are formed, the grains of this mineral varying from the size of a bean or pea downward to the finest particles. This sand becomes mixed with the coral detritus and is also interstratified with it in layers.[376]

[373] Bull. Mus. Comp. Zool. xxiii. 1892, p. 70.

[374] See Dana's "Corals and Coral Islands," pp. 152, 194; A. Agassiz, Mem. Amer. Acad. xi. 1882, p. 128.

[375] A. Agassiz mentions that after a storm, the sea is sometimes discolored by this silt to a distance of six to ten miles from the outer reef, and he adds that he has seen between two and three inches of fine silt deposited in the interval between two tides after a prolonged storm: Amer. Acad. xi. p. 126. The total area of sea-floor covered with coral-sand and mud is estimated by Messrs. Murray and Irvine at 3,219,800 square miles. Proc. Roy. Soc. Edin. xvii. 1889, p. 82.

[376] W. L. Green, Journ. Roy. Geol. Soc. Ireland, iv. 1887, p. 140. This author suggestively points out the resemblance of such a mingling of calcareous material and magnesian silicate to the mingled limestones, serpentines and

As already mentioned (p. 491), the formation of coral-islands has been explained by Darwin on the hypothesis of

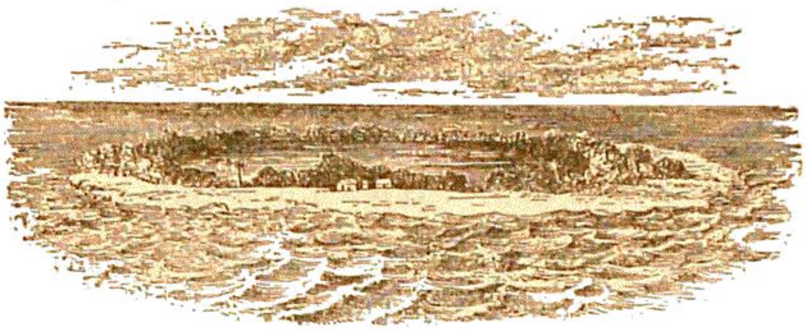


Fig. 182.—View of an Atoll or Coral-Island.

a subsidence of the sea-floor. The circular islands, or atolls, rising in mid-ocean, have the general aspect shown in Fig.

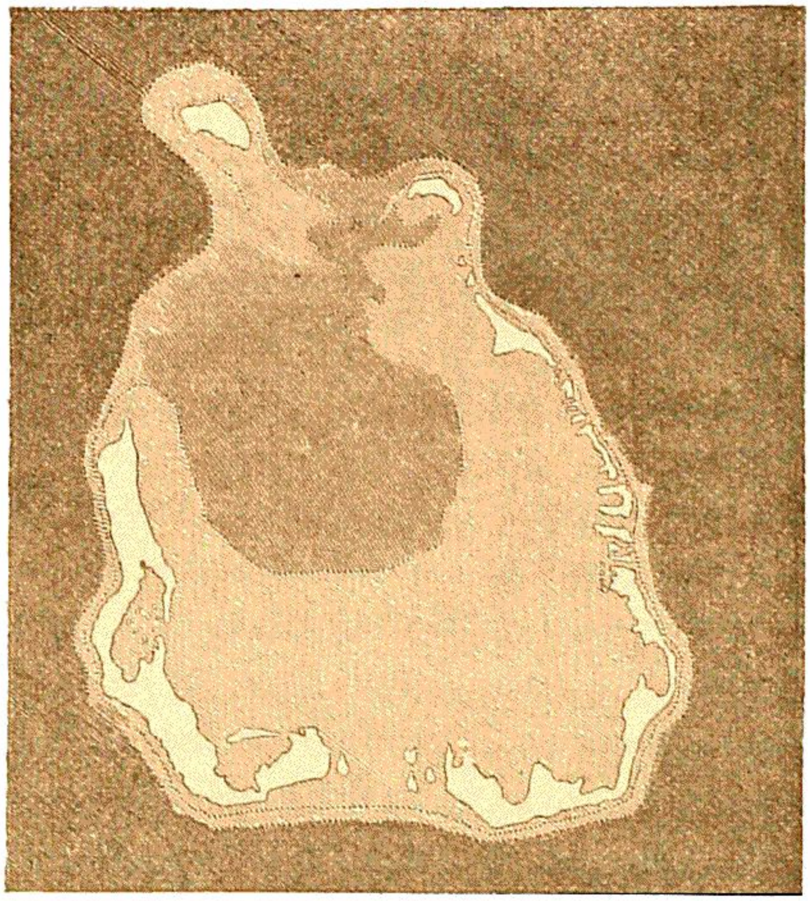


Fig. 183.—Chart of Keeling Atoll, Indian Ocean (after Darwin).
The white portion represents the reef above sea-level, the inner shaded space the lagoon, of which the deepest portion is marked by the darker tint.

182. Their external form may be understood from the chart (Fig. 183), and their structure and the character of their sur-

ophicalcites of the crystalline schists. Sollas, Proc. Royal Dublin Soc. 1891, p. 124.

face from the section (Fig. 184). They rise with sometimes tolerably steep slopes from a depth of 2000 feet and upward, until they reach the surface of the sea. But as the coral polyps do not live at a greater depth than about 15 or 20 fathoms, and could not have grown upward therefore from the bottom of a deep sea, Darwin inferred that the sites of these coral-reefs had undergone a progressive subsidence, the rate of their upward growth keeping pace, on the whole, with that of their depression. On this view, what is termed a *Fringing Reef* (A B, Fig. 185) would first be formed fronting the land (L) between the limit of the 20-fathom line and the sea-level (S S). Growing upward until it reached the surface of the water, it would be exposed to the dash of the waves, which would break off pieces of the coral and heap them upon the reef. In this way islets would be formed upon it, which, by successive accumulations of materials thrown up by the breakers or brought by winds, would

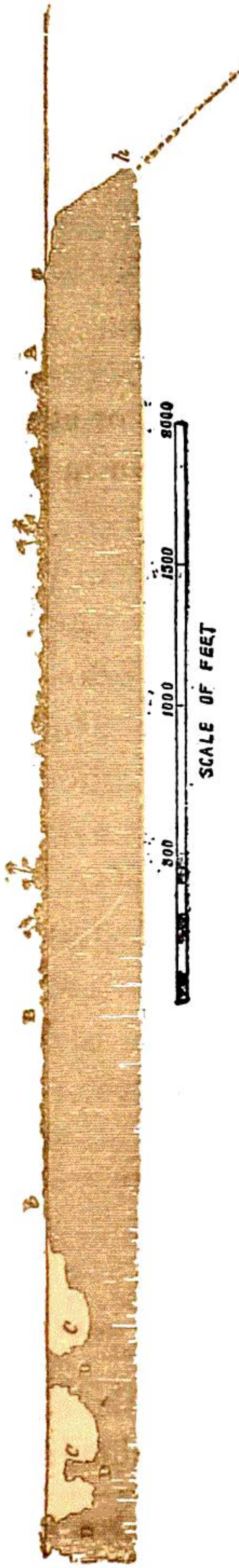


Fig. 184.—Section of a Coral-Reef.
A B, Portion above tide-mark (*a b*), covered with vegetation and habitable; C C, edge of lagoon, with insular masses of coral (D D); the open ocean lies to the right of the slope *a h*.

remain permanently above water. On these islets, palms and other plants, whose seeds might be drifted from distant or adjoining land, would take root and flourish. Inside the reef, there would be a shallow channel of water, communicating, through gaps in the reef, with the main ocean outside. Fringing reefs of this character are of common occurrence at the present time. In the case of a continent, they front its coast for a long distance, but they may entirely surround an island.

If, according to the Darwinian explanation, the site of a fringing reef undergoes depression at a rate sufficiently slow

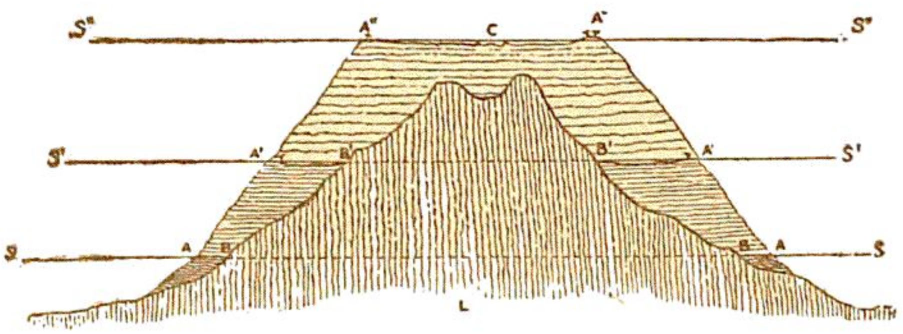


Fig. 185.—Diagram illustrating Darwin's theory of the formation of Atolls.

to allow the corals to keep pace with it, the reef may be conceived to grow upward as fast as the bottom sinks downward. As the reef grows mainly on its upper seaward edge, the lagoon channel inside will become deeper and wider, while, at the same time, the depth of water outside will increase until a *Barrier Reef* (A′ B′, Fig. 185) is formed. In Fig. 186, for example, the Gambier Islands (1248 feet high) are shown to be entirely surrounded by an interrupted barrier reef, inside of which lies the lagoon. Prolonged slow depression would continually diminish the area of the land thus encircled, while the reef might retain much the same size and position. At last the final peak of the original island might disappear under the lagoon (C, Fig. 185), and an *Atoll*, or true coral-island, would be formed (A″ A″, Fig. 185, and Figs. 182 and 183). Should any more rapid or sudden downward movement take place, it might carry the atoll down beneath the surface, like the Great Chagos bank in the Indian Ocean, which is a submarine atoll.

This simple and luminous explanation of the history of

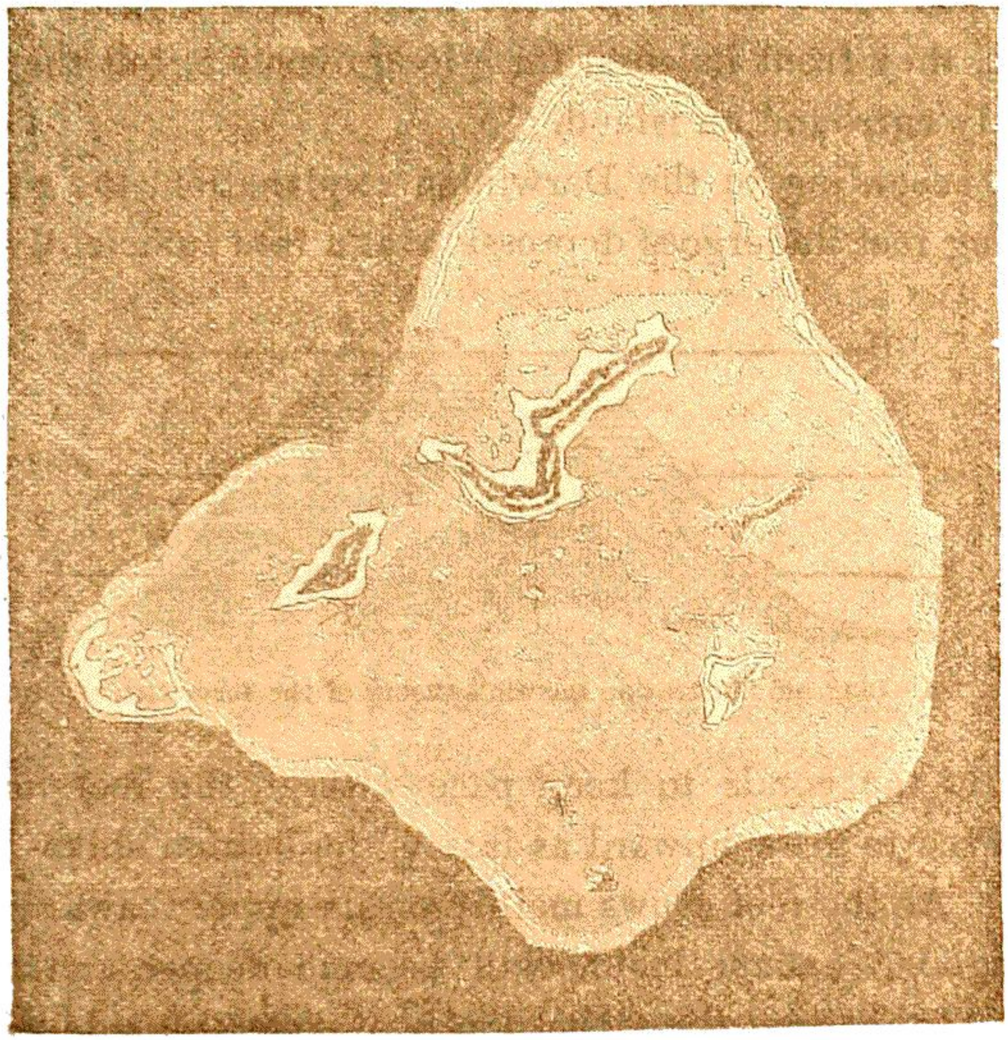


Fig. 186.—Chart of Gambier Islands, Pacific Ocean (after Beechy).

coral-reefs accorded well with all the known facts, and led up to the impressive conclusion that a vast area of the Pacific Ocean, fully 6000 geographical miles from east to west, has undergone a recent subsidence, and may be slowly sinking still.

Mr. Darwin's views having been universally accepted by geologists, coral-islands have been regarded with special interest as furnishing proof of vast oceanic subsidence. In the year 1868, C. Semper pointed to some cases of atolls which, he said, could not be explained by Darwin's theory. The Pelew Islands, at the western end of the Caroline archipelago, show true atolls at their northern extremity, while at their southern end, only 60 miles away, there are raised coral-reefs, and an island entirely destitute of reefs. Semper considered that the atolls had grown up under the influence of peculiar conditions of marine currents and erosion, simultaneously with elevation rather than subsidence.[377] In 1870 J. J. Rein cited the case of Bermuda as one capable of explanation by upgrowth of calcareous accumulations from the bottom without subsidence.[378] More recently, Mr. Murray, whose researches in the "Challenger" Expedition led him to make detailed examination of many coral reefs, has suggested that barrier-reefs do not necessarily prove subsidence, seeing that they may grow outward from the land upon the top of a talus of their own débris broken down by the waves, and may thus appear to consist of solid coral which had grown upward from the bottom during depression, although only the upper layer, 20 fathoms or thereabout in thickness, is composed of solid, unbroken coral growth. He points out that in the coral-seas the islands appear to have always started on volcanic ejections, at least that all the non-calcareous rock now visible is of volcanic origin. Where the submarine peak lay below the inferior limit of coral growth, it may have been brought up to the requisite level by the gradual accumulation of the remains

---

[377] See Semper's papers quoted in footnote on p. 814. In the Appendix to the second edition of his "Coral Reefs" (p. 223) Mr. Darwin replies to Semper's criticism, maintaining that his objections present no insuperable difficulty in the theory of subsidence.

[378] See paper cited in footnote on p. 814.

of organisms.[379] Where the original eminence rose above the sea, the projecting portion (Fig. 187) may be supposed to have been cut down to the lower limit of breaker action (*a a*), so as to offer a platform on which corals might build reefs (*i k*) up to the level of high water (*b b*). Or with less

Fig. 187.—Section of a volcanic cone of loose ashes supposed to have been thrown up on the sea-floor and to have reached the sea-level (*B.*).

denudation, or a loftier cone, a nucleus of the original volcano might remain as an island (Fig. 188), from the sides of which a barrier reef might grow outward, on a talus of its own débris (*r r*), and maintain a steep outer slope. According to this view the breadth of a reef ought, in some degree, to be a measure of its antiquity.

To the obvious objection that this explanation requires

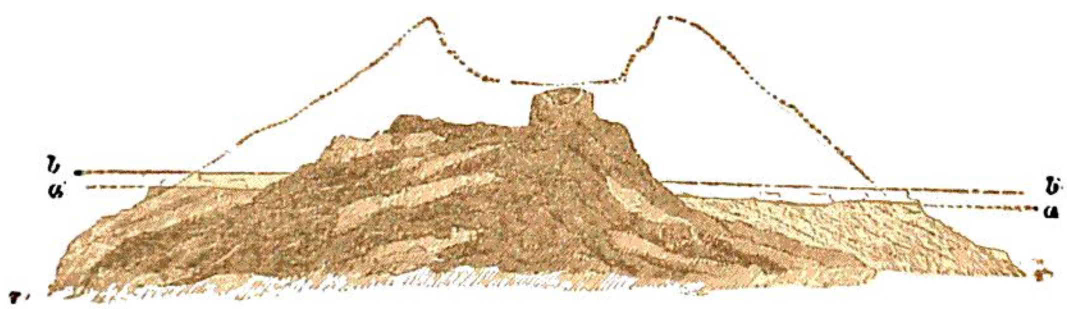


Fig. 188.—Section of denuded volcanic island with lava nucleus and surrounding coral-reef (*B.*).

the existence of so many volcanic peaks just at the proper depth for coral-growth, and that the number of true atolls is so great, Mr. Murray replies that in several ways the limit for the commencement of coral-growth may be reached. Volcanic islands may be reduced by the waves to mere

[379] "A submarine peak," says Prof. A. Agassiz, "is built up by the carcasses of the invertebrates that live upon it, and for which the pelagic fauna serves in part as food," Bull. Mus. Comp. Zool. Harvard, xvii. No. 3, 1889, p. 127.

shoals (Fig. 187), like Graham's Island, in the Mediterranean. On the other hand, submarine volcanic peaks, if originally too low, may conceivably be brought up to the coral-zone by the constant deposit of the detritus of marine life (foraminifera, radiolaria, pteropods, etc.), which, as above stated, is found to be very abundant in the upper waters, whence it descends as a kind of organic rain into the depths. Mr. Murray holds also that the dead coral, attacked by the solvent action of the sea-water, is removed in solution both from the lagoon (which may thus be deepened) and from the dead part of the outer face of the reef, which may in this way acquire greater steepness.[380]

Prof. A. Agassiz has arrived at similar conclusions from detailed explorations among the coral-reefs and submarine banks of the West Indian seas and the Hawaiian Islands. He believes that barrier-reefs and atolls have arisen without the aid of subsidence, upon a platform prepared for them by the upward growth of submarine calcareous banks, under the most favorable condition of ocean-currents, temperature, and food.[381]

That the widespread oceanic subsidence demanded by Darwin's theory cannot be demonstrated by coral-reefs must now, I think, be conceded. The coexistence of fringing and barrier-reefs, and of atolls, in the same neighborhood, with proofs of protracted stability of level or even with evidence of upheaval, likewise the successive stages whereby a true atoll may be formed without subsidence, have been demonstrated so clearly in the West Indian region, that we

---

[380] Proc. Roy. Soc. Edin. 1880, p. 505, ante, pp. 74, 741, 742.

[381] Amer. Acad. xi. 1882, p. 107; Bull. Mus. Comp. Zool. Harvard, xvii. 1889, No. 3. See also the papers of Messrs. Guppy, Wharton, Bourne and Sluiter, cited, ante, p. 814.

must admit the possibility that the same mode of formation may extend all over the coral-seas. At the same time, it must be granted that the necessary conditions for the formation of barrier-reefs and atolls might sometimes be brought about by subsidence. So long as a suitable bottom is provided for coral-growth it is probably immaterial whether this is done by the submergence of land or by the ascent of the sea-floor. That subsidence has in some cases taken place seems to be proved by the depth of some atoll-lagoons—40 fathoms—unless this depth can be supposed to be due to solution by sea-water, and not to the progressive deepening during a subsidence with which the upward growth of the reef could keep pace.

Ooze.—The bed of the Atlantic and other oceans is covered with a calcareous ooze formed of the remains of *Foraminifera*, chiefly species of the genus *Globigerina*. It has been observed that in these deep-sea deposits, the larger and relatively thinner pelagic shells are rare or absent at greater depths than 2000 fathoms, while the thicker-shelled varieties abound. This has been referred to the solvent action of sea-water, whereby the more fragile forms are attacked and removed in solution (ante, pp. 74, 741). Among abysmal deposits, foraminiferal ooze ranks next in abundance to the red and gray clays of the deep sea (p. 767). It is a pale-gray 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. It covers an area of the North Atlantic probably not less than 1300 miles from east to west, by several hundred miles from north to south. The total area of ocean-bottom occupied by globigerina-ooze is estimated at 47,752,500 square miles, the mean depth of the surface of the deposit below sea-level is computed to be 1996 fathoms, and the mean proportion of carbonate of lime in the *ooze* 64·53 per cent.[882]

The consolidation of a soft calcareous ooze or a mass of broken shells, corals, and other calcareous organisms, effected by the percolation of water containing carbonic acid (ante, pp. 620, 762, 816), is most rapid with copious evaporation, as, for instance, on coral-reefs where exposure to the air in the interval between two tides suffices for the deposit of a thin crust of hard limestone over a surface of broken coral or coral-sand.[883] Recently upraised limestone and coral-rock have in some places assumed a crystalline structure by this process, and the more delicate organisms have disappeared from them. But the calcareous deposits may acquire, even under the sea, sufficient cohesion to be capable of being broken up into blocks. On the submarine plateau off Florida, the trawl or dredge frequently brings up large fragments of the limestone now in course of formation on the bottom, consisting of the dead carcasses of the very species that live upon the surface of the growing deposit.[884]

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

---

882 Murray and Irvine, Proc. Roy. Soc. Edin. xvii. 1889, p. 82.

883 A. Agassiz, Amer. Acad. xi. 1882, p. 128.

884 A. Agassiz, op. cit. p. 112. An account of the upraised oceanic deposits of Barbadoes is given by Messrs. Jukes Brown and Harrison, Quart. Journ. Geol. Soc. xlviii. 1892, p. 170. Some of these deposits present a close resemblance to those ascertained by dredging to be seen in progress of accumulation in deep parts of the ocean.

almost entirely of *Radiolaria*. These minute organisms occur, indeed, more or less abundantly in almost all deep oceanic deposits. From the deepest sounding taken by the "Challenger" (4475 fathoms, or more than 5 miles) a radiolarian ooze was obtained (Fig. 189). The spicules of sponges likewise furnish materials toward these siliceous accumulations. The number of marine plants and animals which

Fig. 189.—Radiolarian Ooze,

Dredged up by the "Challenger" Expedition, from a depth of 4475 fathoms, in Lat. 11° 24′ N., Long. 143° 10′ E. Magnified 100 diameters. This is from the deepest abyss whence organisms have yet been obtained.

secrete silica is so great, and the proportion of that constituent in sea-water so minute, that some difficulty has been felt to account satisfactorily for the vast quantities of silica continually being abstracted from the ocean by organic agencies. Messrs. Murray and Irvine, however, as already stated, have shown that an appreciable amount of fine clay is present even in the water of mid-ocean, and they have ascertained by actual experiments with living diatoms that these plants can obtain their silica from diffused clay in suspension.[385]

3. Phosphatic deposits,[386] 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 (p. 248). 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. In 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. From observations made on phosphatic deposits such as the phosphatic chalk of France, Belgium and England, it is evident that phosphate of lime derived from the decomposition of animals (fish, etc.) may be held in solution and gather round any organic body, or fill its cavities and replace original carbonate of lime. Grains and concretions

---

[385] Murray and Irvine on siliceous deposits of modern seas, Proc. Roy. Soc. Edin. xviii. 1891, p. 229, and ante, p. 756.

[386] A useful compendium of information on these deposits is given by R. A. F. Penrose in Bull. U. S. Geol. Surv. No. 46, 1888, already cited (p. 248).

of phosphate are thus formed, especially in the interior of shells and foraminifera.[387]

Wherever terrestrial mammalia congregate, and especially where they die and leave their carcasses, phosphatic deposits may be formed if the conditions are favorable for the preservation of the remains. Caves haunted by hyenas serve as receptacles not only for the bones and excrement of these animals but also for bones of the various animals which they have dragged there as food. Hence in limestone countries "osseous breccias" are often found below the layer of stalagmite on the floor. Again, along the swampy margins of lakes and salt-marshes the bodies of wild animals are often mired in the boggy ground and perish there, and their bodies gradually sink below the surface. Hence phosphatic accumulations arise sometimes on an extensive scale, as has happened in different parts of the United States.[388]

In connection with the organic deposits of the sea-floor, further reference may be made here to the chemical processes in progress there, and to the probable part taken in these processes by living organisms and decaying animal matter. The transformation of sulphate of lime into carbonate, which may now be regarded as the chief source of the calcareous constituents of marine plants and animals, takes place on a gigantic scale in the ocean. The precipitation of manganic oxide and its segregation in concretions, often round organic centres (p. 769), presents a close analogy to the formation of concretionary bog iron-ore through the operation of the humus acids in stagnant water. The crys-

---

[387] A. F. Renard and T. Cornet, Bull. Acad. Roy. Belg. xxi. 1891, p. 126. A. Strahan, Quart. Journ. Geol. Soc. xlvii. 1891, p. 356.

[388] Penrose, Bull. U. S. Geol. Surv. No. 46, 1888, p. 127.

tallization of silicates observed during the "Challenger" expedition is possibly also to be connected with the action of organic compounds (p. 770). The formation of flint concretions has been for many years a vexed question in geology. The constant association of flints with traces, more or less marked, of former abundant siliceous organisms seems to make the inference irresistible that the substance of the flint has been precipitated through the agency of these creatures. The silica has first been abstracted from sea-water by living organisms. It has then been redissolved and redeposited (probably through the agency of decomposing organic matter), sometimes in amorphous concretions, sometimes replacing the calcareous parts of echini, mollusks, etc., while the surrounding matrix was, doubtless, still a soft watery ooze under the sea.[389]

§ 4. 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

---

[389] See Wallich, Q. J. Geol. Soc. xxxvi. p. 68; Sollas, Ann. and Mag. Nat. Hist. 5th series, vi. p. 437; and ante, pp. 247, 811; Brit. Assoc. 1882, sects. p. 549; Hull and Hardman, Trans. Roy. Dublin Soc. new series, 1878, vol. i. p. 71. Julien observes that a substance corresponding to humus appears to enter universally into the constitution of the oceanic oozes, resulting from the decomposition of organisms and containing a high percentage of silica (Proc. Amer. Assoc. xxviii. p. 359). Consult also the paper of Messrs. Murray and Irvine already cited (Proc. Roy. Soc. Edin. xviii. 1891, p. 229) and the suggestive experiments there described as to the solution of silica in sea-water containing living and dead organisms.

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 burned and barren, or washed bare of their soil. It is only in comparatively recent years that he has learned 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 work it is impossible to give more than merely a brief outline of so vast a subject.[390] The action of man is necessarily confined mainly to the land, though it has also to some extent influenced the marine fauna. It may be witnessed on climate, on the flow of water, on the character of the terrestrial surface, and on the distribution of life.

1. On Climate.—Human interference affects meteorological conditions—(1) by removing forests and laying bare

---

[390] See Marsh's "Man and Nature," a work which, as its title denotes, specially treats of this subject, and of which a new and enlarged edition was published in 1874 under the title of "The Earth as modified by Human Action." It contains a copious bibliography. See also Rolleston, Jour. Roy. Geog. Soc. xlix. p. 320, and works cited by him, particularly De Candolle, "Geographie botanique raisonneé," 1855; Unger's "Botanische Streifzüge," in Sitzber. Vienna Acad. 1857–59; J. G. St. Hilaire, "Histoire naturelle generale des Règnes Organiques," tom. iii. 1862; Oscar Peschel, "Physische Erdkunde"; Link, "Urwelt und Alterthum," 1822; G. A. Koch, Jahrb. Geol. Reichsanst. xxv. 1875, p. 114.

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, while in the Tyrol the great increase and destructiveness of the debacles has been attributed to the wholesale deforesting of that region, and the consequent exposure of the soil to rain and melted snow; (2) by drainage, the effect of this operation being to remove rapidly the discharged rainfall, to raise the temperature of the soil, 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 circulation of water over the land. (2) By the drainage-operations, which cause the rain to run off more rapidly than before, he increases floods in rivers. (3) By wells, bores, mines, or other subterranean works, he interferes with 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 moun-

tain 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 herbage 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 pavement of the Cæsars, and this again above the roadways of the early Republic. Over cultivated fields potsherds are turned up in abundance by the plow. The loam has risen within the walls of our 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 dominion 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 unforeseen 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 from 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.[391]

This outline may suffice to indicate how important is the place filled by man as a geological agent, and how in future ages the traces of his interference may introduce an element of difficulty or uncertainty into the study of geological phenomena.

---

[391] See on the subject of man's influence on organic nature, the paper by Prof. Rolleston, quoted on p. 830, and the numerous authorities cited by him.

BOOK IV

GEOTECTONIC (STRUCTURAL) GEOLOGY

OR THE ARCHITECTURE OF THE EARTH'S CRUST

THE nature of minerals and rocks and the operations of the different agencies by which they are produced and modified having been discussed in the two foregoing books, there remains for consideration the manner in which these materials have been arranged so as to build up the crust of the earth. Since by far the largest visible portion of this crust consists of sedimentary or aqueous rocks, it will be of advantage to treat of them first, noting both their original characters, as resulting from the circumstances under which they were formed, and the modifications subsequently effected upon them. Many superinduced structures, not peculiar to sedimentary, but occurring more or less markedly in all rocks, may be conveniently described together. The distinctive characters of the igneous or eruptive rocks, as portions of the architecture of the crust, will then be described; and lastly, those of the crystalline schists and other associated rocks to which the name of metamorphic is usually applied.

PART I. STRATIFICATION AND ITS ACCOMPANIMENTS

The term "stratified," so often applied as a general designation to the aqueous or sedimentary rocks, expresses their leading structural feature. Their materials, laid down for the most part on the bed of the sea and the floors of lakes and rivers, under conditions which have been already discussed in Book III., are disposed in layers or strata, an arrangement characteristic of them alike in hand-specimens and in cliffs and mountains (Figs. 190, 191, 252 and 253). Not that every morsel of aqueous rock exhibits evidence of stratification. But it is this feature which in a sufficiently large mass of material is least frequently absent. The general characters of stratification will be best understood from an explanation of the terms by which they are expressed.

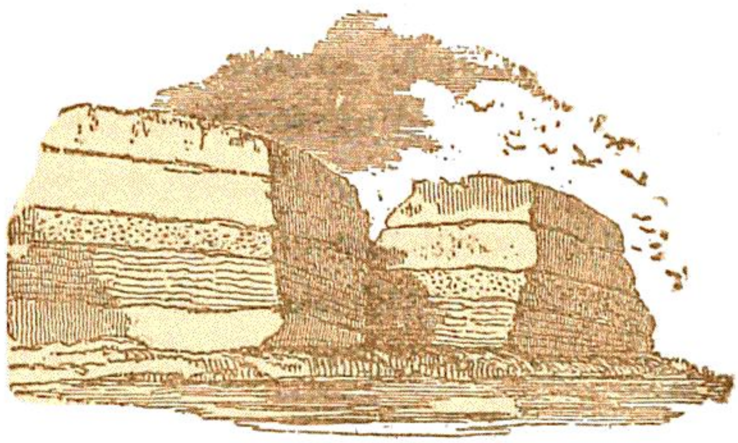


Fig. 190.—Sea-cliff showing a series of Stratified Rocks (*B.*).

Forms of Bedding.—Laminæ are the thinnest paper-like layers in the planes of deposit of a stratified rock. Such fine layers only occur where the material is fine-grained, as in mud or shale, or where fine scales of some mineral have been plentifully deposited, as in micaceous sandstone. In some laminated rocks, the laminæ cohere so firmly that they can hardly be split open, and the rock will break more readily across them than in their direction. More usually, however, the planes of lamination serve as convenient divisional surfaces by means of which the rock can be split open.[1] The cause of this structure has been generally assigned to

[1] M. Daubrée has proposed the term "diastrome" to express the splitting of rocks along their bedding planes. Bull. Soc. Geol. France (3), x. p. 137.

intermittent deposit, each lamina being assumed to have partially consolidated before its successor was laid down upon it. Mr. Sorby, however, has recently suggested that in fine argillaceous rocks it may be a kind of cleavage-structure (see p. 534), due to the pressure of the overlying rocks, with the consequent squeezing out of interstitial water and the rearrangement of the argillaceous particles in lines perpendicular to the pressure.[2]

Much may be learned as to former geographical and geological changes by attending to the characters of strata. In Fig. 191, for example, there is evidence of a gradual diminution of movement in the waters in which the layers of sediment were deposited. The conglomerate (*a*) points to currents of some force; the sandstones (*b c d*) mark a progressive quiescence and the advent of finer sediment; the shales (*e*) show a deposition of fine mud and accretion of ferrous carbonate into nodules round organic remains; while the shell-limestone (*f*) proves that the water no longer carried much sediment, but had become clear enough for an abundant growth of marine organisms. The existence, therefore, of alternations of fine laminæ of deposit may be conceived as pointing to tranquil conditions of slow intermittent sedimentation, where silt has been borne at intervals and has fallen over the same area of undisturbed water. Regularity of thickness and persistence of lithological char-

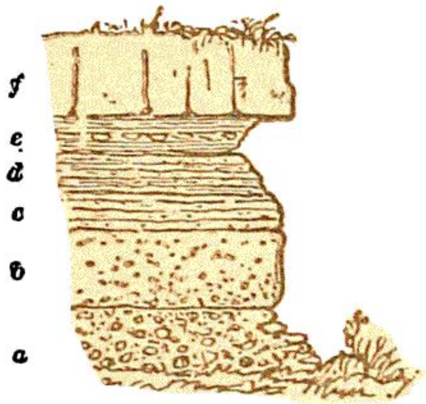


Fig. 191.—Section of Stratified Rocks.
a, conglomerate; *b*, thick-bedded pebbly sandstone; *c*, thin-bedded sandstone; *d*, shelly sandstone; *e*, shale with ironstone nodules; *f*, limestone with marine organisms.

[2] Quart. Journ. Geol. Soc. xxxvi. p. 67, 1880.

acters among the laminæ may be taken to indicate periodic currents, of approximately equal force, from the same quarter. In some cases, successive tides in a sheltered estuary may have been the agents of deposition. In others, the sediment was doubtless brought by recurring river-floods. A great thickness of laminated rock, like the massive shales of Palæozoic formations, suggests a prolonged period of quiescence, and probably, in most cases, slow, tranquil subsidence of the sea-floor. On the other hand, the alternation of thin bands of laminated rock with others coarser in texture and non-laminated, indicates considerable oscillation of currents from different quarters bearing various qualities and amounts of sediment.[3]

Strata or Beds are layers of rock varying from an inch or less up to many feet in thickness. A stratum may be made up of numerous laminæ, if the nature of the sediment and mode of deposit have favored the production of this structure, as has commonly been the case with the finer kinds of sediment. In materials of coarser grain, the strata, as a rule, are not laminated, but form the thinnest parallel divisions. Strata, like laminæ, sometimes cohere firmly, but are commonly separable with more or less ease from each other. In the former case, we may suppose that the lower bed before its consolidation was followed by the deposit of the upper. The common merging of a stratum into that which overlies it must no doubt be regarded as evidence of more or less gradual change in the conditions of deposit. Where the overlying bed is abruptly separable from that below it, the interval was probably of some dura-

---

[3] For a series of experiments to illustrate the origin of the sedimentation of the coal-measures, see H. Fayol, Bull. Soc. "Industrie Minerale, St. Etienne," 2me ser. xv. 1886. "Etudes sur le terrain houiller de Commentry," with atlas.

tion, though occasionally the want of cohesion may arise from the nature of the sediment, as, for instance, where an intervening layer of mica-flakes has been laid down. A stratum may be one of a series of similar beds in the same mass of rock, as where a thick sandstone includes many individual strata, varying considerably in their respective thicknesses; or it may be complete and distinct in itself, as where a band of limestone or ironstone runs through the heart of a series of shales. As a general rule, the conclusion appears to be legitimate that stratification, when exceedingly well-marked, indicates slow intermittent deposition, and that when weak or absent it points to more rapid deposition, intervals and changes in the nature of the sediment and in the direction of force of the transporting currents being necessary for the production of a distinctly stratified structure.

Lines due to original stratification must be carefully distinguished from other divisional planes which, though somewhat like them, are of entirely different origin. Five kinds of fissility may be recognized among rocks—1st, *lamination* of original deposit; 2d, *cleavage*, as in slate; 3d, *shearing*, as near faults and thrust-planes (pp. 537, 538); 4th, *foliation*, as in schists; 5th, *flow-structure*, when extremely developed in some lavas, wherein, by the development of steam-holes or spherulitic concretions and the drawing-out of these into planes during the movement of the molten mass, a kind of fissility is produced which at first might be mistaken for the lamination of deposit. Close-set joints likewise give rise to divisional planes, which, like cleavage, may now and then deceive an observer by their resemblance to stratification.

Originally the planes of stratification, in the great majority of cases, were nearly horizontal. As most sedimentary rocks are of marine origin, and have accumulated on the shallower slopes of the sea-floor, they have generally had from the first a slight inclination seaward; but, save on rapidly shelving shores, the angle of declivity has been usually so slight as to be hardly appreciable by the eye. Slight departures from this predominant horizontality would be caused where sediment accumulated unequally, or where the floor on which deposition took place was of an undulating or more markedly uneven character.

False-bedding, Current-bedding.—Some strata, particularly sandstones, are marked by an irregular lamination, wherein the laminæ, though for short distances parallel to each other, are oblique to the general stratification of the mass, at constantly varying angles and in different directions (*a b c d* in Fig. 192). This

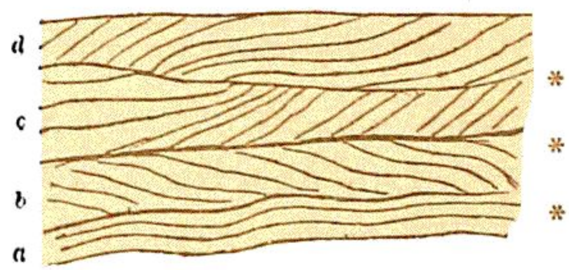


Fig. 192.—Section of False-bedded Strata.

structure, known as false-bedding or current-bedding, points to frequent changes in the direction of the currents by which the sediment was carried along and deposited. Sand pushed over the bottom of a sheet of water by varying currents tends to accumulate irregularly in banks and ridges, which often advance with a steep slope in front. The upper and lower surfaces of the bank or bed of sand (* * in Fig. 192) may remain parallel with each other as well as with the underlying bottom (*a*), yet the successive laminæ composing it may lie at an angle of 30° or even more. We may illustrate this structure by the familiar formation of a railway embankment. The top of the embankment, on which the permanent way is to be laid, is kept level; but the advancing end of the earthwork shows a steep slope over which the workmen are constantly discharging wagon-loads of rubbish. Hence the embankment, if cut open longitudinally, would present a "false-bedded" structure, for it would be

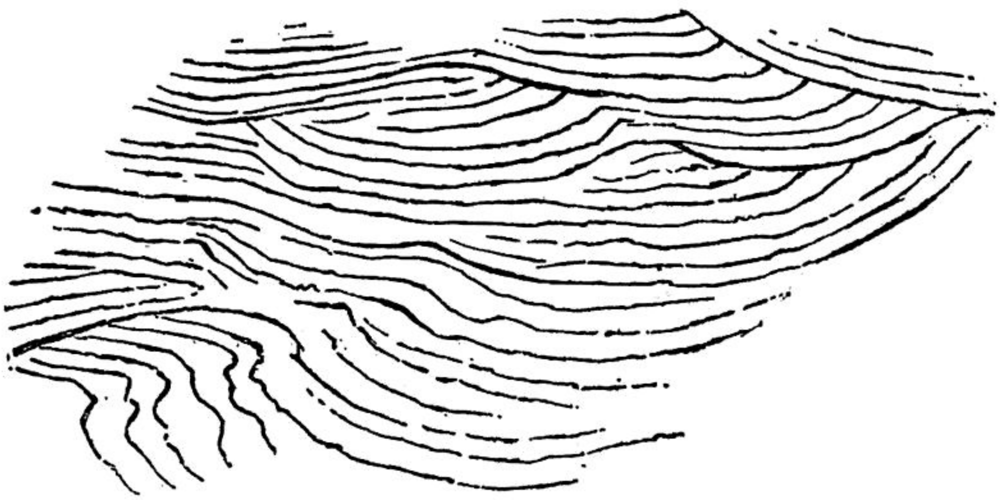


Fig. 193.—Plan of upper surface of a False-bedded Coal-measure Sandstone, Nolton Haven, Pembrokeshire. (By the late Professor John Phillips.)

found to consist of many irregular layers inclined at a high angle in the direction in which the formation of the mound had advanced. Among geological formations of all ages, occasional sections of the upper surfaces of such false-

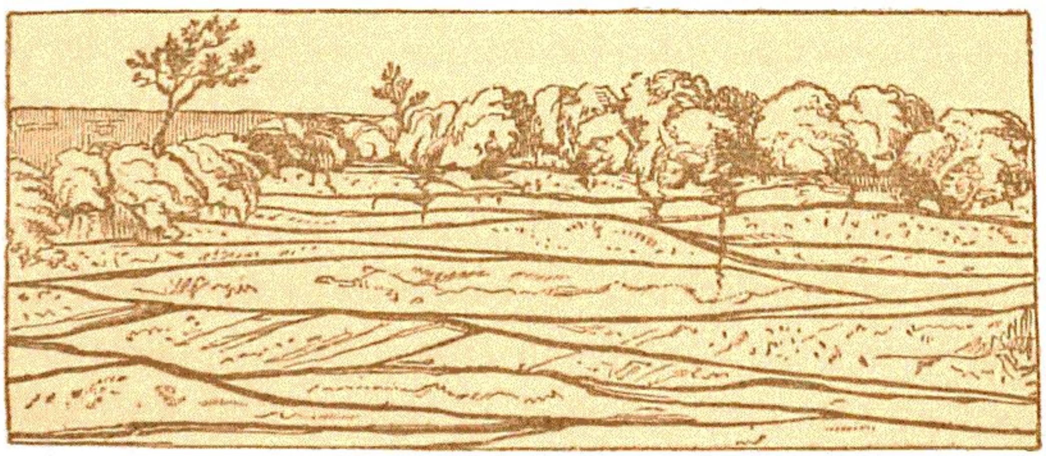


Fig. 194.—False-bedded Strata, Old Red Sandstone, Ross, Herefordshire. (By the late Sir Henry James, R.E.)

bedded strata show the singular irregularity of the structure, and bring vividly before the imagination the feeble shifting currents by which the sediment was drifted about in the shallow water where it accumulated (Fig. 193). A noticeable feature is the markedly lenticular character of false-bedded strata. Even where the usual diagonal lamination is feeble or absent this lenticular structure may remain distinct (Fig. 194). Examples may also be observed, in which, while all the beds are well laminated, in some the

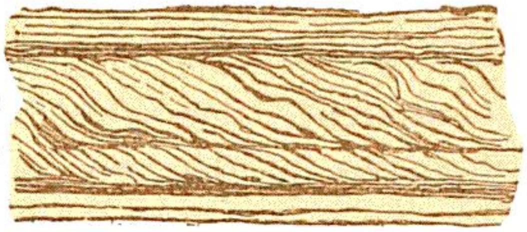


Fig. 195.—Ordinary lamination and current-lamination, Upper Old Red Sandstone, Clowes Bay, Waterford (*B.*).

a, *d*, *e*, beds of sand and silt deposited horizontally and apparently from mechanical suspension; *b*, *c*, beds of sand which have been pushed along the bottom.

laminæ run parallel with the general bedding, and in others obliquely (Fig. 195). Though current-bedding is most frequent among sandstones, or markedly arenaceous strata, it may be observed occasionally in detrital formations of organic origin, as in a section (Fig. 196) by De la Beche,

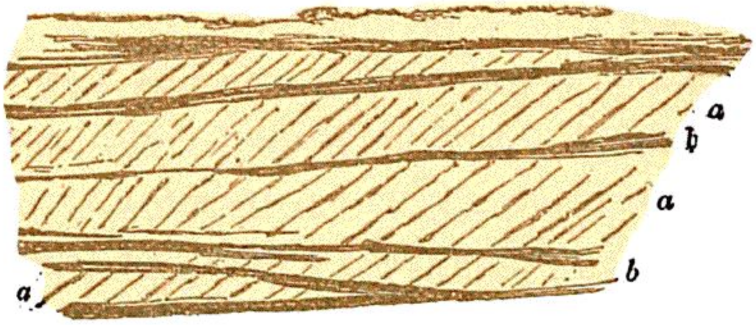


Fig. 196.—Section in the Forest Marble, the Butts, Frome, Somerset (*B.*).

a, *a*, beds formed of broken shells, fish-teeth, pieces of wood, and oolitic grains; *b*, *b*, layers of clay.

where a portion of one of the calcareous members of the Jurassic series of England consists of beds composed mostly of organic fragments with a strongly marked current-bedding (*a a*), while others, formed of muddy layers and not obliquely laminated (*b b*), point to intervals when, with the cessation of the silt-bearing currents, the water became still enough to allow the mud suspended in it to settle on the bottom.[4]

Intercalated Contortion.—Diagonal lamination is sometimes contorted as well as steeply inclined, and highly contorted beds are interposed between others which are undisturbed and horizontal. Curved and contorted lamination is of frequent occurrence among Palæozoic sandstones. In Fig. 196 an example is given from one of the oldest formations in Britain, and in Fig. 197 another

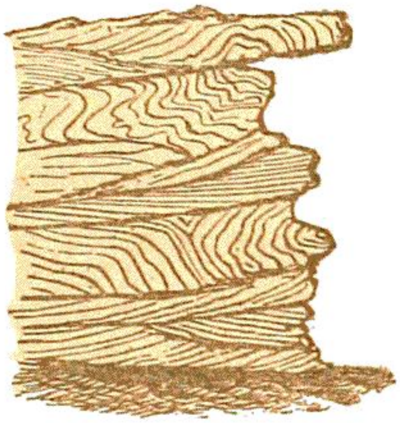


Fig. 197.—Contorted false-bedding, Torridon Sandstone, Gairloch.

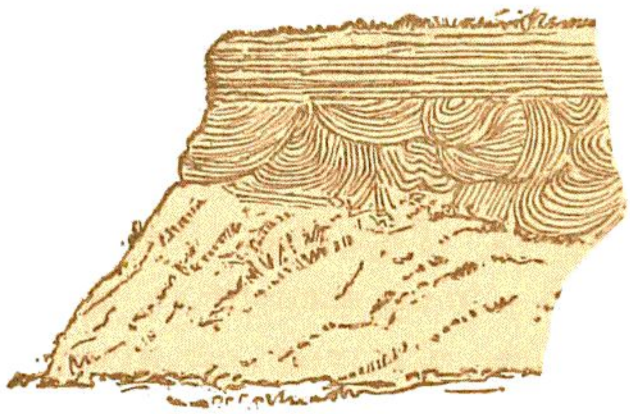


Fig. 198.—Contorted Post-Tertiary sands and clays, near Forres.

from one of the youngest. The cause of this structure is not well understood. Among glacial deposits local examples of contortion occur, which may be accounted for by the intercalation and subsequent melting of sheets of frozen mud, or by the stranding of heavy masses of drift-ice upon still unconsolidated sand and mud. The removal of mineral matter in solution (as among saliferous and gypseous deposits) leads to the subsidence and crumpling of overlying beds. The hydration of anhydrite (pp. 506, 587), by aug-

[4] "Geological Observer," p. 536. The memoir by H. Fayol cited on p. 837 is accompanied with an atlas which contains many excellent illustrations of the exceedingly irregular stratification of the Coal-measures.

menting the volume of the mass, subjects the adjacent strata to crushing and contortion. It is possible that some of the extraordinary labyrinthine and complex contortions of certain schistose rocks may be due to the subsequent crumpling of strata already full of diagonal or contorted lamination.

Irregularities of Bedding due to Inequalities of Deposition or of Erosion.—A sharp ridge of sand or gravel may be laid down under water by current-

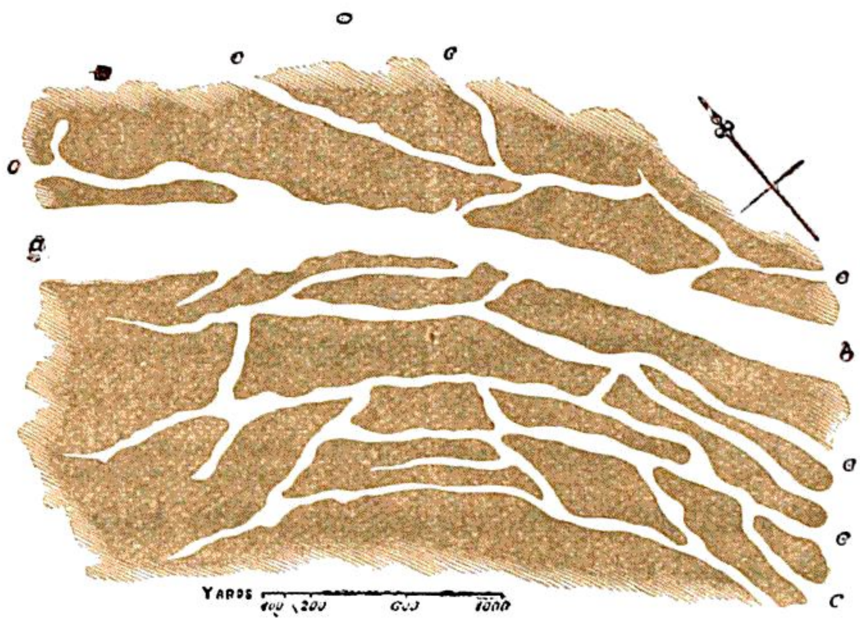


Fig. 199.—Plan of channels in coal, Forest of Dean (after Buddle).

action of some strength. Should the motion of the water diminish, finer sediment may be brought to the place and be deposited around and above the ridge. In such a case, the stratification of the later accumulation may end off abruptly against the flanks of the older ridge, which will appear to rise up through the overlying bed. Appearances of this kind are not uncommon in coal-fields, where they are known to the miners as "rolls," "swells," or "horses' backs." A structure exactly the reverse of the preceding, where a stratum has been scooped out before the deposition of the layers which cover it, has also often been observed in mining for coal, when it is termed a "want." Channels have been cut out of a coal-seam, or rather out of the bed of vegetation which ultimately became coal, and these winding and branching channels have been filled up with sandy or muddy sediment. The accompanying plan (Fig. 199) represents a portion of a remarkable series of such channels traversing the Coleford High Delf coal-seam in the Forest of Dean. The chief one, locally known as the "Horse" (*a b*), has been traced for about two miles, and varies in width from 170 to 340 yards. It is joined by smaller tributaries (*c c*), which run for some way approximately parallel to it. The coal has either been prevented from accumulating in contemporaneous water-channels, or, while still in the

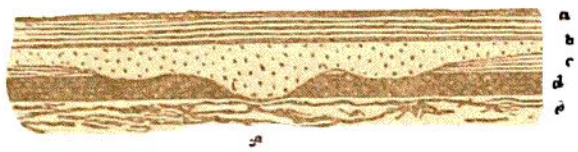


Fig. 200.—Section of a channel in a coal-seam (*B.*).

condition of soft bog-like vegetation, has been eroded by streamlets flowing through it.[5] A section drawn across such a buried channel exhibits the structure represented in Fig. 200, where a bed of fire-clay (*e*), full of roots and evidently an old soil, supports a bed of coal (*d*) and of shale (*c*), which, during the deposition of this series of strata, have been cut out into a channel at *f*. A deposition of sand (*b*) has then filled up the excavation, and a layer of mud (*a*) has covered up the whole.

Currents of very unequal force and transporting power may alternate in such a way that after fine silt has for some time been accumulated, coarse shingle may next be swept along, and may be so irregularly bedded with the softer

[5] Buddle, Geol. Trans. vi. 1842, p. 215.

strata as to simulate the behavior of an intrusive rock (Fig. 201).[6] The section (Fig. 202) taken by De la Beche from a cliff of Coal-measures on the coast of Pembrokeshire, shows a deposit of shale (*a*) that during the course of its formation

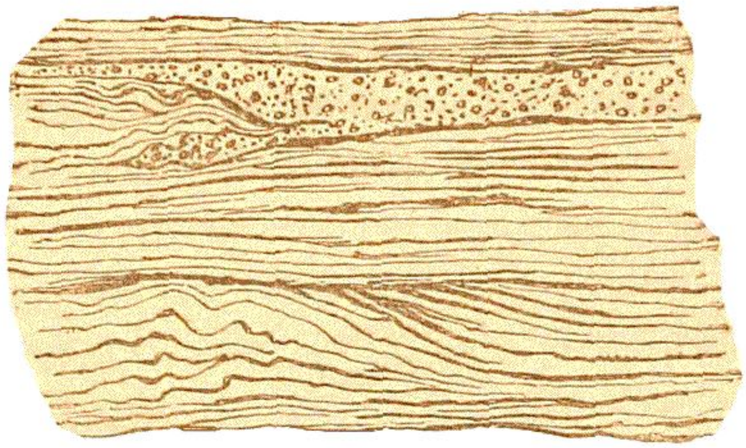


Fig. 201.—Irregular bedding of coarse and fine Lower Silurian detritus. Flanks of Glydyr, N. E. of Snowdon (*B.*).

was eroded by a channel at *b*, into which sand was carried; after which, the deposit of fine mud recommenced, and similar shale was again laid down upon the top of the sandy layer, until, by a more potent current, the shale deposit was cut away on the left side of the section, and a series of sand-

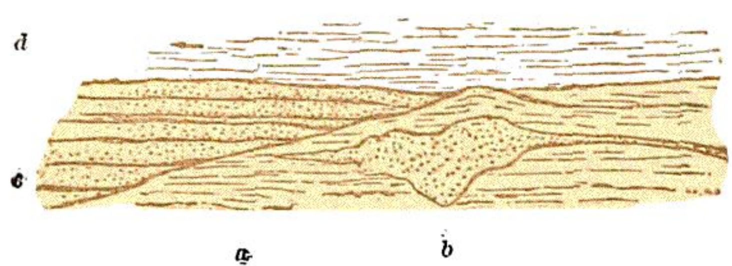


Fig. 202.—Contemporaneous Erosion and Deposit (*B.*).

beds (*c*) was laid down upon its eroded edges. An interruption of this kind, however, may not seriously disturb the earlier conditions of a deposit, which, as shown in the same section, may be again resumed, and new layers (*d*) may be laid down conformably over the whole. Among the lessons

[6] De la Beche, "Geol. Observer," p. 533.

to be learned from such sections of local irregularity, one of the most useful is the reminder that the inclination of strata may not always be due to subterranean movement. In Fig. 203, for example, the lower strata of shale and sandstone are nearly horizontal. The upper thick sandstone (*b*′) has been cut away toward the left, and a series of shales (*a*′) and a coal-seam (*c*′) have been deposited against and over it. If the sandstone was then level, the shales must have been laid

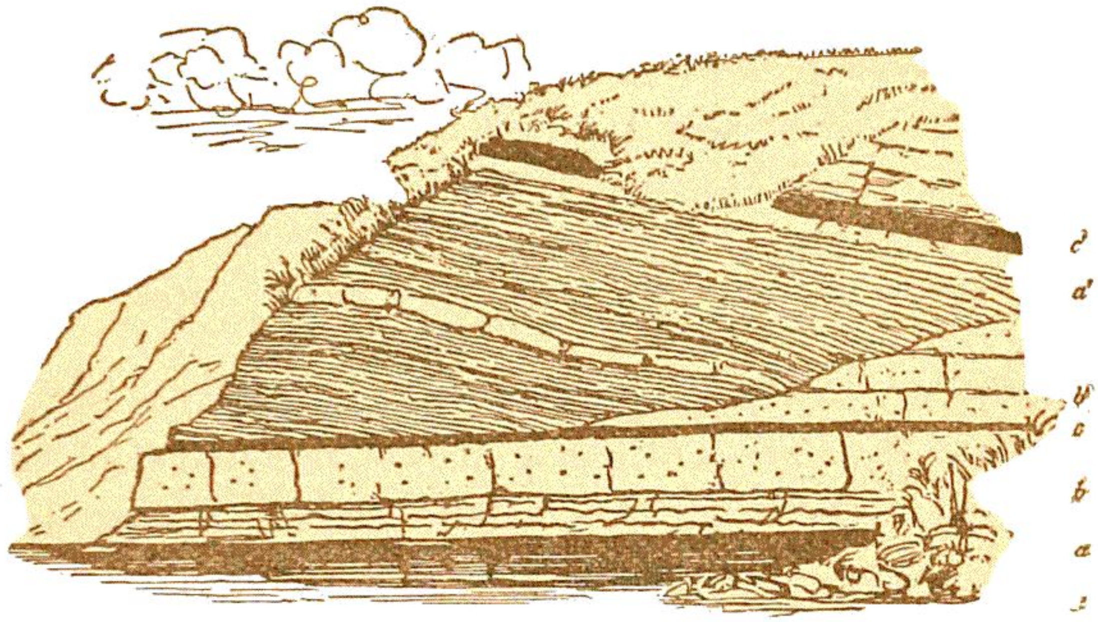


Fig. 203.—Contemporaneous Erosion with inclined and horizontal deposits, in Coal-measures, Kello Water, Sanquhar, Dumfriesshire.
a, *a*′, shales and ironstones; *b*, *b*′, sandstones; *c*, *c*′, coal-seams.

down at a considerable angle, or, if these were deposited in horizontal sheets, the earlier sandstone must have accumulated on a marked slope. As deposition continued, the inclined plane of sedimentation would gradually become horizontal until the strata were once more parallel with the series *a b c* below. A structure of this kind, not infrequent in the Coal-measures, must be looked upon as a larger kind of false-bedding, where, however, terrestrial movement may sometimes have intervened.

In the instances here cited, it is evident that the erosion took place, in a general sense, during the same period with the accumulation of the strata. For, after the interruption was covered up, sedimentation went on as before, and there is usually an obvious close sequence between the continuous strata. Though it may be impossible to decide as to the relative length of the interval that elapsed between the formation of a given stratum and that of the next stratum which lies upon its eroded surface, or to ascertain how much depth of rock has been removed in the erosion, yet, when the structure occurs among conformable strata, evidently united as one lithologically continuous series of deposits, we may reasonably infer that the missing portions are of small moment, and that the erosion was merely due to the irregular and more violent action of the very currents by which the sediment of the successive strata was supplied.

The case is very different when the eroded strata, besides being inclined at a different angle from those above them, are strongly marked off by lithological distinctions, particularly when fragments of them occur in the overlying deposits. In some of the coal-mines in central Scotland, for instance, deep channels have been met with entirely filled with sand, gravel, or clay belonging to the general superficial drift of the country. These channels have evidently been water-courses worn out of the Coal-measure strata at a comparatively recent geological period, and subsequently buried under glacial accumulations. There is a complete discordance between them and the Palæozoic strata below, pointing to the existence of a vast interval of time.

Surface-markings.—The surface of many beds of sandstone is marked with lines of wavy ridge and hollow, such as may be seen on a sandy shore from which the tide has retired, on the floors of shallow lakes and of river-pools, and on surfaces of dry wind-blown sand. To these markings the general name of Ripple-mark has been given. They have been produced by an oscillation of the medium (water or air) in which the loose sand has lain. In water, an oscillatory movement, sometimes also with a more or less marked current, is generated by wind blowing on its surface. The sand-grains are carried backward and forward. By degrees, inequalities of surface are produced, which give rise to vortices in the water. In irregular ripple-mark, the direct current carries the sand up the weather-slope, while the vortex pushes it up the lee-slope, until the surface of the sand becomes mottled over with little prominences or dunes. In regular ripple-mark, the forms are produced by water oscillating relatively to the bottom and the consequent establishment of a series of vortices.[7] The long gentle slope toward the wind, and the short steep slope away from it, are well marked (Fig. 204, compare also Fig. 91). Considerable

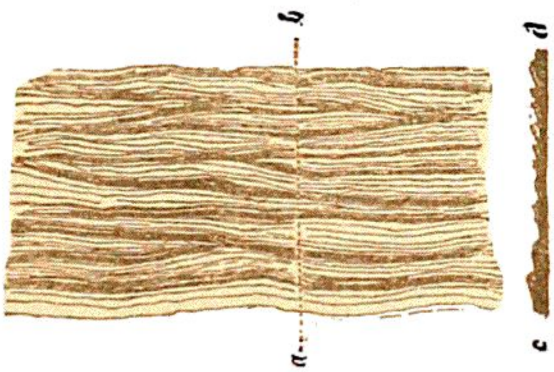


Fig. 204.—Plan and section of Rippled Surface.

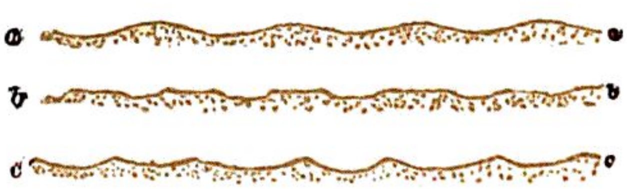


Fig. 205.—Sections of Ripple-marks.

diversity in the form of the ripple, however, may be observed (as at *a b c* in Fig. 205), depending on conditions of wind, water, and sediment which have not been thoroughly studied. No satisfactory inference can be drawn from the existence of ripple-marks as to the precise depth of water in

---

[7] Prof. Darwin, Proc. Roy. Soc. xxxvi. 1883, p. 18. See also H. C. Sorby, Edin. New Phil. Journ. new ser. iii. iv. v. vii.; Geologist, ii. 1859, p. 137; A. R. Hunt, Proc. Roy. Soc. xxxiv. p. 1; C. de Candolle, Arch. Sci. Phys. Nat. Geneva, ix. 1883; M. Forel, in same volume.

which the sediment was accumulated. As a rule, it is in water of only a few feet or yards in depth that this characteristic surface is formed. But it may be produced at any depth to which the agitation caused by wind on the upper waters may extend (p. 736). Examples of it may be observed among arenaceous deposits of all ages from pre-Cambrian upward. In like manner, we may frequently detect, among these formations, small isolated or connected linear ridges (rill-marks) directed from some common quarter, like the current-marks frequently to be found behind projecting fragments of shell, stones, or bits of seaweed on a beach from which the tide has just retired.

On an ordinary beach, each tide usually effaces the ripple-marks made by its predecessor, and leaves a new series to be obliterated by the next tide. In the process of obliteration, the tops of the ridges are levelled off (see *b* in Fig. 205), while sometimes the hollows, where they serve as receptacles for surface drainage, are deepened. Where the markings are formed in water which is always receiving fresh accumulations of sediment, a rippled surface may be gently overspread by the descent of a layer of sediment upon it, and may thus be preserved. By a renewal of the oscillation of the water another series of ripples may then be made in the overlying layers, which in turn may be buried and preserved under a renewed deposit of sand. In this way, a considerable thickness of such ripple-marked strata may be accumulated, as has frequently taken place among geological formations of all ages.

Sun-cracks, Rain-prints, Vestiges of former Shores.—One of the most fascinating parts of the work of a field-geologist consists in tracing the shores of former seas and lakes, and in endeavoring thereby to reconstruct the geography of successive geological periods. There are not a few pieces of evidence, which, though in themselves individually of apparently small moment, combine to supply him with reliable data. Among these he lays special emphasis upon the proofs that, during their deposition, strata have at intervals been laid bare to sun and air.

The nature and validity of the arguments founded on this evidence will be best realized by the student if he can make observations at the margin of the sea, or of any inland sheet of water, which from time to time leaves tracts of mud or fine sand exposed to sun and rain. The way in which the muddy bottom of a dried-up pool cracks into polygonal

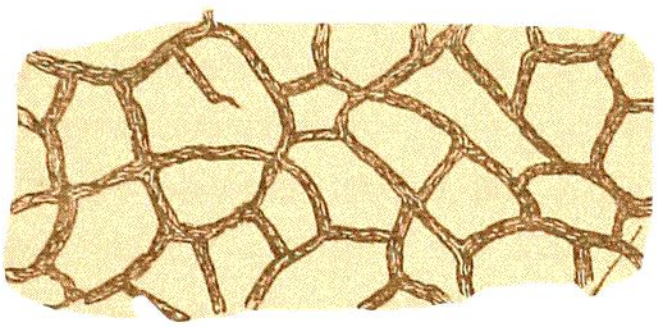


Fig. 206.—Sun-cracked surface of mud or muddy sand.

cakes when exposed to the sun may be illustrated abundantly among sedimentary rocks. These desiccation-cracks, or sun-cracks (Fig. 206), could not have been produced so long as the sediment lay under water. Their existence therefore among any strata proves that the surface of rock on which they lie was exposed to the air and dried, before the next layer of water-borne sediment was deposited upon it.

With these markings are occasionally associated prints of rain-drops. The familiar effects of a heavy shower upon a surface of moist sand or mud may be witnessed among rocks even as old as the Cambrian period. In some cases, the rain-prints are found to be ridged up on one side, in such a manner as to indicate that the rain-drops as they fell were driven aslant by the wind. The prominent side of the markings, therefore, indicates the side toward which the wind blew.

Numerous proofs of shallow shore-water, and likewise of exposure to the air, are supplied by markings left by animals. Castings, tubular burrows and trails of worms, tracks of mollusks and crustaceans, fin-marks of fishes, footprints of reptiles (Fig. 207), birds, and mammals, may all be preserved and give their evidence regarding the physical conditions under which sedimentary formations were accumulated. It may frequently be noticed that such impressions are as-

Fig. 207.—Footprints from the Triassic Sandstone of Connecticut (Hitchcock).

sociated with ripple-marks, rain-prints, or sun-cracks (Fig. 208); so that more than one kind of evidence may be gleaned from a locality to show that it was sometimes laid bare of water.

The more striking indications of littoral conditions being comparatively infrequent, the geologist must usually content himself with tracing the gravelly detritus, which suggests, if it does not always prove, proximity to some former line of shore. Such a section, for instance, as that depicted in Fig. 209 may often be found, where lower strata (*a*) having been tilted, raised into land, and worn away, have yielded materials for a coarse littoral bowlder bed (*b*), over which, as it was carried down into deeper and clearer water, limestone eventually accumulated. Beds of conglomerate, especially where, as in this example, they accompany an un-

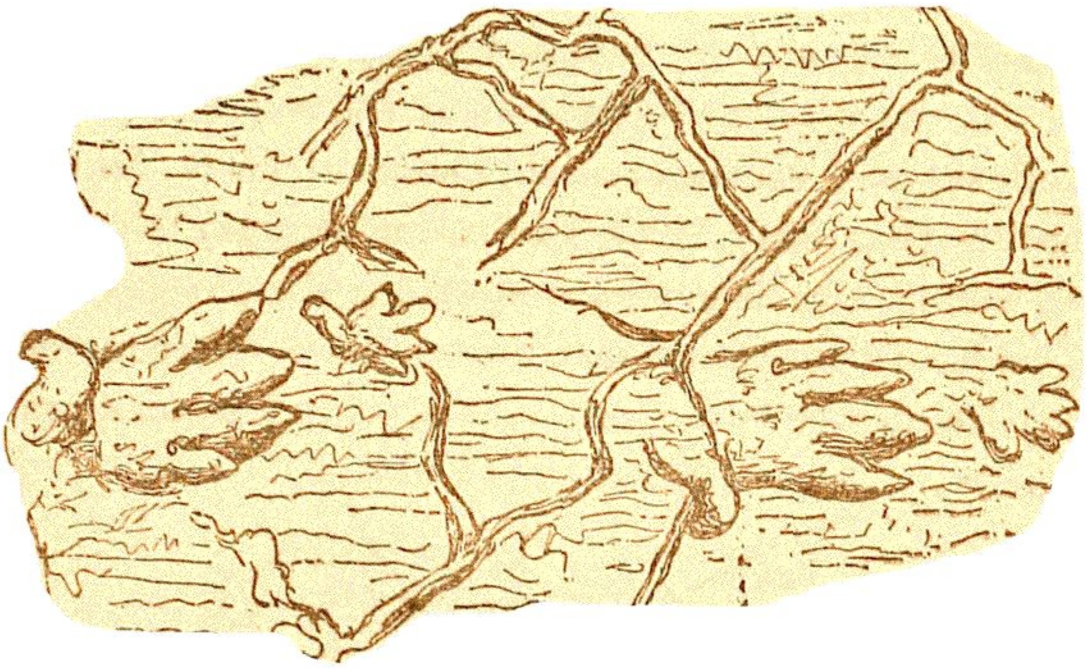


Fig. 208.—Footprints and Sun-cracks, Hildburghausen, Saxony (Sickler).

conformability in the stratification, are of much service in tracing the limits of ancient seas and lakes (see Part X.).

G a s - s p u r t s.—The surfaces of some strata, usually of a dark color and containing organic matter, may be observed to be raised into little heaps of various indefinite shapes, not

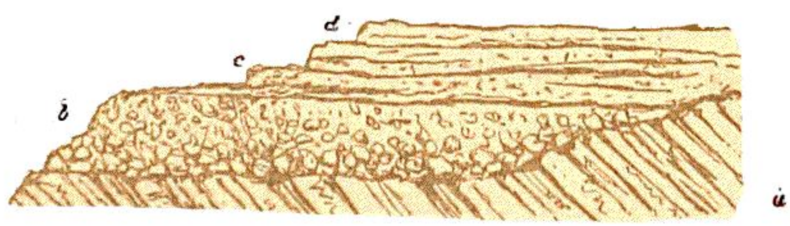


Fig. 209.—Section of a beach of early Mesozoic age, near Clifton, Bristol (*B.*).

***a*, Carboniferous limestone; *b*, dolomitic conglomerate—a mass of bowlders and angular fragments of *a* (some of them almost two tons in weight), passing up into finer conglomerate *c*, with sandstone and marl, and thence into dolomitic limestone *d*.**

like the heaps associated with worm-burrows, connected with pipes descending into the rock, nor composed of different material from the surrounding sandstone or shale. These may be conjectured to be due to the intermittent escape of gas from decomposing organic matter in the original sand or mud, as we may sometimes witness in operation among the mud-flats of rivers and estuaries, where much organic matter is decomposing among the sediment. On a small scale, these protrusions of the upper surface of a deposit may be compared with the mud-lumps at the mouths of the Mississippi, already described (p. 674).

Concretions.—Many sedimentary rocks, more particularly clays, ironstones, and limestones, exhibit a concretionary structure. This arrangement may be part of the original

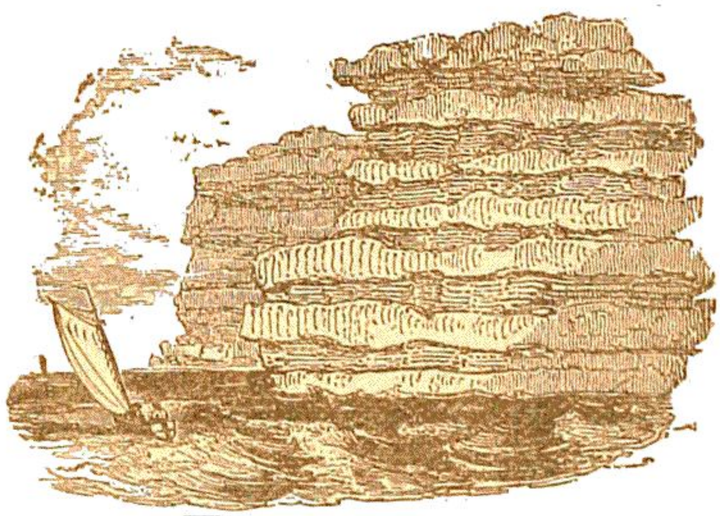


Fig. 210.—Section of alternations of shale and concretionary limestone (*B.*).

sedimentation, or may be due to subsequent segregation from decomposition round a centre. Concretionary structures of contemporaneous origin, particularly in calcareous materials, may lie so closely adjacent as to form continuous or nearly continuous beds (Fig. 210). The Magnesian Limestone of Durham is built up of variously shaped concretionary masses, sometimes like cannon-balls, grape-shot, or bunches of coral. Connected with concretionary beds are the seams of gypsum, which may occasionally be observed to send out veins into other gypsum beds above and below them. De la Beche describes a section at Watchet, Somersetshire, where, amid the Triassic marls (*b b* in Fig. 211), beds of gypsum (*a a*) connect themselves by means of fibrous veins with the overlying and underlying beds.

The most frequent form of concretions is that of isolated spherical, elliptical, or variously shaped nodules, disposed in certain layers of a stratum or dispersed irregularly through it (Fig. 212). They most commonly consist of ferrous or calcic carbonates, or of silica. Many clay-iron-stone beds assume a nodular form, and this mineral occurs abundantly in the shape of separate nodules in shales and clay-rocks. The nodules have frequently formed round some organic body, such as a fragment of plant, a shell, bone, or coprolite. That the carbonate was slowly precipitated during the formation of the bed of shale in which its nodules lie, may often be satisfactorily proved by the lines of deposit passing continuously through the nodules (Fig. 213). In many cases, the internal first-formed parts of a nodule have contracted more than the outer and more compact crust; and have cracked into open polygonal spaces, which are commonly filled with calcite (Fig. 26). Such *septarian nodules*, whether composed of clay-ironstone or limestone, are abundant in many shales, as in the Carboniferous and Liassic series of England.

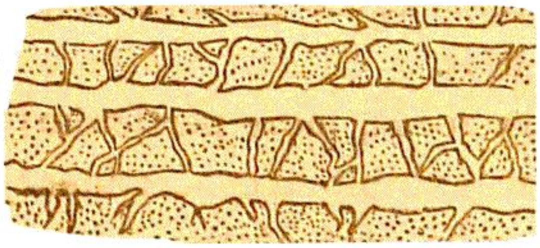


Fig. 211.—Sections of beds and connecting strings of gypsum in the Trias, Watchet, Somersetshire (*B.*).

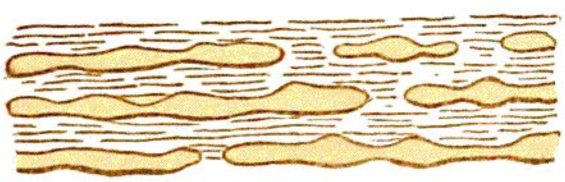


Fig. 212.—Concretions of limestone in shale.

Fig. 213.—Concretions surrounding organic centres and exhibiting the continuation of the lines of stratification of the surrounding shales.

Alluvial clays sometimes contain fantastically shaped concretions due to the consolidation of the clay by a calcareous or ferruginous cement round a centre. These are known in Scotland as fairy-stones, in the valley of the Rhine as Lösspuppen, Lössmänchen, and in Finland as Imatra-stones (Fig. 214 and p. 566). They not uncommonly show the bedding of the clay in which they may have been formed. Their quaint imitative forms have naturally given rise to

Fig. 214.—Clay concretions of alluvium (nat. size).

a popular belief that they are petrifications of various kinds of organic bodies and even of articles of human manufacture. In Norway they occur in glacial and post-glacial deposits up to heights of 360 feet above sea-level, and inclose remains of fishes (of which 16 species have been noticed), as well as other organisms.[8]

[8] Kjerulf, "Geologie des südl. und mittl. Norwegens," 1880, p. 5; R. Collet, Nyl. Mag. Nat. xxiii. No. 3, p. 11.

Concretions of silica occur in limestone of many geological ages (p. 829). The flints of the English Chalk are a familiar example, but similar siliceous concretions occur in Carboniferous and Cambrian limestones. The silica, in these cases, has not infrequently been deposited round organic bodies, such as sponges, sea-urchins, and mollusks, which are completely enveloped in it, and have even themselves been silicified. Iron-disulphide often assumes the form of concretions, more particularly among clay-rocks, and these, though presenting many eccentricities of shape —round, like pistol-shot or cannon-balls, kidney-shaped, botryoidal, etc.—agree in usually possessing an internal fibrous radiated structure. Phosphate of lime is found as concretions in formations where the coprolites and bones of reptiles and other animals have been collected together (see p. 827).

Concretions produced subsequently to the formation of the rock occur in some sandstones, which, when exposed to the weather, decompose into large round balls. In other instances, a ferruginous cement is gradually aggregated by percolating water in lines which curve round so as to inclose portions of the rock. These lines, owing to abstraction of iron from within the spheroid and partly from without, harden into dark crusts, inside of which the sandstone becomes quite bleached and soft.[9] Some shales exhibit a concretionary structure in a still more striking manner, inasmuch as the concretions consist of the general mass of the laminated shale, and the lines of stratification pass through them and mark them out distinctly as superinduced upon the rock. Examples of this structure are not infrequent

[9] See Penning, Geol. Mag. Dec. 2, iii. May, 1876.

among the argillaceous strata of the Carboniferous system. The concretionary olive-green shales and mud-stones of the Ludlow group, in the Upper Silurian system, exhibit on weathered surfaces, all the way from South Wales into central Scotland, a peculiar structure which consists in the development of concentric spheroids varying from less than an inch up to several feet in diameter, the successive shells being separated from each other by a fine dark ferruginous film (Fig. 215). The lines of stratification are sometimes well marked by layers of fossils, but the rock splits up mainly along the curved surfaces separating the concentric shells. Concretionary structures are found also in rocks formed from chemical precipitation, as for instance in beds of rock-salt. The pseudo-concretions probably due to pressure (stylolites) have been described on (p. 537).

Fig. 215.—Concretionary structure in Upper Silurian shales, Cwm-ddu, Llangammarch, Brecknockshire (*B*.).

Alternations and Associations of Strata.—Though great variations occur in the nature of the strata composing a mass of sedimentary rocks, it may often be observed that certain repetitions occur. Sandstones, for example, are found to be interleaved with shale above, and then to pass into shale; the latter may in turn become sandy at the top and be finally covered by sandstone, or may assume a calcareous character and pass up into limestone. Such alternations bring before us the conditions under which the sedimentation took place. A sandstone group indicates water of comparatively little depth, moved by changing currents, bringing the sand, now from one side, now from another. The passage of such a group into one of shale points to a diminution in the motion and transporting power of the water, perhaps to a sinking of the tract, so that only fine mud was intermittently brought into it. The advent of limestone above the shale serves to show that the water cleared, owing to a deflection of the sediment-carrying currents, or to continued and perhaps more rapid subsidence, and that foraminifera, corals, crinoids, mollusks, or other lime-secreting organisms, established themselves upon the spot. Shale overlying the limestone would tell of fresh inroads of mud, which destroyed the animal life that had been flourishing on the bottom; while a return of sandstone

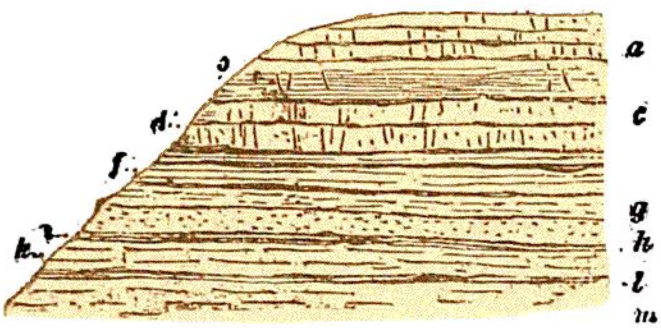


Fig. 216.—Section of Strata from the base of the Lias down to the top of the Trias, Shepton Mallet (*B.*).

a, Gray Lias limestone and marls; *b*, earthy whitish limestone and marls; *c*, earthy white limestone; *d*, arenaceons limestone; *f*, gray marls; *g*, red marls; *h*, sandstone with calcareous cement; *i*, blue marl; *k*, red marl; *l*, blue marl; *m*, red marls.

beds would mark how, in the course of time, the original conditions of troubled currents and shifting sandbanks returned. Such alternating groups of sandy, calcareous, and argillaceous strata are well illustrated among the Jurassic formations of England (Fig. 216).

Certain kinds of strata commonly occur together, because the conditions under which they were formed were apt to arise in succession. One of the most familiar examples is the association of coal and fire-clay. In Britain a seam of coal is generally found to lie on a bed of fire-clay, or on some argillaceous stratum. The reason of this union becomes at once apparent when we learn that the fire-clay was the soil on which the plants grew that went to form the coal. Where the clay was laid down under suitable circumstances, vegetation sprang up upon it. This appears to have taken place in wide shallow lagoon-like expansions of the sea, bordering land clothed with dense vegetation, and to have been accompanied by slow, intermittent, but prolonged subsidence of the sea-bottom. Hence, during pauses of the downward movement, when the water shoaled, an abundant growth of water-loving or marshy plants sprang up on the muddy bottom, somewhat like the mangrove-swamps of the present day, and continued to flourish until the muddy soil was exhausted,[10] or until subsidence recommenced and the matted jungles, carried under the water, were buried under fresh inroads of sand or mud. Each coal-field thus contains a succession of buried forests with a constant repetition of the same kind of intervening strata (Fig. 217).

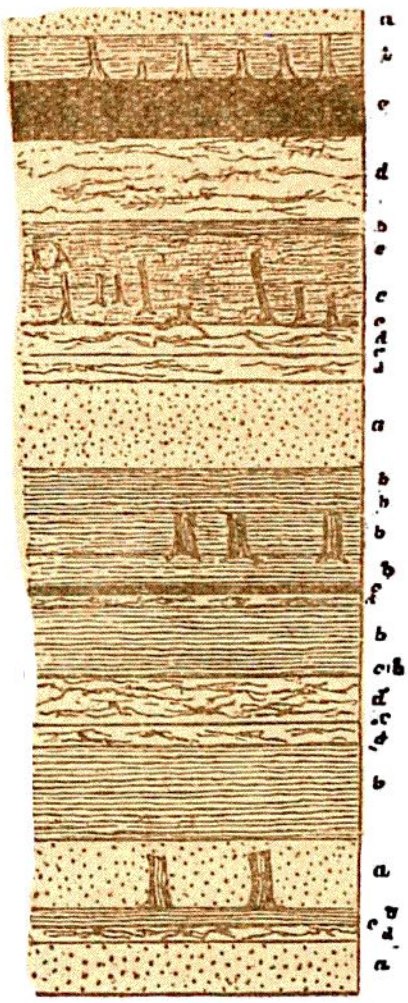


Fig. 217.—Succession of buried coal-growths and erect tree-stumps, Sydney Coal-Field, Cape Breton (R. Brown).[11]
a, sandstones; *b*, shales; *c*, coal-seams; *d*, beds containing roots and stumps *in situ*.

---

[10] Sterry Hunt has called attention to the fact that the underclays of the Coal-measures have generally been deprived of their alkalies by the vegetable growth which they supported. In the little coal-basins of France evidence has been obtained that much of the coal was formed out of vegetation that had been swept down and buried by rapid currents. See the Memoir of M. Fayol cited on p. 837.

[11] See R. Brown, Quart. Journ. Geol. Soc. vi. p. 115; and De la Beche, "Geol. Observer," p. 505.

For obvious reasons, conglomerate and sandstone occur together, rather than conglomerate and shale. The agitation of the water which could form and deposit coarse detritus, like that composing conglomerate, was too great to admit of the accumulation of fine silt. On the other hand, we may look for shale or clay rather than sandstone, as an accompaniment of limestone, inasmuch as when the gentle currents by which fine argillaceous silt was carried in suspension ceased, they would be succeeded by intervals of quiet clearing of the water, during which calcareous material might be elaborated either chemically or by the action of living organisms.

Relative persistence of Strata.—A little reflection will convince the student that all sedimentary rocks must thin out and disappear, and that even the most persistent, when regarded on the great scale, are local and lenticular accumulations. Derived from the degradation of land, they have accumulated near land. They are necessarily thickest in mass, as well as coarsest in texture, nearest to the source of supply, and become more attenuated and fine-grained as they recede from it. We have only to observe what takes place at the present time on lake-bottoms, estuaries, or sea-margins, to be assured that this is now, and must always have been, the law of sedimentation.

But while all sedimentary deposits must be regarded as essentially local, same kinds possess a far greater persistence than others. As a general rule, it may be said that the coarser the grain, the more local the extent of a rock. Conglomerates are thus by much the most variable and inconstant of all sedimentary formations. They suddenly sink down from a thickness of several hundred feet to a few yards or die out altogether, to reappear, perhaps further on, in the same wedge-like fashion. Sandstones are less liable to such extremes of inconstancy, but they too are apt to thin away and to swell out again. Shales are much more persistent, the same zone being often traceable for many miles. Limestones sometimes occur in thick local masses, as among the Silurian formations, but they often also display remarkable continuity. Three thin limestone bands, each of them only two or three feet in thickness, and separated by a considerable thickness of intervening sandstones and shales, can be traced through the coal-fields of central Scotland over an area of at least 1000 square miles. Coal-seams also possess great persistence. The same seams, varying slightly in

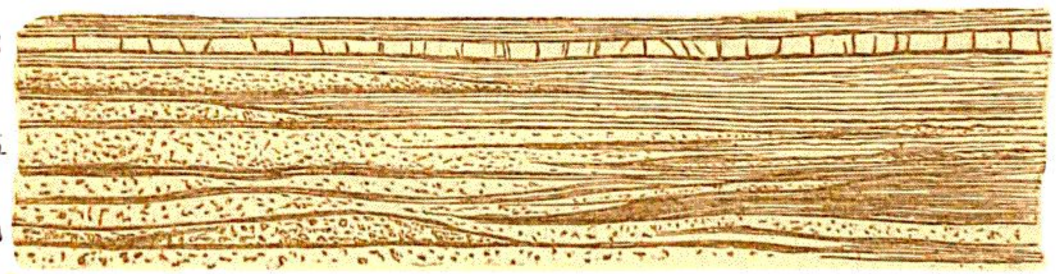


Fig. 218.—Section to illustrate the great lithological differences of contemporaneous deposits occupying the same horizon.
a, conglomerate; *b*, sandstone; *c*, shale; *d d*, limestone.

thickness and quality, may often be traced throughout the whole of an extensive coal-field.

What is thus true of individual strata may be affirmed also of groups of such strata. A thick mass of sandstone will be found as a rule to be more continuous than one of conglomerate, but less so than one of shale. A series of limestone beds usually stretches further than either arenaceous or argillaceous sediments. But even to the most extensive stratum or group of strata there must be a limit. It must end off, and give place to others, either suddenly, as a bank of shingle is succeeded by the sheet of sand heaped against its base, or, as is more usual, very gradually, by insensibly passing into other strata on all sides.

Great variations in the character of stratified rocks may frequently be observed in passing from one part of a country to another along the outcrop of the same rocks. Thus, at one end, we may meet with a thick series of sandstones which, traced in a certain direction, may be found passing into shales (Fig. 218). A group of strata may consist of massive conglomerates at one locality, and may graduate into fine fissile flagstones in another. A thick mass of clay may be found to alternate more and more with shelly sands as it is traced outward, until it loses its argillaceous natrre altogether.

Interesting illustrations of such arrangements occur in the southwest of England, where what are now groups of hills, like the Mendip, Malvern, and other eminences formerly existed as islands in the Mesozoic sea. De la Beche

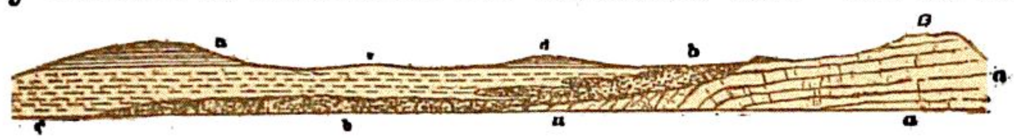


Fig. 219.—Section near Bristol to show how conglomerate may pass into clay along the same horizon.
B, Blaize Castle Hill; *s*, Mount Skitham (*B.*).

pointed out that the upturned Carboniferous limestone (*a a* in Fig. 219) has formed the shore against which the coarse shingle of the dolomitic conglomerate (*b b*) accumulated; that the latter, traced away from its shore-line, passes on the

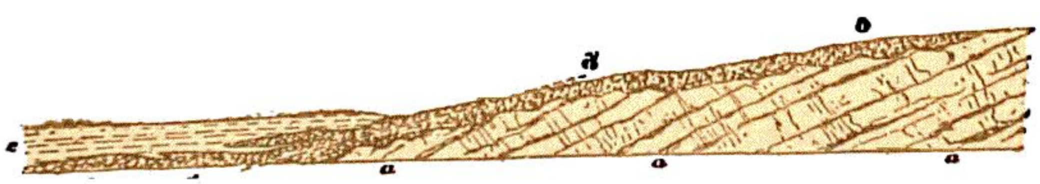


Fig. 220.—Section of part of the flank of the Mendip Hills (*B.*), showing the Carboniferous Limestone (*a a*) overlaid by dolomitic conglomerate (*b b*), and that by red marls (*c*).

same plane into red marl (*c*), and that during a gradual subsidence, the clays and limestones of the Lias (*d*) crept over the depressed shore-line. He likewise called attention to the important fact that, in such cases, a continuous zone of conglomerate may belong to many successive horizons. In Fig. 220 a section is given from one of the islands in the southwest of England, round which the Trias and Lias were deposited. Denudation has stripped off a portion of the overlying red marls. If the rest of the section to the left of the dotted line (*d d*) were removed, there would remain a continuous mass of conglomerate, which, in default of other evidence to the contrary, would be regarded as one bed laid down upon the sloping surface of limestone, instead of, what it really is, a series of shore gravels piled upon each other, and belonging to a consecutive series of deposits.

Mere difference of lithological character, even within a limited geographical space, does not necessarily mean diversity of age. At the present day, coarse shingle may be formed along the beach, at the same time that the finest mud is being laid down on the same sea-bottom further from land. The existing differences of character between the deposits of the shore and of the opener sea would no doubt continue to be maintained, with slight geographical displacements, even if the whole area were undergoing subsidence, so that a thick group of littoral deposits might gather in one tract, and of deeper-water accumulations in another.

Among the formations of former geological periods, the same conditions of deposition appear sometimes to have continued for enormous periods. The thick Carboniferous Limestone of western Europe evidently accumulated during a slow subsidence, when the same conditions of clear water with abundant growth of crinoids, corals, etc., continued for a period vast enough to admit of the gradual growth of thousands of feet of calcareous matter. Traced northward into Scotland, this massive limestone is gradually replaced by sandstones, shales, ironstones, and coal-seams. These strata prove that the deeper and clearer water of Belgium, central England, and Ireland passed northward into muddy flats and sandy shoals, which at one time were overspread with coal-growths, and at another, owing to more rapid subsidence, were depressed beneath the clearer sea which brought with it the corals, crinoids, mollusks, etc., whose remains are now to be seen in intercalations of crinoidal limestone.

Influence of the Attenuation of Strata upon apparent Dip.—Where a thick mass of sedimentary materials rapidly thins away in a given direction, a deceptive resemblance to the effects of underground movement may be observed. If, for example, we suppose that on a perfectly level bottom, a series of sedimentary beds is accumulated at one place to a depth of 5000 feet, and that this series dies out in a distance of 80 miles, the inclination due to this attenuation will amount to a slope of about 62 feet in a mile. That this structure has not been without considerable influence on the apparent dip of stratified rocks has been well shown by Mr. W. Topley with reference to the Mesozoic rocks of the southeast of England.[12]

Overlap.—Sediment laid down in a subsiding region, wherein the area of deposit is gradually increased, spreads over a progressively augmenting surface. Under such circumstances, the later portions of a formation, or series of

Fig. 221.—Section of Overlap in the Lower Jurassic series of the Southwest of England (*B.*).

The Old Red Sandstone (*c*), Lower Limestone Shale (*b*), and Carboniferous Limestone (*a*) having been previously upraised and denuded, the older beaches (*d m*), laid down unconformably upon them, were successively covered by conformable Jurassic beds. The Lias (*e*), with its upper sands (*f*), is overlapped by the extension of the Inferior Oolite (*g*) completely across their edges, until this formation comes to rest directly on the Palæozoic strata at *n*. The corresponding extension of the overlying Fuller's Earth (*h l*) and limestone (*i*) has been removed by denudation.[13]

sedimentary accumulations, will extend beyond the limits of the older parts, and will repose directly upon the shelving bottom. This relation, called Overlap (Fig. 221), in which the higher or newer members are said to "overlap"

---

[12] Quart. Journ. Geol. Soc. xxx. 1874, p. 186.
[13] De la Beche, "Geol. Observer," p. 485.

the older, may often be detected among formations of all geological ages. It brings before us the shore-lines of ancient land-surfaces, and shows how, as these sank under water, the gravels, sands, and silts gradually advanced and covered them.

This structure must be carefully distinguished from Unconformability (postea, Part X.). In Overlap there is no break in the sequence of formations; the strata that overlap follow on continuously upon these which are overlapped. But in unconformability there is a break in the succession, the overlying rocks have been laid down on the previously uptilted and denuded edges of those below them. In Fig. 221, for example, the upper or Mesozoic formations (*d* to *i*) form an unbroken series, so do the lower or Palæozoic strata (*a b c*), but the latter have been disturbed and worn down before the deposition of the strata above them. The two series are said therefore to be unconformable.

Relative Lapse of Time represented by Strata and by the Intervals between them.—Of the absolute length of time represented by any strata or groups of strata, no satisfactory estimates have yet been possible. Certain general conclusions may indeed be drawn, and comparisons may be made between different series of rocks. Sandstones full of false-bedding were probably accumulated more rapidly than finely-laminated shales or clays. It is not uncommon in certain Carboniferous sandstones to find huge sigillarioid and coniferous trunks imbedded in upright or inclined positions. Where, as in Fig. 222, the trees actually grew on the spot where their stems remain, it is evident that the rate of deposit of the sediment which entombed them must have been sufficiently rapid to have allowed a mass of twenty or thirty feet to accumulate before the decay of the wood.

Of the durability of these ancient trees we of course know nothing; though modern instances are on record where, under certain circumstances, submerged trees may last for some centuries. We may conjecture that where upright or inclined stems are enveloped in one continuous stratum, the rate of accumulation was probably, on the whole, somewhat rapid. The general character of the strata among which

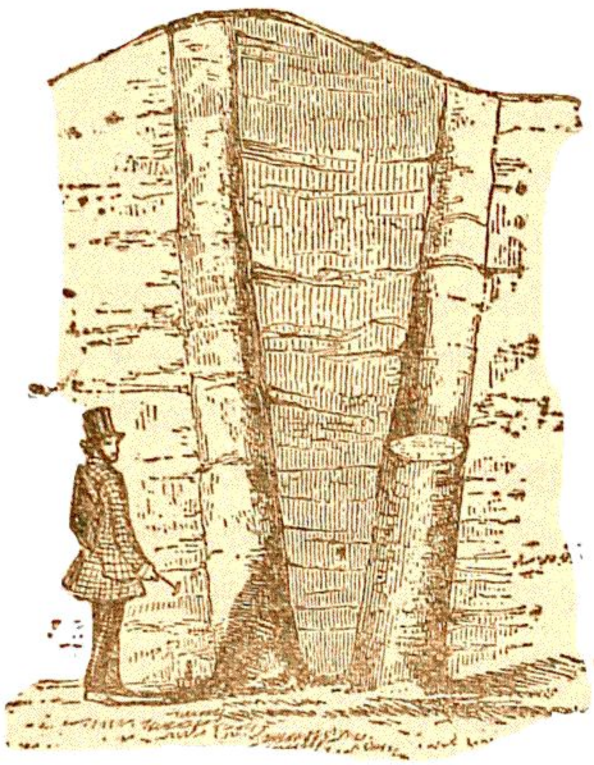


Fig. 222.—Erect trunks of Sigillaria in sandstone, Cwm Llech, head of Swansea Valley, Glamorganshire. (Drawn by the late Sir W. E. Logan.)

These stems (the largest five and a half feet in circumference) formed part of a series in the same rock, their roots being imbedded in a seam of shale (an old soil) full of fern leaves, etc. The specimens were removed to the Museum of the Royal Institution of South Wales at Swansea.[14]

such erect tree-trunks occur, obviously indicates extremely shallow water conditions with continuous or intermittent subsidence. Unless soon submerged, dead trees would be subject to speedy subaerial decomposition. It occasionally happens that an erect trunk has kept its position even during the accumulation of a series of strata around it (Fig.

[14] De la Beche, "Geol. Observer," p. 501.

223). We can hardly believe that in such cases any considerable number of years could have elapsed between the death of the tree and its final entombment. From the decayed condition of the interior of some imbedded trees, we may likewise infer that accumulation of sediment is not always an extremely slow process. Instances occur where, as Fig. 224, while sand and mud have been accumulating round the submerged stem, its interior has been rotting, so that eventually a mere hollow cylinder has been left, into which sediment and different plants (sometimes with the bodies of land animals) were introduced from above.[15] Large coniferous trunks (as in the neighborhood of Edinburgh) have been imbedded in sandstone, and have had their internal microscopic structure well preserved. In such examples, the drifted trees seem to have sunk with their heavier or root-end touching the bottom, and their upper end pointing upward in the direction of the current, like the snags of the Mississippi, and to have been completely buried in sediment before decay.

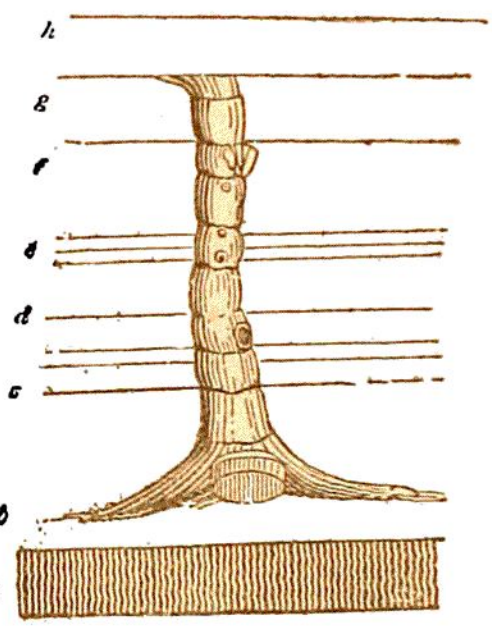


Fig. 223.—Erect tree-trunk rising through a succession of strata, Killingworth Colliery, Newcastle. *a*, High Main Coal-Seam; *b*, bituminous shale; *c*, blue shale; *d*, compact sandstone; *e*, shales and sandstones; *f*, white sandstones; *g*, micaceous sandstone; *h*, shale.

Continuous layers of the same kind of deposit suggest a persistence of geological conditions; numerous alternations of different kinds of sedimentary matter point to

[15] The hollow tree-trunks of the Nova Scotian coal-fields have yielded a most interesting series of terrestrial organisms—land-snails and reptiles. For illustrations of trees in Coal-measure strata and the deposition of sediment round them see the Atlas to M. Fayol's Memoir cited on p. 837.

vicissitudes or alternations of conditions. As a rule, we should infer that the time represented by a given thickness of similar strata was less than that shown by the same thickness of dissimilar strata, because the changes needed to bring new varieties of sediment into the area of deposit would usually require the lapse of some time for their completion. But this conclusion might often be erroneous. It would be best supported when, from the very nature of the rocks, wide variations in the character of the water-bottom could be established. Thus a group of shales followed by a fossiliferous limestone, would mark a period of slow deposit and quiescence, almost always of longer duration than would be indicated by an equal depth of sandy strata, pointing to more active sedimentation. Thick limestones, made up of remains of organisms which lived and died upon the spot, and whose remains are crowded together generation above generation, must have demanded prolonged periods for their formation.

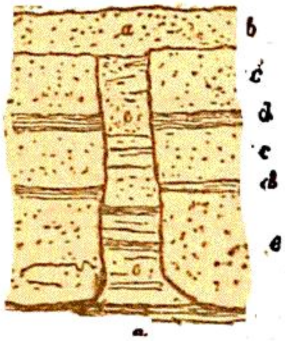


Fig. 224.—Erect tree-trunk (*a a*) imbedded in sandstones (*c c*) and shales (*d d*), its interior filled with different sandy and clayey strata (*e e*), and the whole covered by a sandstone bed (*b*) (*B.*).

But in all speculations of this kind, we must bear in mind that the relative length of time represented by a given depth of strata is not to be estimated merely from thickness or lithological characters. It has already been pointed out that the interval between the deposit of two successive laminæ of shale may have been as long as, or even longer than, that required for the formation of one of the laminæ. In like manner, the interval needed for the transition from one stratum or kind of strata to another may often have been more than equal to the time required for the formation of the strata of either kind. But the relative chronological importance of the bars or lines in the geological record can seldom be satisfactorily discussed merely on lithological grounds. This must mainly be decided on the evidence of organic remains, as will be shown in Book V. By this kind of evidence, it can be made nearly certain that the intervals represented by strata were in many cases much shorter than those not so represented —in other words, that the time during which no deposit of sediment went on at any particular locality was longer than that wherein deposit did take place.

Ternary Succession of Strata.—In following the order of sedimentation among the stratified rocks of the earth's crust, the observer will be led to remark a more or less distinct threefold arrangement or succession in which the sandy, muddy, and calcareous sediments have followed each other. Prof. John Phillips and Mr. Hull have called attention to this structure, illustrating it by reference to the geological formations of Great Britain, while Prof. Newberry, Dr. Sterry Hunt, and Principal Dawson have discussed it in relation to the stratigraphical series of North America. According to Mr. Hull a natural cycle of sedimentation consists of three phases; 1st, a lower stage of sandstones, shales, and other sedimentary deposits, representing prevalence of land with downward movement; 2d, a middle stage, chiefly of limestone, representing prevalence of sea with general quiescence and elaboration of calcareous organic formations; 3d, an upper stage, once more of mechanical sediments indicative of proximity to land.[16] Where the strata are interrupted by disturbance

---

[16] Phillips, Mem. Geol. Surv. ii.; "Geol. Yorkshire," ii.; "Geol. Oxford," p. 293; Hull, Quart. Jour. Sci. July, 1869; Newberry, Proc. Amer. Assoc.

and unconformability, we may suppose the cycle of sedimentation to have been completed by upheaval after prolonged subsidence. But where the continuity of the formations is unbroken, as it is over such vast tracts in North America, upheaval is not required, and the facts seem explicable, as Phillips long ago showed, on the idea of prolonged but intermittent subsidence. Let us suppose a downward movement to commence, and to depress successive sheets of gravel, shingle, sand, and other shallow water accumulations, derived from the erosion of neighboring land. If the depression be comparatively rapid, the bottom may soon be carried beyond the reach of at least the coarser kinds of sediment, and marine lime-secreting organisms may afterward begin to form a calcareous floor beneath the sea. Let us imagine, further, that the subsidence ceases for a time, and that by the accumulation of organic remains, and partly also by the deposit of fine muddy sediment, the water is shallowed. With this gradual change of depth, the coarser detritus begins once more to be able to stretch seaward, and to overspread the limestones, which, under the altered circumstances, cease to be formed. A gradual silting up of the area takes place, marked by beds of sand and mud, until a renewal of the subsidence, either suddenly or slowly, restores the previous depth and clearness of water, and allows either the old marine organisms, which had been driven off, or their modified descendants to reoccupy the area and build new limestone.

Groups of Strata.—Passing from individual strata to

1873, p. 185; Proc. Lyceum Nat. Hist. New York, 2d ser. No. 4, p. 122; Hunt, in Logan's "Geology of Canada," 1863, p. 627; Amer. Journ. Sci. (2d series), xxxv. p. 167; Dawson, Q. J. Geol. Soc. xxii. p. 102; "Acadian Geology," p. 135. Compare on this subject E. van den Broeck, Bull. Mus. Roy. Bruxelles, ii. 1883, p. 341; A. Rutot, op. cit. p. 41.

large masses of stratified rock, the geologist finds it needful for convenience of reference to subdivide these into groups. He avails himself of two bases of classification—(1) lithological character, and (2) organic remains.

1. The subdivision of stratified rocks into groups according to their mineral aspect is an obvious and easily applied classification. Moreover, it often serves to connect together rocks formed continuously in certain circumstances which differed from those under which the strata above and below were laid down—so that it expresses natural and original subdivisions of strata. In the middle of the English Carboniferous system of rocks, for example, a zone of sandy and pebbly beds occurs, known as the Millstone Grit. No abrupt and sharp line can be drawn between these strata and those above and below them. They shade upward and downward into the beds between which they lie. Yet they form a conspicuous belt, traceable for many miles by the scenery to which it gives rise. Again, the red rocks of central England, with their red sandstones, marls, rock-salt, and gypsum, form a well-marked group, or rather series of groups. It is obvious, however, that characters of this kind, though sometimes wonderfully persistent over wide tracts of country, must be at best but local. The physical conditions of deposit must always have been limited in extent. A group of strata, showing great thickness in one region, will be found to die away as it is traced into another. Or its place is gradually taken by another group which, even if geologically contemporaneous, possesses totally different lithological characters. Just as at the present time a group of sandy deposits gradually gives place along the sea-floor to others of mud, and these to others of shells or of gravel, so in former geological periods,

contemporaneous deposits were not always lithologically similar. Hence mere resemblance in mineral aspect cannot usually be regarded as satisfactory evidence of contemporaneity, except within comparatively contracted areas. The Carboniferous Limestone has already (p. 863) been cited as a notable example. Typically in Belgium, central England, and Ireland, it is a thick calcareous group of rocks, full of corals, crinoids, and other organisms, which bear witness to the formation of these rocks in the open sea. But traced into the north of England and Scotland it passes into sandstones and shales, with numerous coal-seams, and only a few thin beds of limestone. The soft clay beneath the city of London is represented in the Alps by hard schists and contorted limestones. We conclude, therefore, that lithological agreement, when pushed too far, is apt to mislead us, partly because contemporaneous strata often vary greatly in lithological character, and partly because the same lithological characters may appear again and again in different ages. By trusting too implicitly to this kind of evidence, we may be led to class together rocks belonging to very different geological periods, and, on the other hand, to separate groups which really, in spite of their seeming distinction, were formed contemporaneously.

2. It is by the remains of plants and animals imbedded among the stratified rocks that the most satisfactory subdivisions of the geological record can be made, as will be more fully stated in Books V. and VI. A chronological succession of organic forms can be made out among the rocks of the earth's crust. A certain common facies or type of fossils is found to characterize particular groups of rocks, and to hold true even though the lithological constitution of the strata should greatly vary. Moreover, though

comparatively few species are universally diffused, they possess remarkable persistence over wide areas, and even when they are replaced by others, the same general facies of fossils remains. Hence the stratified formations of two countries geographically distant, and having little or no lithological resemblance to each other, may be compared and paralleled simply by means of their inclosed organic remains.

Order of Superposition—the Foundation of Geological Chronology.—As sedimentary strata were laid down upon one another in a more or less nearly horizontal position, the underlying beds must be older than those which cover them. This simple and obvious truth is termed the Law of Superposition. It furnishes the means of determining the chronology of rocks; and though other methods of ascertaining this point are employed, they must all be based originally upon the observed order of superposition. The only case where the apparent superposition may be deceptive is when the strata have been inverted, as in the Alps (pp. 900, 901), where the rocks composing huge mountain masses have been so completely overturned that the highest beds appear as if regularly covered by others which ought properly to underlie them. But these are exceptional occurrences, wherein the true order can usually be made out from other sources of evidence.

PART II. JOINTS

All rocks are traversed more or less distinctly by vertical or highly inclined divisional planes termed J o i n t s.[1]

[1] M. Daubrée has proposed a classification of the various divisional planes of rocks due to rupture of original continuity, which he groups together as Lithoclases. 1. Under the term Leptoclase he classes minor fractures, which may be either (*a*) Synclases, produced by some internal mechanical or molecular

Soft rocks, indeed, such as loose sand and uncompacted clay, do not show these lines; but where a sedimentary mass has acquired some degree of consolidation, it usually shows them more or less distinctly. It is by means of the intersection of joints that rocks can be removed in blocks; the art of quarrying consists in taking advantage of these natural planes of division. Joints differ in character according to the nature of the material which they traverse; those in sedimentary rocks are usually distinct from those in crystalline masses.

1. **In Stratified Rocks.**—To the presence of joints some of the most familiar features of rock-scenery are due (Fig.

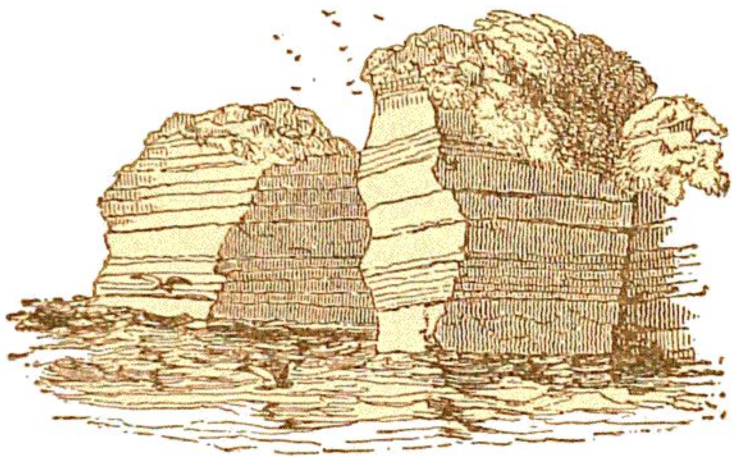


Fig. 225.—Cliffs cut into re-entering angles by lines of Joint (*B.*).
(The faces in shadow are one set of joints, those in light another set.)

225). Joints vary in the angles at which they cut the planes of bedding, in the sharpness of their definition, in the regularity of their perpendicular and horizontal course, in their lateral persistence, in number, and in the directions of their

action, and generally by contraction, as in cooling and drying; or (*b*) Piësoclases, produced by some external mechanical movement, particularly by pressure, as in the structures called cone-in-cone, stylolites and ruiniform marble. 2. Diaclases correspond to what in English are called joints. 3. Paraclases are faults. Bull. Soc. Geol. France (3), x. p. 136. On jointing, faulting and cleavage in rocks see O. Fisher, Geol. Mag. 1884, 204. A. Harker, Geol. Mag. 1885, Brit. Assoc. 1885, p. 813. G. K. Gilbert, Amer. Journ. Sci. xxiii. 1882, p. 25, xxiv. 1882, p. 50, xxvii. 1884, p. 47; W. O. Crosby, Proc. Boston Soc. Nat. Hist. xxii. 1882, p. 72, xxiii. p. 243.

intersection. As a rule, they are most sharply defined in proportion to the fineness of grain of the rock. In limestones and close-grained shales, for example, they often occur so clean-cut as to be invisible until revealed by fracture or by the slow disintegrating effects of the weather. The rock splits up along these concealed lines of division, whether the agent of demolition be the hammer or frost. In coarse-textured rocks, on the other hand, joints are apt to show themselves as more irregular sinuous rents.

As a rule, they run perpendicular, or approximately so, to the planes of bedding, and descend vertically at not very unequal distances, so that the portions of rock between them, when seen in profile, appear marked off into so many wall-like masses. But this symmetry often gives place to a more or less tortuous course with lateral joints in various random directions, more especially where the different strata vary considerably in lithological characters. A single joint may be traced for many yards, sometimes, it is said, for several miles, more particularly when the rock is fine-grained, as in limestone. But where the texture is coarse and unequal, the joints, though abundant, run into each other in such a way that no one in particular can be identified for more than a limited distance. The number of joints in a mass of stratified rock varies within wide limits. Among strata which have undergone little disturbance the joints may be separated from each other by intervals of several yards. But in other cases, where terrestrial movement has been considerable, the rocks are so jointed as to have acquired therefrom a fissile character that has nearly or wholly obliterated their tendency to split along the lines of bedding.

An important feature in the joints of stratified rocks is the direction in which they intersect each other. In general they have two dominant trends, one coincident, on the whole, with the direction in which the strata are inclined from the horizon, and the other running transversely at a right angle or nearly so. The former set is known as *dip-joints*, because they run with the *dip* or inclination of the rocks; the latter is termed *strike-joints*, inasmuch as they conform to the *strike* or general outcrop. It is owing to the existence of this double series of joints that ordinary quarry-

Fig. 226.—Jointing in quarry of Caithness Flags, near Holburn Head.

ing operations can be carried on. Large quadrangular blocks can be wedged off, which would be shattered if exposed to the risk of blasting. A quarry is usually worked to the dip of a rock; hence the strike-joints form clean-cut faces in front of the workmen as they advance. These are known as "backs," and the dip-joints, which traverse them, as "cutters." The way in which this double set of joints occurs in a quarry may be seen in Fig. 226, where the close parallel lines traversing the shaded and unshaded faces mark the planes of stratification, which here are inclined from the spectator. The steep faces in light are defined by the strike-joints or "backs." The faces in shadow have been quarried out along dip-joints or "cutters." It will be observed that the long face in sunlight is cut by parallel lines of dip-joints not yet opened in quarrying, while, in like manner, the shaded face to the right is that of a dip-joint which is traversed by parallel lines of strike-joint.

Ordinary household coal presents a remarkably well-developed system of joints. A block of such coal may be observed to be traversed by fine laminæ, the surfaces of many of which are soft and soil the fingers. These are the planes of stratification. Perpendicular to them run divisional planes, which cut each other at right angles or nearly so, and thus divide the mineral into cubical fragments. One of these sets of joints makes clean sharply defined surfaces, and is known as the *face*, *slyne*, *cleat*, or *bord*; the other has rougher, less regular surfaces, and is known as the *end*. The face remains persistent over wide areas; it serves to define the direction of the roadways in coal-mines, which must run with it.

According to observations made by Jukes, both strike-joints and dip-joints occur in beds of recently-formed coral-rock in the Australian and other reefs.[2] In like manner, a remarkably definite system of jointing has been noticed by Mr. Gilbert in the recent clays and muds of the dried-up bed of the Sevier lake in Utah. Such modern sediments have certainly never been subject to the pressure of any superincumbent rock, nor to the torsion or other disturbance incident to subterranean movement. That great force has

---

[2] "Manual of Geology," 3d edition, p. 184.

sometimes been concerned in the production of the structure is instructively shown in some conglomerates, where the joints traverse the inclosed pebbles, as well as the surrounding matrix, in such a way that large blocks of hard quartz are cut through by them as sharply as if they had been sliced in a lapidary's machine, and the same joints can be traced continuously through many yards of the rock (Fig. 227).[3] Indication of relative movement of the sides of a joint is often supplied by their rubbed and striated sur-

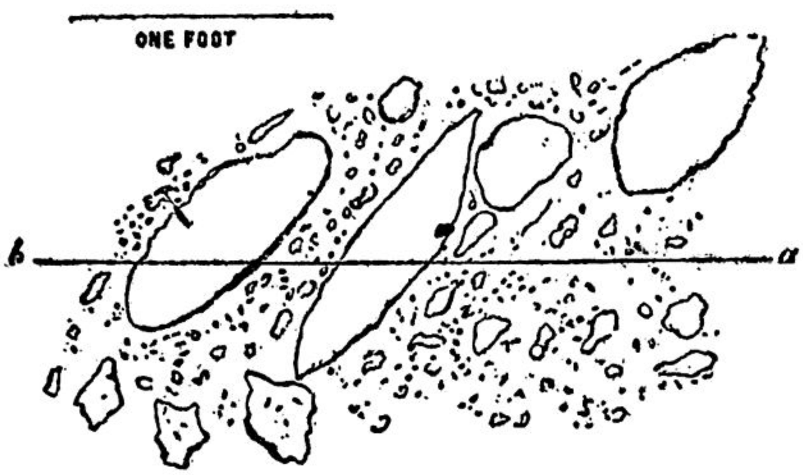


Fig. 227.—Plan of coarse conglomerate of blocks of Cambrian rocks in Carboniferous Limestone, traversed by a line of joint cutting the individual bowlders in the line *a b*. Coast near Skerries, Dublin County (*B.*).

faces, termed *slickensides*, which have evidently been ground against each other. They are often coated with hæmatite, calcite, chlorite, or other mineral, which has taken a cast of the striæ and then seems itself to be striated.

The cause of jointing has not been satisfactorily explained. Various theories have been proposed to account for the structure; but as no one will explain every case, it is probable that what we call joints may have originated in several different ways, or, in other words, that the results of several distinct natural processes are all indiscrimi-

[3] De la Beche, "Geol. Observer," p. 628.

nately comprised under the term joint. The following theories may be enumerated.

(1) Contraction.—The contraction of rocks gives rise to fissures of retreat in their mass, whether it results from the drying and consolidation of aqueous sediments, or from the cooling of masses that have been molten or have been highly heated. The prismatic or columnar system of joints observable in the gypsum of the Paris Basin, of which the beds are divided from top to bottom into vertical hexagonal prisms, may be an instance of this cause.[4] A columnar structure has often been superinduced upon stratified rocks (sandstone, shale, coal) by contact with intrusive igneous masses (Book IV. Part VIII).

(2) Crystalline or Magnetic Forces.—Jointing has been regarded as referable to forces analogous to those that have produced the cleavage of minerals, the difference between the two arising perhaps from the forces in the case of jointing being subordinated to terrestrial magnetism, while those concerned in mineral cleavage are obedient to crystalline polarity.[5] But this theory has met with little support.

(3) Compression.—Jointing has been associated by some authors with cleavage as a result of the lateral compression of rocks (p. 532).

(4) Torsion.—From experiments on the behavior of various substances under the strain of torsion, M. Daubrée concludes that a system of joints may be explained as the results of the torsion of strata arising during the movements to which the crust of the earth has been subjected.[6]

---

[4] Jukes's "Manual," 3d edition, p. 180.
[5] Prof. W. King, Trans. Roy. Irish Acad. xxv. 1875, p. 641.
[6] "Etudes de Geologie Experimentale," p. 300, and ante, p. 541.

(5) Earthquakes.—The existence of joints has been referred to the results of the earth-waves generated during earthquakes, the rocks through which the waves pass being exposed to such powerful alternate compression and tension as to rupture them.[1]

Joints form natural lines for the passage downward and upward of subterranean water. They likewise furnish an effective lodgment for the action of frost, which wedges off blocks of rock in the manner already described (p. 698). As they serve, in conjunction with bedding, to divide stratified rocks into large quadrangular blocks, their influence in the weathering of these rocks is seen in the symmetrical and architectural as well as splintered, dislocated aspects so familiar in the scenery of sandstone and limestone districts.

2. **In Massive (Igneous) Rocks.**—While in stratified rocks the divisional planes consist of lines of bedding and of joint,

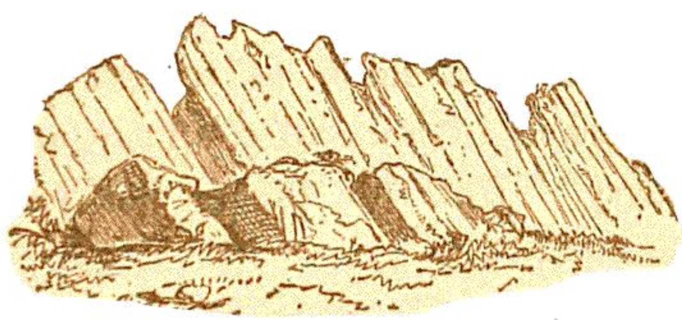


Fig. 228.—Porphyry, near Clynog Vawr, Caernarvonshire, divided into slabs by a system of close parallel joints (*B.*).

cutting each other usually at a high, if not a right angle; in massive (igneous) rocks, they include joints only; and as these do not, as a rule, present the same parallelism as lines of bedding, unstratified rocks, even though as full of joints, have not the regularity of arrangement of stratified formations. Some massive rocks indeed may have one system of divisional planes so largely developed as to acquire

[1] W. O. Crosby, Proc. Boston Soc. Nat. Hist. xxii. 1882, p. 72.

a bedded or fissile character. This structure, characteristically shown by phonolites, may also be detected among ancient porphyries (Fig. 228). Most massive rocks are traversed by two intersecting sets of chief or "master" joints, whereby the rock is divided into long quadrangular, rhomboidal, or even polygonal columns. A third set may usually be noticed cutting across the columns and articulating them into segments, though generally less continuous and dominant than the others (Fig. 229). When these last-

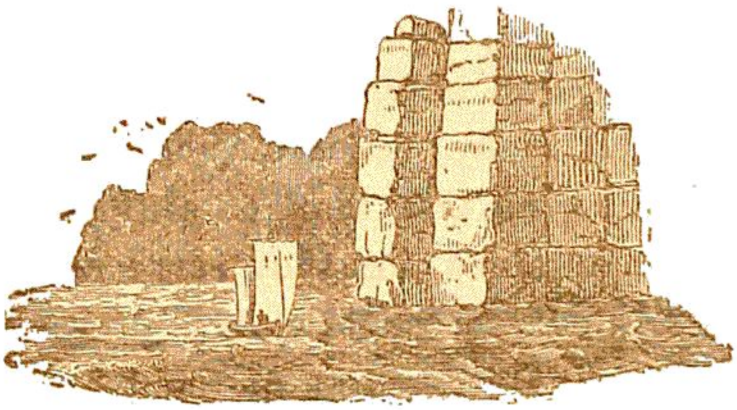


Fig. 229.—Jointed structure of Granite.

named cross-joints are absent or feebly developed, columns many feet in length can be quarried out entire. Such monoliths have been from early times employed in the construction of obelisks and pillars.

In large masses of granite, an outward inclination of the natural divisional planes of the rock may sometimes be observed, as if the granite were really a rudely bedded mass, having a dip toward and under the strata which rest upon its flanks. It is not a foliated arrangement of the constituent minerals analogous to the foliation of gneiss, for it can be traced in perfectly amorphous and thoroughly crystalline granite, but is undoubtedly a form of jointing by reason of which the rock weathers into large blocks piled one upon another like a kind of rude cyclopean masonry.[8] In the quarrying of granite, the workmen recognize that the rock splits into blocks much more easily in one direction, though externally there is no trace of any structure which could give rise to this tendency.

Rocks of finer grain than granite, such as many diorites and dolerites, acquire a prismatic structure from the number and intersection of perpendicular joints. The prisms, however, are unequal in dimensions, as well as in the number and proportions of their sides, a frequent diameter being 2 or 3 feet, though they may sometimes be observed three times thicker, and extending up the face of a cliff for 300 or 400 feet. It is by means of joints that precipitous faces of crystalline, no less than of sedimentary rock are produced and maintained, for they serve as openings into which frost drives every year its wedges of ice. They likewise give rise to the formation of the fantastic pinnacles and fretted buttresses characteristic of massive rocks.

As lava, erupted to the surface, cools and passes into the solid condition, a contraction of its mass takes place. This diminution of bulk is accompanied by the development of divisional planes or joints, more especially diverging from the upper and under surfaces, and intersecting at irregular distances, so as to divide the rock into rude prisms. Occasionally another series of joints, at a right angle to these, traverses the mass, parallel with its upper and under surfaces, and thus the rock acquires a kind of fissile or bedded appearance. The most characteristic structure, however, among volcanic rocks is the prismatic, or, as

---

[8] In the granite of the axes of the Rocky Mountains and parallel ranges to the westward, a kind of bedded structure has been described as passing under the crystalline schists.

it is incorrectly termed, "basaltic." Where this arrangement occurs, as it so commonly does in basalt, the mass is divided into tolerably regular pentagonal, hexagonal, or irregularly polygonal prisms or columns, set close together at a right angle to the main cooling surfaces (Fig. 230). These prisms vary from 1 inch or even less to 18 or more inches in diameter, and range up to 100 or even 150 feet in height. Many excellent and well-known examples of columnar structure are exhibited on the coast-cliffs of the Tertiary volcanic region of Antrim and the west of Scotland, as in the Giant's Causeway and Fingal's Cave. In many cases, no sharp line can be drawn between a columnar basalt and the beds above and below, which show no similar structure, but into which the prismatic mass seems to pass.

Considerable discussion has arisen as to the mode in which this columnar structure has been produced. That it is a species of jointing, due to contraction, was long ago pointed out by Scrope, and is now generally conceded, though the conditions under which it is produced are not quite clear.[9] Prof. James Thomson showed how the columnar structure might be explained as a phenomenon of contraction, and subsequently Mr. Mallet concluded that "all the salient phenomena of the prismatic and jointed structure of basalt can be accounted for upon the admitted laws of cooling, and contraction thereby, of melted rocks possessing the known properties of basalt, the essential conditions being a very general homogeneity in the mass cooling, and that

---

[9] G. P. Scrope, "Geology and Extinct Volcanoes of Central France," p. 92. J. Thomson, Brit. Assoc. 1863, sects. p. 95. R. Mallet, Proc. Roy. Soc. 1875; Phil. Mag. ser. 4, vol. i. pp. 122, 201. T. G. Bonney, Q. J. Geol. Soc. 1876, p. 140. J. Walther, Jahrb. Geol. Reichsanst. 1886, p. 295. J. P. Iddings, Amer. Journ. Sci. xxxi. 1886, p. 321.

the cooling shall take place slowly, principally from one or more of its surfaces." In the more perfectly columnar basalts, the columns are sometimes articulated, each prism being separable into vertebræ, with a cup-and-ball socket at each articulation (Figs. 231 and 232). This peculiarity was traced by Mr. Mallet to the contraction of each prism in its length and in its diameter, and to the consequent production of transverse joints, which, as the resultant of the two contracting strains, are oblique to the sides of the prism, but, as the obliquity lessens toward the centre, assume necessarily when perfect, a cup-shape, the convex surface pointing in the same direction as that in which the prism has grown.

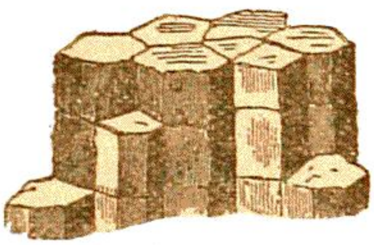


Fig. 230.—Ordinary columnar structure of lava.

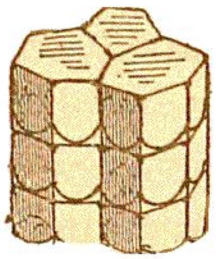


Fig. 231.—Ball-and-socket jointing of columns.

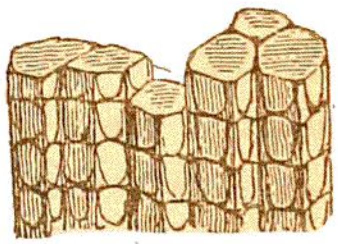


Fig. 232.—Modification of ball-and-socket structure.

This explanation, however, will hardly account for cases, which are not uncommon, where the convexity points the other way, or where it is sometimes in one direction and sometimes in the other.[10] The remarkable spheroids (Fig. 94) which appear in many weathered igneous rocks besides basalts may be due, where they are not the result of weathering, to continued contraction within the hexagonal or polygonal spaces defined by the columnar joints and cross-joints of a cooling mass. The contraction of these blocks would

---

[10] Mr. Scrope pointed this out (Geol. Mag. September, 1875), though Mr. Mallet (ibid., November, 1875) replied that in such cases the articulations must be formed just about the dividing surface, between the part of the rock which cooled from above and that which cooled from below. See also on this subject J. P. O'Reilly, Trans. Roy. Irish Acad. xxvi. 1879, p. 641.

tend to the development of successive spheroidal shells, which might remain mutually adherent and invisible in a fresh fracture of the rock, yet might make their presence effective during the complex processes of weathering."[11] After some exposure, the spheroids of basalt begin to appear, and gradually crumble away by the successive formation and disappearance of external weathered crusts or coats, which fall off into sand and clay. Almost all augitic or hornblendic rocks, with many granites and porphyries, exhibit the tendency to decompose into rounded spheroidal blocks. The columnar structure, though abundant among modern volcanic rocks, is by no means confined to these. It is as well displayed among the lavas of the Lower Old Red Sandstone, and of the Carboniferous Limestone in central Scotland, as among those of Tertiary age in Auvergne or the Vivarais.

As already stated, prismatic forms have been superinduced upon rocks by a high temperature and subsequent cooling, as where coal and sandstone have been invaded by basalt. They may likewise be observed to arise during the consolidation of a substance from aqueous solution. In starch, for example, the columnar structure may be well developed, and not infrequently radiates from certain centres, as in basalt and other igneous rocks.

3. **In *Foliated (Schistose)* Rocks.**—The schists likewise possess their joints, which approximate in character to those among the massive igneous rocks, but they are on the whole less distinct and continuous, while their effect in dividing the rocks into oblong masses is considerably modified by the transverse lines of foliation. These lines play somewhat the

---

[11] Bonney, Q. J. Geol. Soc. 1876, p. 151. The perlitic structure is probably a microscopic example of the same kind of contraction.

same part as those of stratification among the stratified rocks, though with less definiteness and precision. The jointing of the more massive foliated rocks, such as the coarser varieties of gneiss, approaches most closely to that of granite; in the finely fissile schists, on the other hand, it is rather linked with that of sedimentary formations. Upon these differences much of the characteristic variety of outline presented by cliffs and crests of foliated rocks depends.

Part III. Inclination of Rocks

The most casual observation is sufficient to satisfy us that the rocks now visible at the earth's surface are seldom in their original position. We meet with sandstones and conglomerates composed of water-worn particles, yet forming the angular scarps of lofty mountains; shales and clays full of remains of fresh-water shells and land-plants, yet covered by limestones made up of marine organisms, and these limestones rising into great ranges of hills, or undulating into fertile valleys, and passing under the streets of busy towns. Such facts, now familiar to every reader, and even to many observers who know little or nothing of systematic geology, point unmistakably to the conclusion that most of the rocks of the land have been formed under water, sometimes in lakes, more frequently in the sea, and that they have been elevated into land.

But further examination discloses other and not less convincing evidence of movement. Judging from what takes place at the present time on the bottoms of lakes and of the sea, we confidently infer that when the strata now constituting so much of the solid framework of the land were formed, they were laid down nearly horizontally, or at least at low angles (ante, p. 839). When, therefore, we find them inclined at all angles, and even standing on end, we conclude that they have been disturbed. Over wide spaces, they have been upraised bodily, with little alteration of horizontality; but in most places some departure from that original position has been effected.

Dip.—The inclination thus given to rocks is termed their **Dip**. Its amount is expressed in degrees measured from the plane of the horizon. Thus a set of rocks half-way between the horizontal and vertical position would be said to dip at an angle of 45°, while if vertical they would be marked with the angle of 90°. The inclination is measured with an instrument termed the Clinometer, which is vari-

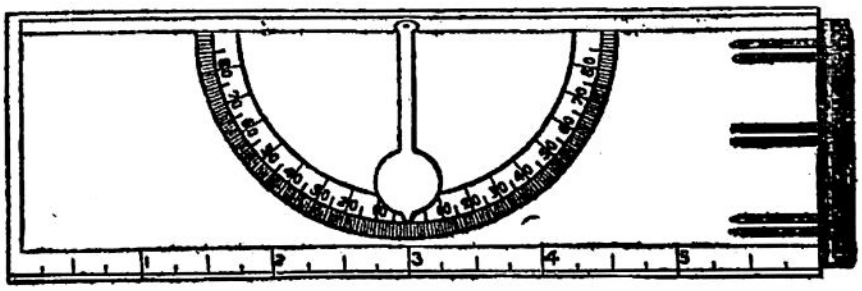


Fig. 233.—Clinometer—the leaf containing the pendulum and index.

ously made, but of which one of the simplest forms is shown in Fig. 233. This consists of a thin strip of boxwood, two inches broad, strengthened with brass along the edges, and divided into two leaves, each 6 inches long, hinged together so that when opened out they form a foot-rule. On the inside of one of these leaves, a graduated arc with a pendulum is inserted. When the instrument is held horizontally, the pendulum points to zero. When placed vertically, it marks 90°. By retiring at a right angle to the direction of dip of a group of inclined beds, and holding the clinometer before the eye until its upper edge coincides with the line of bedding, we readily obtain the amount or angle of dip. In observations of this nature it is of course necessary either to place the clinometer strictly parallel with the direction of dip, or, if this be impossible, to take two measurements, and calculate from them the true angle.[1] Simple as observation of dip is, it is attended with some liabilities to error,

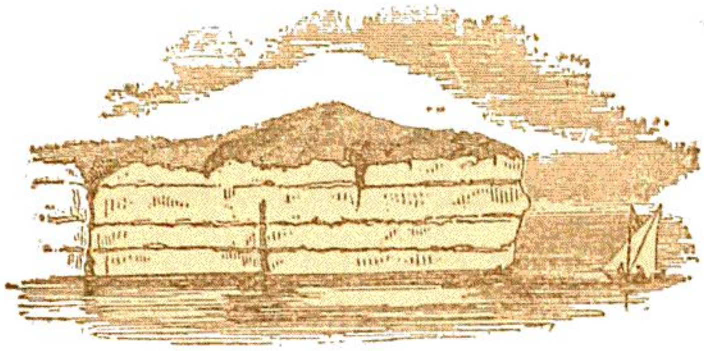


Fig. 234.—Apparently horizontal strata (*B.*).

against which the observer should be on his guard. A single face of rock may not disclose the true dip, especially if it be a clean-cut joint-face. In Fig. 234, for example, the strata might be supposed to be horizontal; but another side

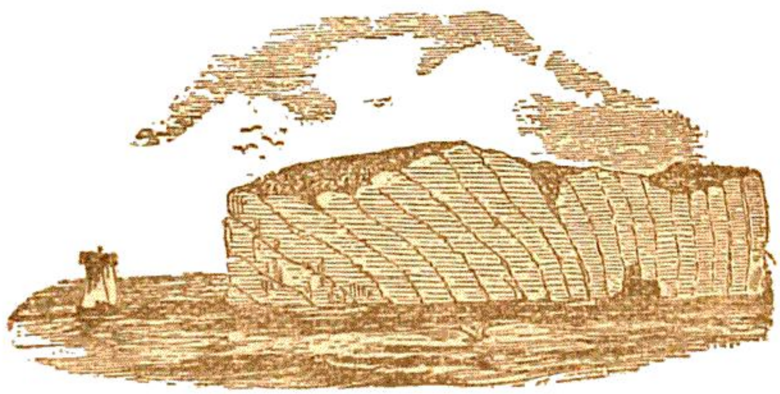


Fig. 235.—Real inclination of strata shown in Fig. 234 (*B.*).

view of them (as Fig. 235) might show them to be gently inclined or even nearly vertical.

Again, a deceptive surface inclination is not infrequently to be seen among thin-bedded strata. Mere gravitation,

[1] In Jukes's "Memoir on the South Staffordshire Coal-Field," in Memoirs of Geol. Survey (2d edit. p. 213), a formula is given for calculating the true dip from the apparent dip seen in a cliff. A graphical method of computing the true dip from observations of two apparent dips has been suggested by Mr. W. H. Dalton, Geol. Mag. x. p. 332. See also Green's "Physical Geology," 1882, p. 460. A. Harker, Geol. Mag. 1884, p. 154.

aided by the downward pressure of sliding detritus or "soil-cap," suffices to bend over the edges of fissile strata, which, though really dipping into the hill, are thus made to appear superficially to dip away from it (Fig. 236). Similar effects, with even proofs of contortion, may be noticed under bowlder clay, or in other situations where the rocks have been bent over and crushed by a mass of ice.

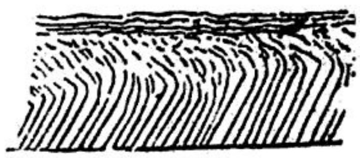


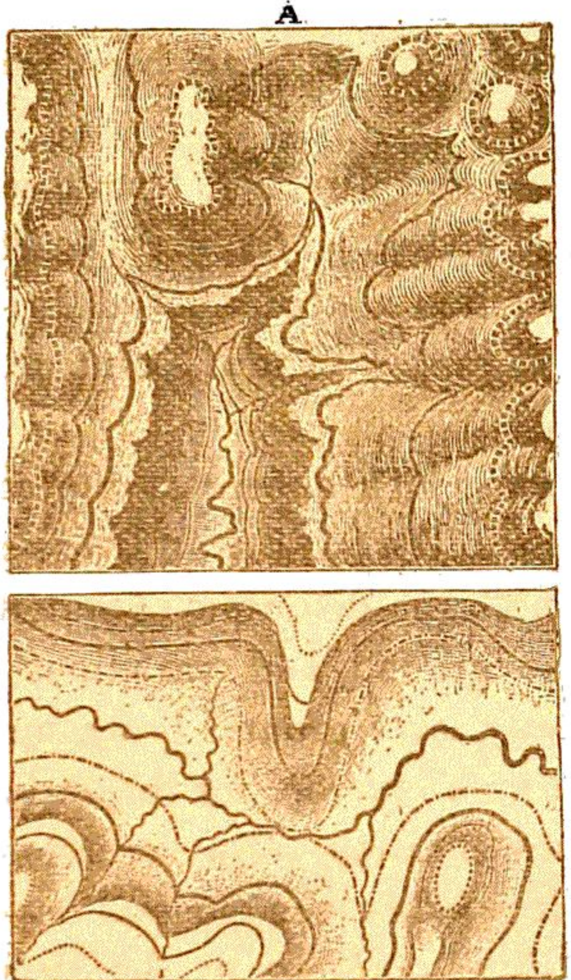
Fig. 236.—Deceptive superficial dip.

When the dip is outward in every direction from a central point, it is said to be *quâ-quâ-versal* (A in Fig. 238). Strata thus affected are thrown into a dome-shaped structure, while when the dip is toward a central point they have a basin-shaped structure.

Outcrop.—The edges of strata which appear at the surface of the ground are termed their Outcrop or Basset. If the strata are quite horizontal, the direction of outcrop depends on inequalities of the ground and variations in amount of denudation. Perfectly level ground lying upon horizontal beds shows, of course, no outcrop, for the surface coincides with a plane of stratification. But occasional water-courses have been eroded below the general level, so as to reveal along their sides outcrops of the strata. The remarkable sinuosities of outcrop produced by the unequal erosion of horizontal strata are illustrated in Fig. 237, where A is a map of a piece of ground deeply trenched by valleys, and B that of an area comparatively little denuded. In both cases the outcrops are seen to wind round the sides of the slopes.

Where strata are inclined, the course of their outcrop is regulated partly by the direction and amount of inclination, and partly by the form of the ground. When with low angles of dip they *crop out*, that is, rise to the surface, along a perfectly level piece of ground, the outcrop runs at a right angle to the dip. But any inequalities of the surface, such as valleys, ravines, hills, and ridges, will, as in the case of horizontal beds, cause the outcrop to describe a circuitous course, even though the dip should remain perfectly steady all the while. If a line of precipitous gorge should run directly with the dip, the outcrop will there be coincident with the dip. The occurrence of a gently shelving valley in that position will cause the outcrop to descend on one side and to mount in a corresponding way on the other, so as to form a V-shaped indentation in its course. A ridge, on the other hand, will produce a deflection in the opposite direction. Hence a series of parallel ridges and valleys, running in the same direction as the dip of the strata underneath, causes the outcrop to describe a widely serpentinous course.

A



B

Fig. 237—Sinuous outcrops of horizontal strata depending on inequalities of surface.
The wavy black lines mark the outcrops of successive conformable horizontal beds.

The breadth of the outcrop depends on the thickness of the stratum and on the angle of dip. A bed one foot thick inclined at an angle of 1°, on a perfectly level piece of ground would have an outcrop about 60 feet broad. At a dip of 5° the breadth of the outcrop would be a little over 11 feet. At 30° it would be reduced to 2 feet, and the diminution would continue until, when the bed was on end, the breadth of the outcrop would, of course, exactly correspond with the thickness of the bed. It is further to be observed that among vertical rocks, the direction of the outcrop necessarily corresponds with the strike, and con-

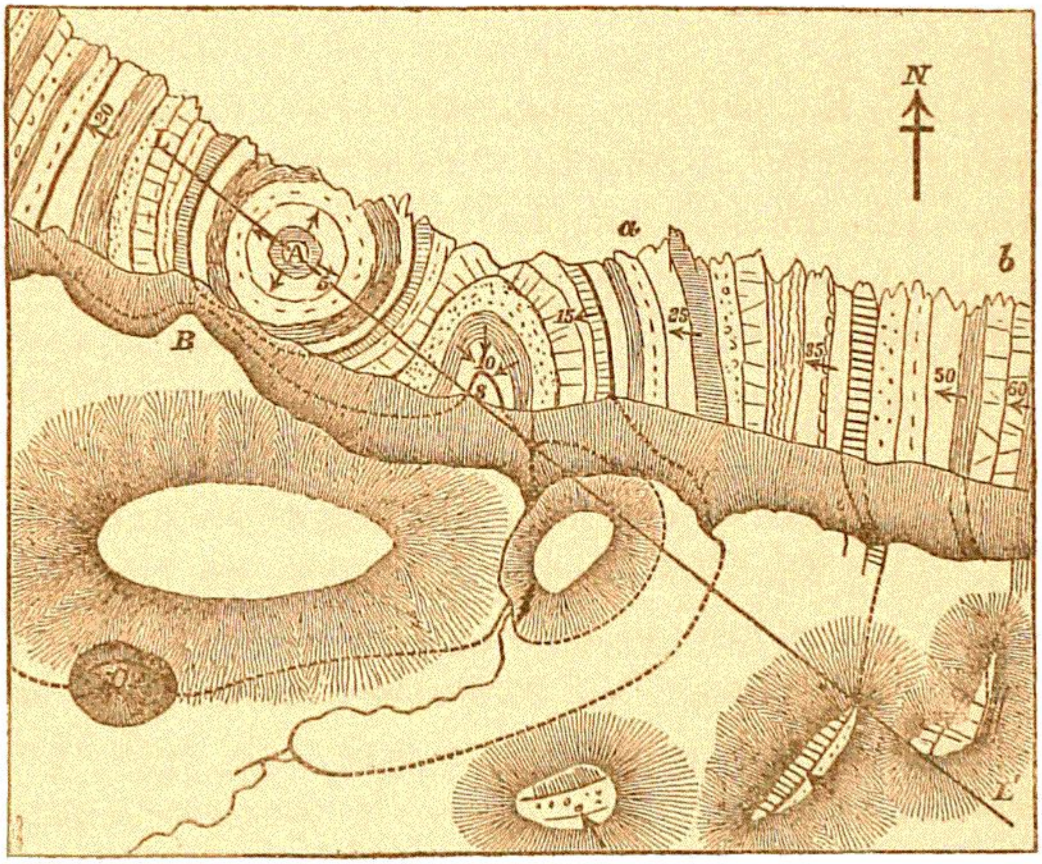


Fig. 238.—Geological Map, showing strata exposed continuously along a beach and occasionally in the interior.

tinues to do so irrespective altogether of any irregularities of the ground. The lower therefore the angle of inclination, the greater is the effect of surface-inequalities upon the line of outcrop; the higher the angle, the less is that influence, till when the beds stand on end it ceases.

Strike.—A horizontal line drawn at a right angle to the dip is called the Strike of the rocks. From what has just been said, this line must coincide with outcrop when the surface of the ground is quite level, as on the beach in Fig. 238, and also when the beds are vertical. At all other times, strike and outcrop are not strictly coincident, but the latter wanders to and fro across the former according to changes in the contour of the ground. The strike may be a straight line, or may curve rapidly in every direction, according to behavior of the dip. A set of beds dipping westward for half a mile (*a* to *b*, Fig. 238) have a north and south strike for the same distance. If the dip changes to S.W., S., S.E., and E., the strike will bend round in a curving line (as at S). In the case of a *quâ-quâ-versal* dip the strike forms a complete circle (as at A). The dip being ascertained gives the strike, but the strike does not certainly indicate the direction of dip, which may be either to the one side or the other. Two groups of strata, dipping the one east and the other west, have both a north and south strike. Strike may be conceived as always a level line on the plane of the horizon, so that, no matter how much the ground may undulate, or the outcrop may vary, or the dip may change, the strike will remain horizontal. Hence, in mining operations, it is commonly spoken of as the *level-course* or *level-bearing*. A "level" or underground roadway, driven through a coal-seam at right angles to the dip, will undulate in its trend if the dip changes in direction, but it may be made perfectly level, and kept so throughout a whole coal-field so long as it is not interfered with by dislocations.

In Fig. 238, the strike and outcrop are coincident on the flat beach, but cease to be so the moment the ground begins to slope up into the coast-cliff. This is seen in the eastern half of the map, where the lines of outcrop slant up into the cliff at an angle dependent mainly on the amount of the dip. A section drawn in the line L L′ would show the geological structure represented in Fig. 239. By noting the angles of dip it is possible to estimate the thickness of a series of beds, and how far beneath the surface any given bed might be expected to be found. If, for instance, the horizontal distance across the strike between beds S and A (Fig. 238) were found to be 200 feet, with a mean dip of 15°, the actual thickness would be 51·8 feet, and bed A would be found at a depth of 53·8 feet below the outcrop of S. If the same development of strata continues inland, the bed *a* should be found at a little more than 200 feet beneath the surface, if a bore were sunk to it in the quarry (Q). If the total depth of rock between *a* and *b* be 1000 feet, then evidently, if the strata could be restored to their original approximately horizontal position, with bed *a* at the surface, bed *b* would be covered to a depth of 1000 feet. It will be noticed also that, as the angle of dip increases, the outcrops

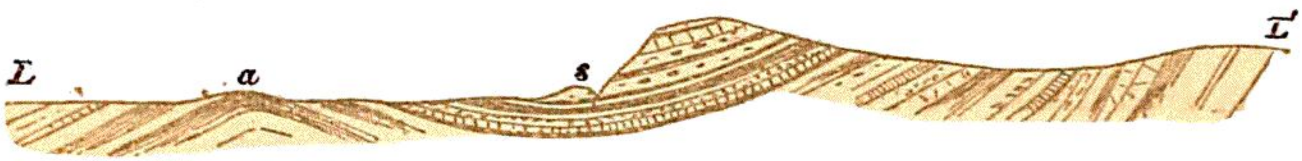


Fig. 239.—Section along the line L L' in Fig. 238.

are thereby brought closer together. Where the outcrops run along the face of a cliff or steep bank (B) they must likewise be drawn together on a map. In reality, of course, these variations take place though the same vertical thickness of rock may everywhere intervene between the several outcrops.

It is usually desirable to estimate the thicknesses of strata, especially where, as in Fig. 239, they are exposed in continuous section. A convenient though not strictly accurate rule for this purpose may be applied in cases where the angle of inclination is less than 45°. The real thickness of a mass of inclined strata may be taken to be $\frac{1}{12}$ of its apparent thickness for every 5° of dip. Thus if a set of beds dips steadily in one direction at 5° for a horizontal space of 1200 feet measured perpendicularly to the strike, their actual thickness will be $\frac{1}{12}$, or 100 feet. If the dip be 15°, the true thickness will be $\frac{3}{12}$, or 300 feet, and so on.[9]

---

[9] Maclaren's "Geology of Fife and the Lothians," 2d edit. p. xix. For tables for estimating dip and thickness see Jukes's "Manual," p. 748; Green's "Physical Geology," p. 460.

PART IV. CURVATURE[1]

A little reflection will show that though, so far as regards the trifling portions of the rocks visible at the surface, we might regard the inclined surfaces of strata as parts of straight lines, they must nevertheless be parts of large curves. Take for example the section in Fig. 240. At the left hand the strata descend beneath the surface at an angle of no more than 15°, but at the opposite end the angle has risen to 60°. There being no dislocation or abrupt change of inclination, it is evident that the beds cannot proceed indefinitely downward at the same angle which they have at the surface, otherwise they would run away from each other, but must bend round to accommodate themselves to

Fig. 240.—Section of inclined strata.

the difference of inclination. By prolonging the lines of bedding for some way beneath and above sea-level, we can show graphically that the strata are necessarily curved (Fig. 241). A section of this kind brings out clearly the additional fact that an upward continuation of the curved beds must have been carried away by the denudation of the surface. In every instance therefore where, in walking over the surface, we traverse a series of strata which gradually, and without dislocations, increase or diminish in inclination, we cross part of a curvature in the strata

[1] A useful compendium of information regarding geological terms for the dislocations and curvatures of rocks has been prepared by M. E. de Marjerie and Prof. A. Heim, "Les dislocations de l'ecorce terrestre," 1888, Zürich (in French and German).

of the earth's crust. The foldings, however, can often be distinctly seen on cliffs, coast-lines, or other exposures of rock (Fig. 242). The observer cannot long continue his researches in the field without discovering that the strata composing the earth's outer crust have been almost everywhere thrown into curves, usually so broad and gentle as to escape observation except when specially looked for.

If the inclination and curvature of rocks are so closely

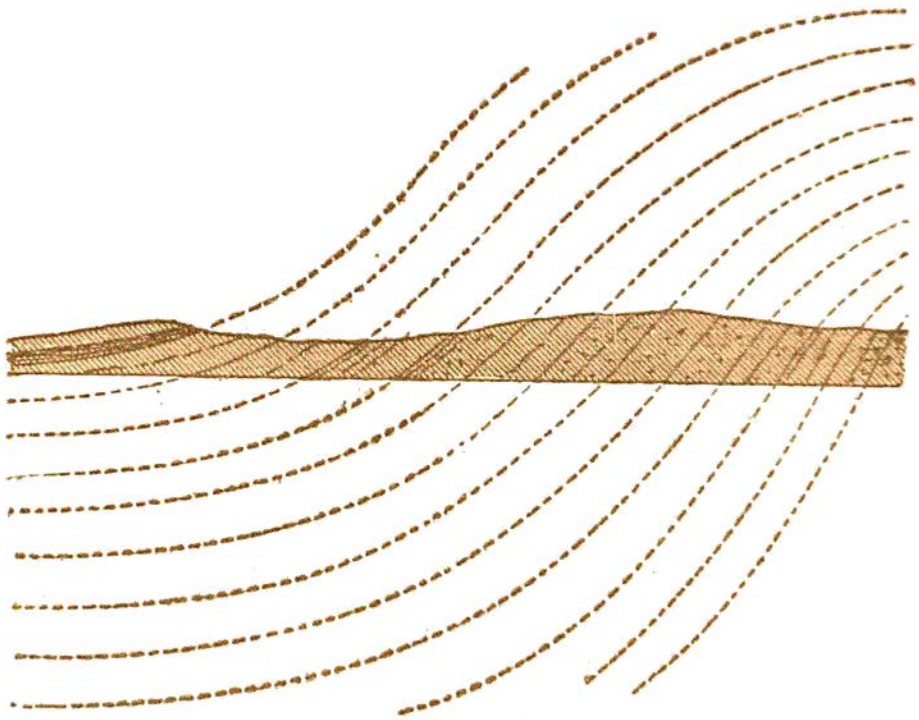


Fig. 241.—Section of inclined strata, as in Fig. 240, showing that they form part of a large curve.

connected, a corresponding relation must hold between their strike and curvature. In fact, the prevalent strike of a region is determined by the direction of the axes of the great folds into which the rocks have been thrown. If the curves are gentle and inconstant, there will be a corresponding variation in the strike. But should the rocks be strongly plicated, there will necessarily be the most thorough coincidence between the strike and the direction of the plication.

Monoclines.—Curvature occasionally shows itself among horizontal or gently inclined strata in the form of an abrupt inclination, and then an immediate resumption of the previous flat or gently sloping character. The strata are thus bent up and continue on the other side of the fold at a higher

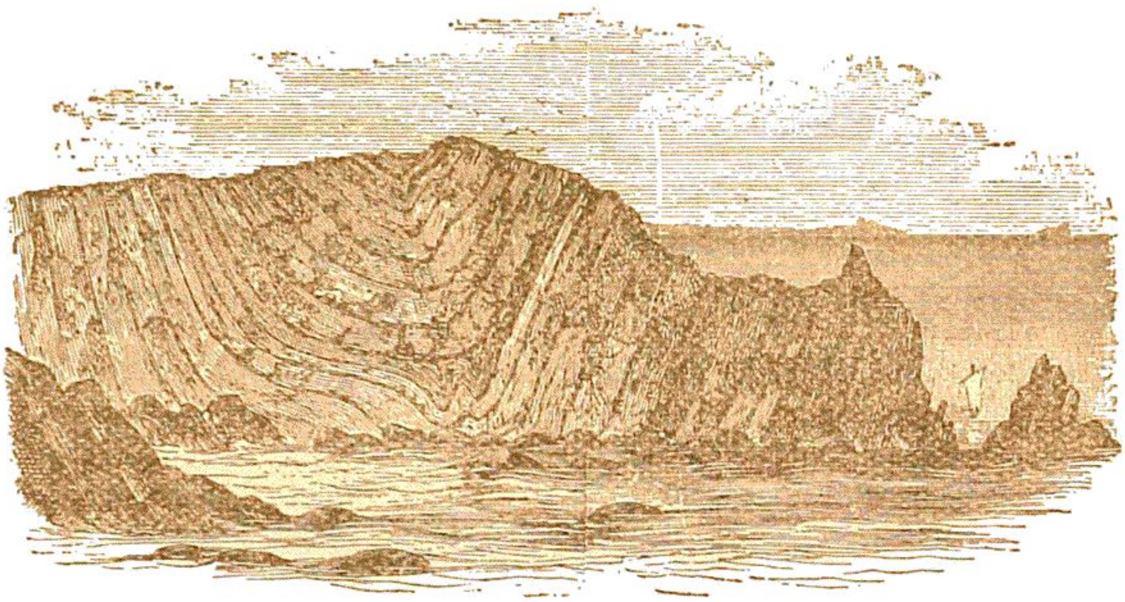


Fig. 242.—Curved Silurian rocks on the coast of Berwickshire.

level. Such bends are called Monoclines or monoclinal folds, because they present only one fold, or one-half of a fold, instead of the two in an arch or trough (Fig. 265, section 1). The most notable instance of this structure in Britain is that of the Isle of Wight (Fig. 243), where the Cretaceous rocks (*c*) on the south side of the

Fig. 243.—Section of a Monoclinal Fold, Isle of Wight.

island rapidly rise in inclination till they become nearly vertical, while the Lower Tertiary strata (*t*) follow with a similar steep dip, but rapidly flatten down toward the north coast. Probably the most gigantic monoclinal folds in the world are those into which the remarkably horizontal and undisturbed rocks of the Western States and Territories of the American Union have been thrown.[2]

From the abundance of inclined strata all over the world, we may readily perceive that the normal structure of the visible part of the earth's crust is one of innumerable foldings of the rocks. Sometimes more steeply, sometimes more gently undulated, not infrequently dislocated and displaced, the sedimentary accumulations of former ages everywhere reveal evidence of great internal movement. Here and there, the movement has resulted in the formation of a dome-shaped elevation of the strata, wherein, as if pushed up from a single point, they slope away on all sides from the centre of greatest upthrust, with a *quâ-quâ-versal* dip. Where the top of the dome has been removed, the successive outcrops of the strata form concentric rings, the lowest at the centre, the highest at the circumference (A in Figs. 238 and 239).

Anticlines and Synclines.—But in the vast majority of cases, the folding has taken place, not round a point but

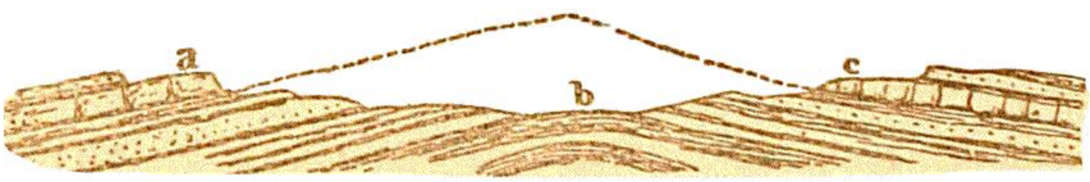


Fig. 244.—Arch, or Anticline, which has been denuded by the removal of beds, as shown by the dotted line *a c* above the axis *b*.

along an axis. Where strata dip away from an axis so as to form an arch or saddle, the structure is termed an Anticline, or anticlinal axis (Fig. 244). Where they dip toward an axis, forming a trough or basin, it is called a

[2] See Powell's "Exploration of the Colorado River of the West," and "Geology of the Uinta Mountains," in the Reports of the United States Geographical and Geological Survey. Dutton's "High Plateaus of Utah," and "History of the Grand Cañon"; Gilbert's "Geology of the Henry Mountains." Compare Richthofen's "China," vol. ii.

Syncline, or synclinal axis (Fig. 245). An anticlinal or synclinal axis must always die out unless abruptly terminated by dislocation. In the case of the anticline, the axis, after continuing horizontal, or but slightly inclined, at last begins to turn downward, the angle of inclination lessens, and the arch then ends or "noses out." In a syncline, the axis eventually bends upward, and the beds, with gradually lessening angles, swing round it. In a symmetrical anticline or syncline, the angle of slope is the same or nearly so on either side (Figs. 244, 245). But a difference of inclination

Fig. 245.—Trough, or Syncline, with strata (*a* *c*) rising from each side of a central axis (*b*).

is frequently to be observed. The Appalachian coal-field, for example, as shown by H. D. and W. B. Rogers, presents an instructive series of plications, beginning with symmetrical folds, succeeded by others with steep fronts toward the west, until at last these steeper fronts pass under the opposite sides of the arches, giving rise to a series of inverted folds (Fig. 246).

Fig. 246.—Section across the folded rocks of the Appalachian Chain (H. D. Rogers).

Inversion.—Inverted folds occur abundantly in regions of great plication. The Silurian uplands of the south of Scotland, for instance, have the arches and troughs tilted in one direction for miles together, so that in one-half of each of them the strata lie bottom upward

(Fig. 247).[3] It is in large mountain-chains, however, that inversion can be seen on the grandest scale. The Alps furnish numerous striking illustrations. On the north side

Fig. 247.—Inverted Folds and Isoclinal Structure.

of that chain, the Secondary and Tertiary rocks have been so completely turned over for many miles that the lowest beds now form the tops of the hills, while the highest lie deep below them. Individual mountains, such as the

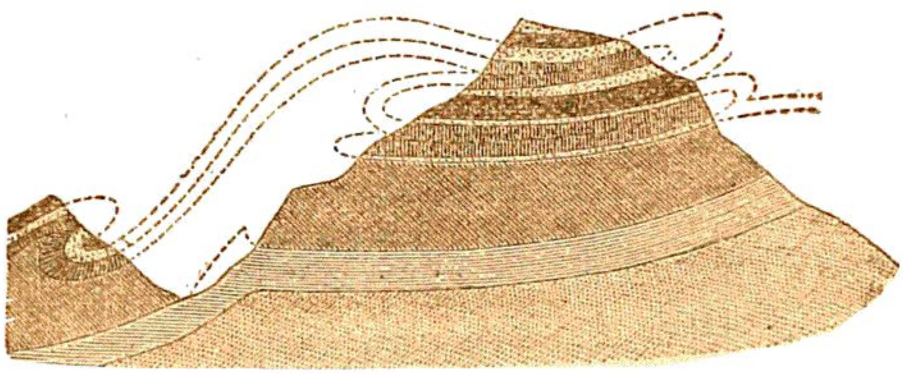


Fig. 248.—Inversion in the Glarnisch Mountain (Baltzer).

Glärnisch and some in the Cantons Glarus and St. Gall (Figs. 248, 249), present stupendous examples of inversion, great groups of strata being folded over and over each other as we might fold carpets.[4]

---

[3] Prof. Lapworth has worked out with much skill the inverted anticlines and synclines of the "Moffat Shales" (Q. J. Geol. Soc. xxxiv. 1878, p. 240); and see also his papers on the "Secret of the Highlands" (Geol. Mag. 1883).

[4] The Glärner double fold has been the subject of considerable discussion. According to Heim ("Mechanismus der Gebirgsbildung") the whole of the rocks, schists included, remained undisturbed until the time of the post-eocene folding. Vacek, however, contends, with evident probability, that the older schists are unconformably overlain by later formations. See M. Vacek, Jahrb. Geol. Reichsanst. 1879, p. 726; 1884, pp. 233, 620; Verhandl. Geol. Reichs. 1880, p. 189; 1881, p. 43. A. Heim, Verhandl. Geol. Reichs. 1880, p. 155; 1881, p. 204. See also Arch. Sci. Phys. Nat. Geneva, November, 1882, p. 24; Lory, Bull. Soc. Geol. France, 3me ser. xi. 1882, p. 14. In Fig. 249, no mere plica-

Where a series of strata has been so folded and inverted that its reduplicated members appear to dip regularly in one direction, the structure is termed isoclinal. This structure, illustrated on a small scale among the curved Silurian rocks shown in Fig. 247, occurs on a grand scale among the Alps, where the folds have sometimes been so squeezed together that, when the tops of the arches have been worn away, the strata could scarcely be supposed to have been really inverted, save for the evidence as to their

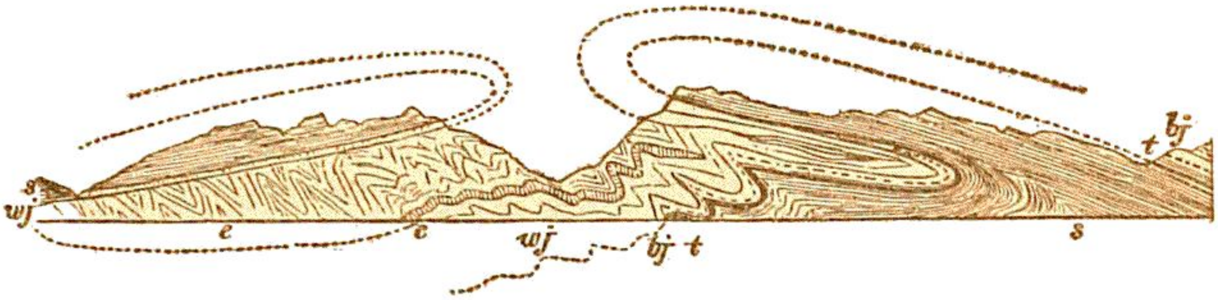


Fig. 249.—Inversion and Thrust-plane among the mountains south of the Lake of Wallenstadt, Cantons Glarus and St. Gall (A. Heim).

e, Eocene; *c*, Cretaceous; *w.j.* White Jura thrust upward on the left hand over the plicated Eocene; *b.j.* Brown Jura; *t*, Trias; *s*, Schistose rocks, perhaps metamorphosed Palæozoic formations.

true order of succession supplied by their included fossils. The extent of this compression in the Alps has been already (p. 539) referred to.[5] So intense has been the plication, and so great the subsequent denudation, that portions of Carboniferous strata appear as if regularly interbedded among

tion could bring the White Jura where it lies comparatively undisturbed on the edge of the excessively plicated Eocene beds. It has evidently been pushed over the latter, the line of junction between them being a "thrust-plane" (p. 915).

[5] See also F. M. Stapff, "Zur Mechanik der Schictenfaltungen," Neues Jahrb. 1879, pp. 292, 792. A fine series of sections illustrating the various features of mountain structure may be found in the plates accompanying the "Materiaux pour la Carte Geologique de la Suisse." See especially Livraison xvi. on the Vaudois Alps by Prof. Renevier; Livraison xxi. by E. Favre and Schardt, on Canton de Vaud, etc., and xxv. by A. Heim on the High Alps between Reuss and Rhine. An interesting study of an abnormal system of folds and faults involving Triassic, Jurassic and Cretaceous rocks in the south of France, will be found in M. Bertrand's monograph, "Le Massif d'Allauch," Bull. Carte. Geol. France, iii. No. 24, 1891, p. 283.

Jurassic rocks, and indeed could not be separated save after a study of their inclosed organic remains.

A further modification of the folded structure is presented by the fan-shaped arrangement (*structure en eventail*, *Fächer-Falten*) into which highly plicated rocks have been

Fig. 250.—Fan-shaped structure, Central Alps.
j', Upper Jurassic Limestone; *j*, Brown Jura and Lias; *t*, Trias; *s*, Schistose rocks.

thrown. The most familiar example is that of Mont Blanc, where the sedimentary strata at high angles seem to dip under the crystalline schists (Fig. 249).

Crumpling.—In the general plication of a district there are usually localities where the pressure has been locally so

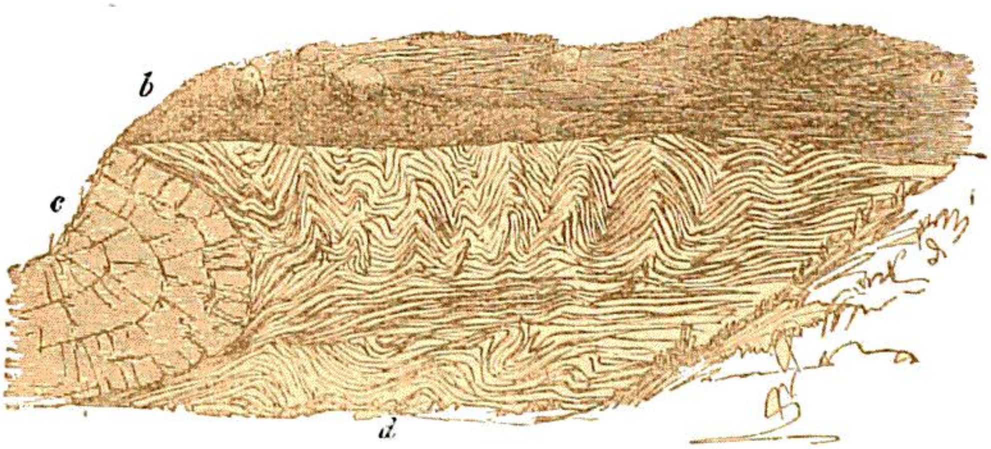


Fig. 251.—Locally crumpled strata near a fault, Dalquharran, Ayrshire.
d, Shales; *c*, Limestone; *b*, Bowlder-clay.

intensified that the strata have been corrugated and crumpled, till it becomes almost impossible to follow out any particular bed through the disturbed ground. On a small scale, instances of such extreme contortion may now and then be found at faults and landslips, where fissile shales have been corrugated by subsiding heavy masses of more solid rock (Fig. 251). But it is, of course, among the more plicated parts of mountain-chains that the structure receives its best illustrations. Few travellers who have passed the upper end of the Lake of Lucerne can have failed to notice the remarkable cliffs of contorted rocks near Fluelen. But innumerable examples of equal or even superior grandeur may

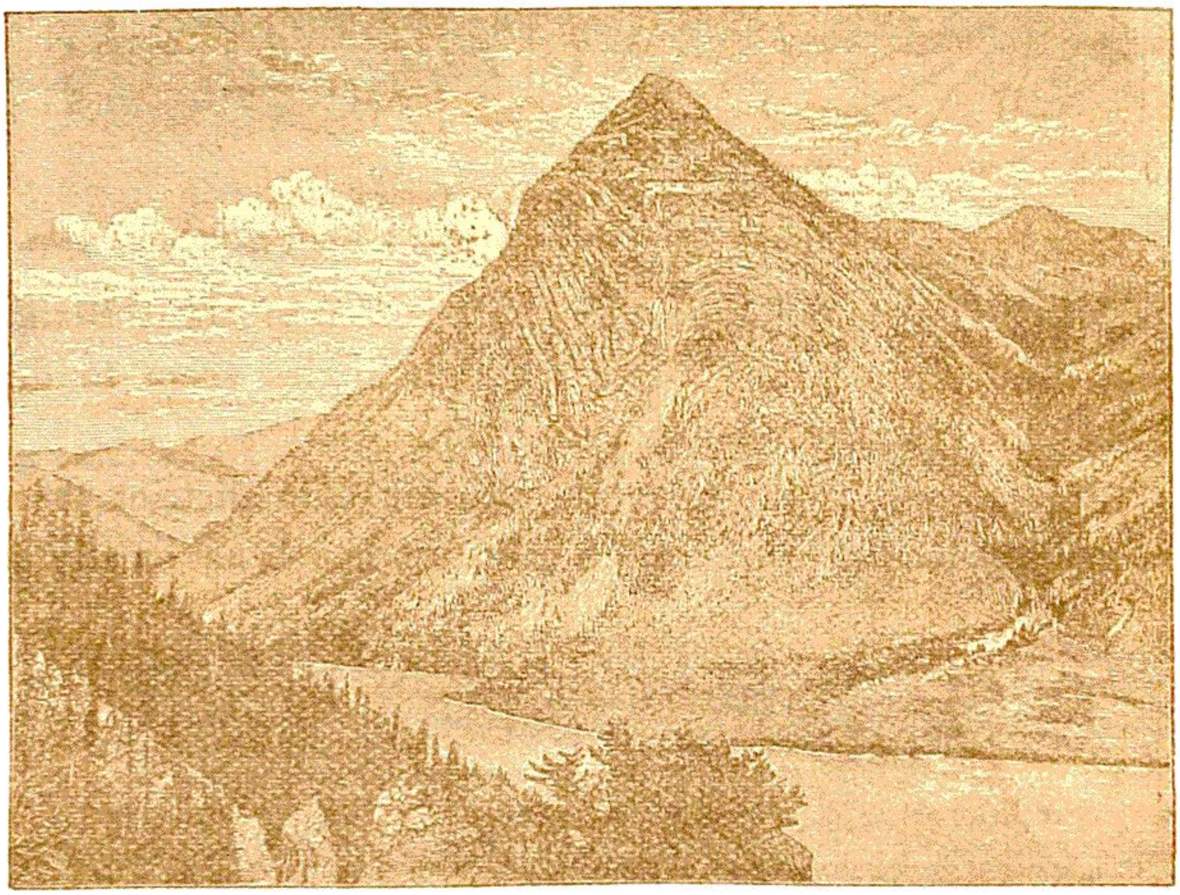


Fig. 252.—Contorted Rocks, east end of Lake Minnewonka, Banff, Canadian Pacific Railway.

be observed among the more precipitous valleys of the Swiss Alps. Striking illustrations of the same structure may be found in any great mountain-chain (Fig. 252). No more impressive testimony could be given to the potency of the force by which mountains were upheaved. And yet, striking as are these colossal examples, involving as they do whole mountain masses in their folds, their effect upon the mind is even heightened when we discover that such has been the strain to which solid limestones and other rocks have been subjected that even their finer layers have been intensely puckered. Some of these minor crumplings are

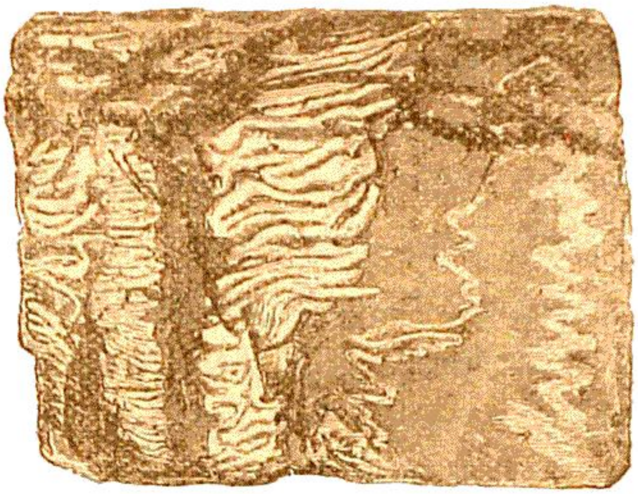


Fig. 253.—Piece of Alpine limestone, showing fine puckering produced by great lateral compression (real size).

readily visible to the eye in hand-specimens (Figs. 36, 253, 254). But in many foliated, crumpled rocks the puckering is so minute as to be best seen with the microscope (Fig. 37). Frequently the puckerings have been ruptured and a fine

Fig. 254.—Crumpled Triassic rock, Todi group, Switzerland (real size).

cleavage or jointing has been produced (Ausweichungsclivage, strain-slip cleavage).

It may often be observed that in strata which have been intensely crumpled, the same bed is reduced to the smallest thickness in the arms of the folds, but swells out at the bends as if squeezed laterally into these loops. This appearance, so noticeable in mountain structure, may be seen on lower grounds, as in Pembrokeshire, where De la Beche has shown that the roofs and pavements of coal-seams are brought together, the coal itself, as having least resistance, being thrust into the loops (*a a*, Fig. 255).[6]

Deformation and Crushing.—During the intense shearing movements to which rocks have been subjected, their individual particles have been compressed, elongated, and made to move past each other, as is instructively shown by the deformation of pebbles and of fossils (p. 535). The most important consequence of this process is the production of the shear-structure already noticed (p. 538). Massive coarsely crystalline pegmatites may be traced through successive stages wherein the component orthoclase and felspar are more and more crushed and drawn out, until in the end the rock becomes a compact finely fissile schist, with a peculiar thready or streaky structure, which can hardly be distinguished from the flow-structure of a rhyolite. This change is more particularly developed along great thrust-planes, but may be observed throughout a mass of rock that has undergone intense shearing.

Fig. 255.—Unequal compression of Coal in crumpling, Pembrokeshire (*B.*).

In many cases lenticular "eyes" of the original rock have been left little or not at all affected, while the portions between them have been crushed and rolled out and have recrystallized more or less completely as true schists (Fig. 332). Sections showing the close connection between

[6] For illustrations of this structure see Heim's "Mechanismus der Gebirgsbildung," where a terminology for the different parts of folds is proposed.

mechanical crushing and the production of a schistose structure may be seen abundantly among the Scottish Highlands.[7] In the Silurian district of Guldalen in Norway diabases and other igneous rocks exhibit every stage in the crushing down of eruptive material and its conversion into schists. Similar structures are well displayed among the schists and their accompaniments in Anglesey.

Fig. 256.—Shear-structure.

Torridon sandstone, Loch Keeshorn, Mag. 30 diam. (drawn by Mr. F. W. Rudler). The felspars and other grains have been crushed and flattened, and the matrix made to move past them as in flow-structure. (Compare Fig. 80.)

Not only are the individual particles of rocks drawn out by shearing, but in the complicated process of mountain-building, larger features of geological structure likewise undergo deformation. The anticlinal and synclinal folds developed in the earlier stages of the process are sometimes bent over and crushed together, so as to be nearly or completely effaced.

Various experiments have been devised to illustrate the facts of mountain-structure. By a combination of parallel layers of different substances exposed to lateral compression and tension it is possible to imitate many of the features of that structure and to produce very instructive diagrams.[8]

PART V. CLEAVAGE

Cleavage-structure having been described at p. 531, we have to notice here the manner in which it presents itself

[7] See Quart. Journ. Geol. Soc. xliv. 1888, p. 392.

[8] See for example, A. Favre, Nature, xix. p. 103; H. M. Cadell, Trans. Roy. Soc. Edin. xxxv. 1888, p. 337. Much information will also be found in Mellard Reade's "Origin of Mountain Ranges," 1886.

on the large scale among rock-masses. The direction of cleavage usually remains persistent over considerable regions, and, as was shown by Sedgwick,[1] corresponds, on the whole, with the strike of the rocks. It is, however, independent of bedding. Among curved rocks, the cleavage-planes may be seen traversing the plications without sensible deflection from their normal direction, parallelism, and high angle. They must thus be strictly later than these plications. But their general coincidence with the trend of the axes of folding serves to indicate a community of origin for cleavage and folding, as concomitant though not absolutely simultaneous effects of the lateral compression of rocks.[2] Among curved strata, the planes of cleavage some-

Fig. 257.—Curved and contorted Devonian Rocks, near Ilfracombe (*B.*). Bedding and cleavage planes are coincident at *a* and *c*, but nearly at right angles at *b*.

times coincide with, and are sometimes at right angles to the planes of bedding, according to the angles of the folding (Fig. 257). The persistence of cleavage-planes across even the most diverse kinds of rock, both sedimentary and igneous, was first described by Sedgwick. Jukes also pointed out that over the whole of the south of Ireland the trend of the cleavage seldom departs 10° from the normal direction E. 25° N., no matter what may be the

[1] "On the Structure of large Mineral Masses," Trans. Geol. Soc. 2d ser. iii. 1835—an admirable memoir, in which the structure of a great cleavage region is clearly and graphically described. Phillips gave a good summary of our knowledge up to 1856 in his "Report on Cleavage" in the British Assoc. Rep. for that year. But the most exhaustive memoir on the subject is that by Mr. A. Harker in the Reports of the British Association for 1885, p. 813, where copious references to the bibliography will be found. See also papers by the Rev. O. Fisher in Geol. Mag. 1884–85, and his "Physics of the Earth's Crust."

[2] Harker, Brit. Assoc. Rep. 1885, p. 852.

differences in character and age of the rocks which it crosses. But though cleavage is so persistent, it is not equally well developed in every kind of rock. As already explained (p. 533), it is most perfect in fine-grained argillaceous rocks, which have been altered by it into slates. It is often well developed in felsites and other igneous rocks, which then furnish good flags or even slates. It may be observed at once to change its character as it passes from fine-grained rocks into others of a more granular or gritty texture. Occasional traces of distortion

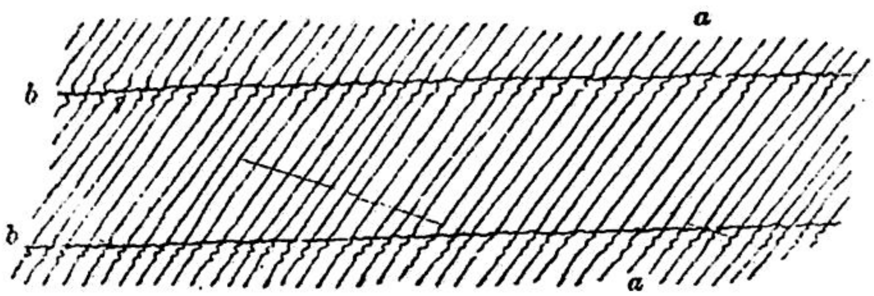


Fig. 258.—Cleaved strata, Wiveliscombe, West Somerset (*B.*).
Showing the cleavage-lines *a a* slightly undulating at the partings of the strata *b b*.

or deviation of the cleavage-planes may be observed at the contact of two dissimilar kinds of rock (Fig. 258).

A region may have been subjected at successive intervals to the compression that has produced cleavage. The Silurian rocks of the southwest of Ireland were upturned, and probably cleaved, before the deposition of the Old Red Sandstone, which has in turn been well cleaved.[8] Evidence of the relative date of cleavage may be obtained from unconformable junctions and from conglomerates. An uncleaved series of strata, lying upon the denuded edges of an older cleaved series, proves the date of cleavage to be intermediate between the periods of the two groups. Fragments of cleaved rocks in an uncleaved conglomerate

[8] De la Beche, "Geol. Observer," p. 620.

show that the rocks whence they were derived had already suffered cleavage, before the detritus forming the conglomerate was removed from them. An intrusive igneous rock, traversed with cleavage-planes like its surrounding mass, points to cleavage subsequent to its intrusion (Fig. 259).[4]

Between cleavage and foliation there is in many cases a close relation. Microscopic examination of some cleaved rocks shows that in original clastic sediment a micaceous mineral has been abundantly developed, the plates of which are ranged along the planes of cleavage. This mica can be distinguished from original mica-flakes in the sediment.

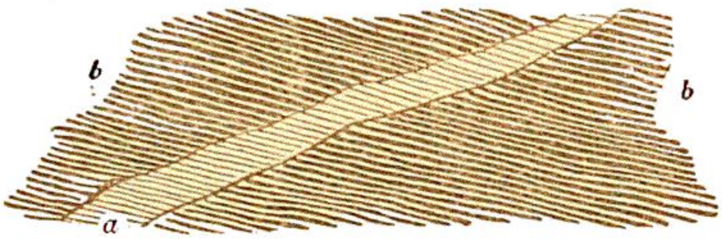


Fig. 259.—Vein of prophyry (*a*) crossing Devonian slates (*b*), Plymouth Sound, both being traversed by cleavage (*B*.).

It may be observed, in many cases, to impart a lustrous silvery or silky sheen to the cleavage-faces of a slate, yet may be at right angles to the original lamination of deposit. Such a crystalline rearrangement is indeed an incipient foliation. It is the same structure, further developed and intensified, which gives their distinctive character to schists. The crystalline metamorphosis naturally proceeds along the lines of least resistance, which in cleaved rocks are the cleavage-planes, and in uncleaved sedimentary rocks are the planes of deposition. Foliation, as already remarked (p. 551), may sometimes represent stratification, sometimes cleavage, and sometimes divisional planes superinduced by shearing or faulting.[5]

---

[4] De la Beche, "Geol. Observer," p. 621.

[5] See Sedgwick, Trans. Geol. Soc. (2), iii. p. 461. Darwin on foliation and

Before passing from this subject it may be well to note how deceptive is the resemblance of cleavage-planes to bedding, especially on weathered exposures of rock. Even experienced observers have been misled by this resemblance. At Llanberis, for example, the lower portion of a section consists of volcanic tuff and the upper of conglomerate. The tuff being compact and fine-grained, has undergone such decided cleavage that at first the flags into which it is divided by the cleavage-planes might be mistaken (as they have in fact been) for bedding, and the conglomerate would then be regarded as a much younger deposit lying unconformably on the tuff. In reality, however, the tuff coincides in its bedding with the conglomerate; they are parts of one continuous series, but the coarse-grained conglomerate has been only slightly affected by the pressure which induced the perfect cleavage in the tuff.

Part VI. Dislocation

The movements which the crust of the earth has undergone have not only folded and corrugated the rocks, but have fractured them in all directions. The dislocations may be either simple Fissures, that is, rents without any vertical displacement of the mass on either side, or Faults, that is, rents where one side has been moved relatively to the other.[1] It is not always possible, in a

---

cleavage, "Geological Observations in South America," 1846, p. 162. A. C. Ramsay, "Geology of North Wales," Mem. Geol. Survey, vol. iii. 2d edit. p. 233. F. M. Stapff, Neues Jahrb. 1882 (i.), p. 82.

[1] The student of this department of geology will find in the joint essay by M. E. de Marjerie and Prof. Heim, cited on p. 536, a valuable handbook of the terms used to decribe the various structures arising from ruptures of the terrestrial crust.

shattered rock, to discriminate between joints and those lines of division to which the term fissures is more usually restricted. Many so-called fissures may be merely enlarged joints. It is common to meet with traces of friction along the walls of fissures, even when no proof of actual vertical displacement can be gleaned. The rock is then often more or less shattered on either side, and the contiguous faces present rubbed and polished surfaces ("slickensides," p. 878). Mineral deposits may also commonly be observed incrusting the cheeks of a fissure, or filling up, together with broken fragments of rock, the space between the two walls. The structure of mineral veins in fissures is described in Part IX., "Ore Deposits."

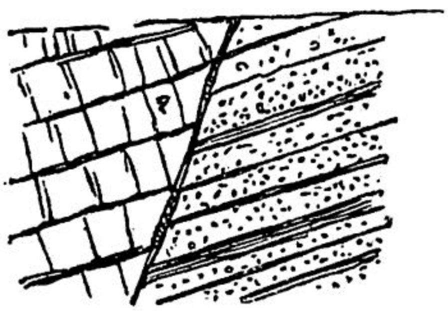


Fig. 260.—Section of sharply-defined Fault without contortion of the rocks.

Nature of Faults.—In a large proportion of cases, however, there has been not only fracture but displacement. The rents have become faults as well as fissures. The movement may have affected only one side of the fissure, or both sides. Sometimes it has consisted in a mere vertical subsidence of one side; in other cases one side has been pushed up, or while one side has moved upward the other has sunk downward, or both sides have been shifted up or down from their original position, but one more than the other. In ordinary faults the displacement is usually vertical or nearly so. But in some regions faults have been produced by a lateral thrust of one side of a fissure past the other side. This structure comes out with remarkable prominence in the gneiss district of western Sutherland, where dikes crossed by such lateral thrusts are disrupted and drawn out along the line of fissure so as to be reduced to a $\frac{1}{16}$ part of their ordinary breadth.[2]

Faults on a small scale are sometimes sharply-defined lines, as if the rocks had been sliced through and fitted together again after being shifted. In such cases, however, the harder portions of the dislocated rocks will usually be found slickensided. More frequently some disturbance has occurred on one or both sides of the fault (Fig. 261). Some-

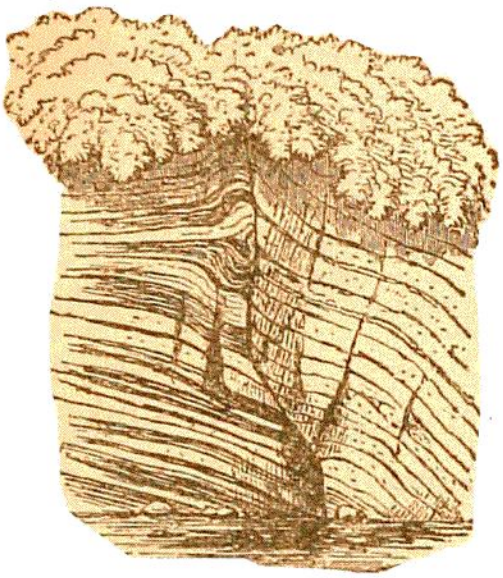


Fig. 261.—Section of a Fault, showing disturbance of rocks.

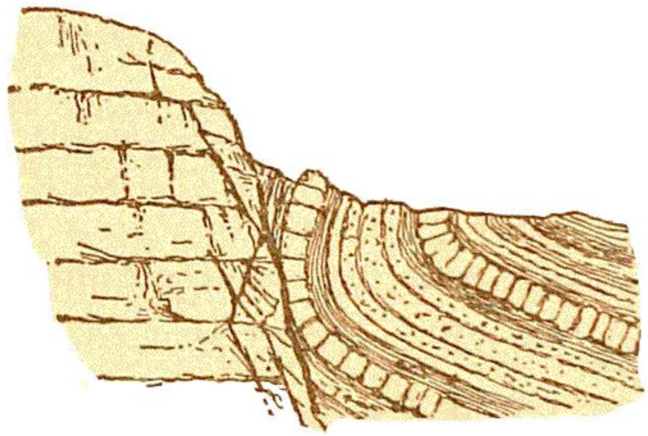


Fig. 262.—Section of Fault with inverted beds on the downthrow side.

times in a series of strata, the beds on the side which has been pushed up (or side of upthrow) are bent down against the fault, while those on the opposite side (or that of downthrow) are bent up (Fig. 262). Most commonly the rocks on both sides are considerably broken, jumbled, and crumpled, so that the line of fracture is marked by a belt or wall-like mass of fragmentary rock, known as "fault-rock." Where a dislocation has occurred through materials of very unequal hardness, such as solid limestone bands and soft shales, or where its course has been undulating, the

[2] See Report on Geological Survey work, Quart. Journ. Geol. Soc. xliv. 1888, p. 393, and postea, Fig. 331.

relative shifting of the two sides has occasionally brought opposite prominences together so as to leave wider interspaces (Fig. 312). The actual breadth of a fault may vary from a mere chink into which the point of a knife could hardly be inserted, up to a band of broken and often consolidated materials many yards wide. Where a fault has a

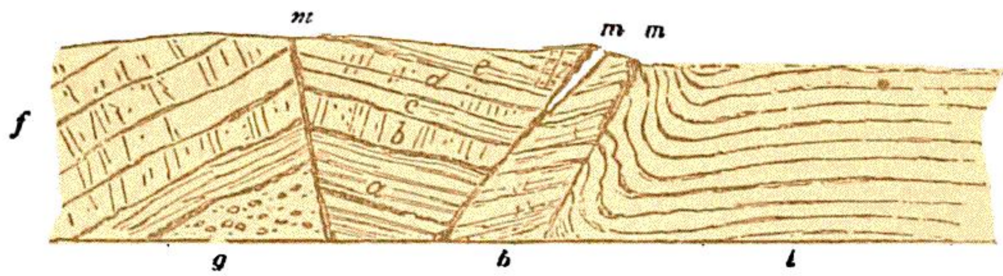


Fig. 263.—Section of group of faults, Coast of Glamorganshire, West of Lavernock Point (*B.*).

m m m, three adjacent faults by which the inclination of the strata is shifted and some of the beds are crumpled; *a*, dolomitic limestone and marl; *b*, *c*, *d*, *e*, *f*, dolomitic limestone; *g*, dolomitic conglomerate; *h*, beds corresponding with those on the left; *l*, Lias, thrown in by a "reversed" fault.

considerable throw, it is sometimes flanked by parallel small faults. The occurrence of these close together will obviously produce the appearance of a broad zone of much fractured rock along the trend of a main fissure. A line of disturbance may consist of several parallel faults of nearly equal magnitude (Fig. 265, section 3).

Faults are sometimes vertical, but are generally inclined.

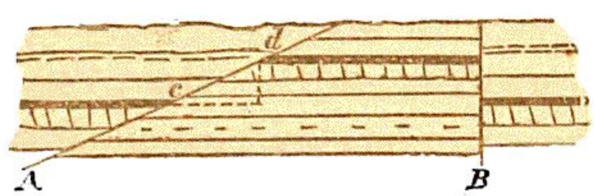


Fig. 264.—Section of inclined and vertical Faults.

The largest faults, or those with the greatest vertical *throw* or displacement, commonly slope at high angles, while those of only a few feet or yards may be inclined as low as 18° or 20°. The inclination of a fault from the vertical is called its *hade*. In Fig. 264, for example, the fault at B, being vertical, has no hade, but that at A hades at an angle of 70° from the vertical to the left hand. The amount of throw is represented as the same in both instances, but with the direction of throw to opposite quarters, so that the level of the beds is raised between the two faults above the uniform horizon which it retains beyond them.

The effect of the inclination of faults is to give the appearance of lateral displacement. In Fig. 264, for example, where the hade of one fault is considerable, the two severed ends (*c* and *d*) of the black bed appear to have been pulled asunder. The horizontal distance to which they are removed does not depend upon the amount of vertical displacement, but upon the angle of hade. A small fault with a great hade will shift strata laterally much more than a large fault with a small hade. It is obvious that the angle of hade must seriously affect the value of a coal-field. If the black bed in the same figure be supposed to be a coal-seam, it could be worked from either side up to *c* and *d*, but there would be a space of barren ground between these two points, where the seam never could be found. The larger the angle of hade the greater the breadth of such barren ground.

Origin of Faults.—In countries where the rocks have not undergone much disturbance, that is, where stratified formations are still not far removed from their original approximate horizontality, faults are probably, for the most part, due to mere subsidence of the crust (Normal Faults). Where, on the other hand, rocks have been much plicated, the more gigantic faults have been produced by tangential thrust, whereby one mass of rock has been pushed bodily over another (Reversed Faults, Thrust-planes). In some cases, both lateral thrust and subsidence have been concerned in the origin of the dislocations of a much-fractured area.

Normal Faults.—In the vast majority of cases, faults hade in the direction of downthrow, or in other words, they slope away from the side which has risen. These are *Normal Faults.* The explanation of the structure is doubtless to be found in the fact that the portion of the terrestrial crust toward which a fault hades presents a less area of base to pressure or support from below than the mass with the broad base on the opposite side. The mere inspection of a fault in any natural or artificial section suffices, in most cases, to show which is the upthrow side. In mining operations, the knowledge of this rule is invaluable, for it decides whether a coal-seam, dislocated by a fault, is to be sought for by going up or down. In Fig. 264, a miner working from the left, and meeting with the fault at *c*, would know from its hading toward him that he must ascend to find the coal. On the other hand, were he to work from the right, and catch the fault at *d*, he would see that it would be necessary to descend. According to this rule, a normal fault never brings one part of a bed below another part, so as to be capable of being pierced twice by the same vertical shaft.

Reversed Faults are those in which lower rocks on one side have been pushed over higher rocks on the other. In these cases, the same stratum may be pierced twice by a vertical shaft. The hade is therefore in the direction of upthrow. Faults of this kind chiefly occur in regions where the rocks have been excessively plicated, and especially where one-half of a fold has been pushed over another (Figs. 263 and 265, section 4).[3] They are closely connected

---

[3] If faults were generally due to rupture from compression we should expect the "reversed" to be the ordinary form. The normal hade of faults points to

with anticlinal and synclinal folding. Thus, a monoclinal fold may by increase of movement be developed into a fracture (Fig. 265). Beautiful examples of this relation have been observed by Powell and others among the little-disturbed formations of the great plateaus of Utah and Wyoming. But it is in mountainous regions that they are chiefly

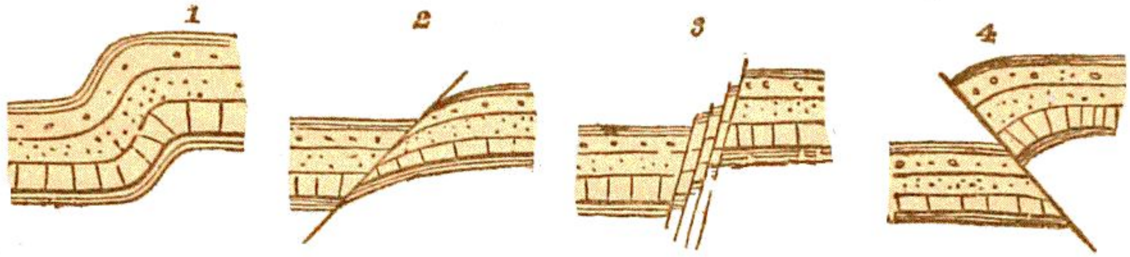


Fig. 265.—Sections to show the relations of Monoclinal folds and faults.
1, Monoclinal fold; 2, Monoclinal fold replaced by a single normal fault; 3, Monoclinal fold converted into a series of parallel normal faults; 4, Monoclinal fold developed by increase of plication into a reversed fault.

developed; they become there, indeed, the common type of dislocation. Many excellent examples have been adduced from the plicated rocks of the Alps.[4]

Thrust-planes.—Under this name the Geological Survey of Scotland has described a remarkable type of reversed fault, where the hade is so low that the rocks on the upcast side have been pushed for miles horizontally across the rocks on which they lie (see Figs. 249, 311, 328, 331, 334).[5] Such a structure points to enormous tangential pressure, under which the very foundations of a country were thrust

---

the existence of stresses in the crust of the earth which are from time to time relieved by dislocation. But the nature of these stresses and the manner in which faults arise are still among the obscure problems of geology.

[4] See Powell in the works cited already on p. 897. Heim, "Mechanismus der Gebirgsbildung," Plate XV. Fig. 14. Compare C. W. Hayes, Bull. Geol. Soc. Amer. ii. 1891, p. 141.

[5] B. N. Peach and J. Horne, Nature, 13th Nov. 1884. The details of this structure with numerous illustrations will be found in the Report of the Geological Survey, Quart. Journ. Geol. Soc. xliv. 1888, p. 378. M. Bertrand has described under the name of "failles courbes" certain curved faults which affect the rocks of the Jura and south of France, but do not, he thinks, descend into the crust; and he cites the Mont Faron near Toulon, which, he says, one cannot climb from any side without crossing a large fault that brings Jurassic down upon Triassic rocks (Bull. Soc. Geol. France (3), xii. 1884, p. 452).

up and driven over younger rocks. The "grande faille du Midi," in the north of France and Belgium, by which the Devonian rocks have been pushed over the Carboniferous, is a well-known and remarkable example of this structure. In some cases so intense have been the mechanical movements, that extensive metamorphism has been induced by them. Along the thrust-planes in the northwest of Scotland, and for a long way above them, the rocks that have been pushed forward have undergone enormous shearing, new divisional planes have been developed in them, and they have become more or less schistose, the new minerals crystallizing along the shearing-surfaces approximately parallel to the thrust-planes.

Throw of Faults.—That normal faults are vertical displacements of parts of the earth's crust is most clearly shown when they traverse stratified rocks, for the regular lines of bedding and the originally flat position of these rocks afford a measure of the disturbance. In Fig. 264, the same series of strata occurs, on either side of each of the two faults, so that measurement of the amount of displacement is here obviously simple. The measurement is made from the truncated end of any given stratum vertically to the level of the opposite end of the same stratum on the other side of the fault. Where the fault is vertical, like that to the right in Fig. 264, the mere distance of the fractured ends from each other is the amount of displacement. In the case of an inclined fault, the level of the selected stratum is protracted across the fissure until a vertical from it will reach the level of the same bed, as shown by the dotted lines. The length of this vertical is the amount of vertical displacement, or the *throw* of the fault. The throw of faults varies from less than an inch to several thousand feet.

Unless beds, the horizons of which are known, can be recognized on both sides of a fault, exposed in a cliff or other section, the fault at that particular place does not reveal the extent of its displacement. It would not, in such a case, be safe to pronounce the fault to be large or small in the amount of its throw, unless we had other evidence from which to infer the geological horizon of the beds on either side. A fault with a considerable amount of displacement may make little show in a cliff, while, on the other hand, one which, to judge from the jumbled and fractured ends of the beds on either side, might be supposed to be a powerful dislocation, may be found to be of comparatively slight importance. Thus, on the cliff near Stonehaven, in Kincardineshire, one of the most notable faults in Great Britain runs out to sea, between the ancient crystalline rocks of the Highlands and the Old Red Sandstones and conglomerates of the Lowlands of Scotland. So powerful have been its effects that the strata on the Lowland side have been thrown on end for a distance of two miles back from the line of fracture, so as to stand upright along the coast-cliffs like books on a library shelf. Yet at the actual point where the fault reaches the sea and is cut in section by the shore-cliff, it is not revealed by a band of shattered rock. On the contrary, no one would at first be likely to suspect the existence of a fault at all. The red sandstone and the reddened Highland schists have been so compressed and, as it were, welded into each other, that some care is required to trace the demarcation between them.

Dip-Faults and Strike-Faults.—The same fault may give rise to very different effects, according to variations in the inclination or curvature of the rocks which it traverses, or to the influence of branch faults diverging from it. Faults among inclined strata may, in most districts, be conveniently grouped into two series, one running in the same general direction as the dip of the strata, the other approximating to the trend of the strike. They are accordingly classified as *dip-faults* and *strike-faults*, which, however, are not always to be sharply marked off from each other, for the dip-faults will often be observed to deviate considerably from the normal direction of dip, and the strike-faults from the prevalent strike, so as to pass into each other.

A dip-fault produces at the surface the effect of a lateral shift of the strata. This effect increases in proportion as the angle of dip lessens, but ceases altogether when the beds are vertical. Fig. 266 may be taken as a plan of a dip-fault (*ff*) traversing a series of strata which dip northward at 20°. The beds on the east side look as if they had been pushed horizontally southward. That this apparent horizontal displacement is due really to a vertical movement, and to the subsequent planing down of the surface by denuding agents, will be clear, if we consider what must be the effect of the vertical ascent or descent of the inclined beds at a dislocation. The part on one side of the fracture may be pushed up, or, what is equivalent, that on the other side may be let down. If the strike of the beds be supposed to be east and west, then a horizontal plane cutting the dislocated strata will show the portion on the west or upthrow side of the fault lying to the north of that on the east or downthrow side. The effect of denudation has usually been practically to produce such a plane, and thus to exhibit an apparently lateral shift. This surface displace-

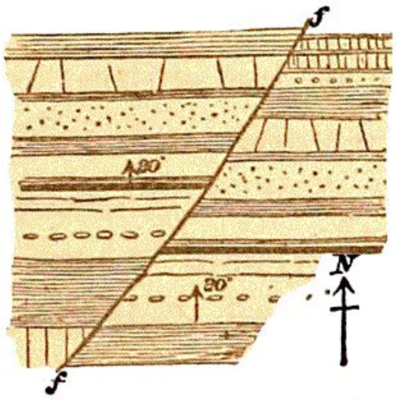


Fig. 266.—Plan of strata cut by a Dip-Fault.

ment has been termed the *heave* of a fault. Its dependence upon the angle of dip of the strata may be seen by a comparison of Sections A and B in Fig. 267. In the former, the bed *a b*, which may be supposed to be one of those in Fig. 266, dipping north at 20°, once prolonged above the present surface (marked by the horizontal line), is represented as having dropped from *w b* to *e d*. The heave amounts to the horizontal distance between *e* and *b*, the throw being the vertical distance between *b* and *d*. But if the angle should rise to 50°, as in B, though the amount of throw or vertical displacement is there one-fourth greater,

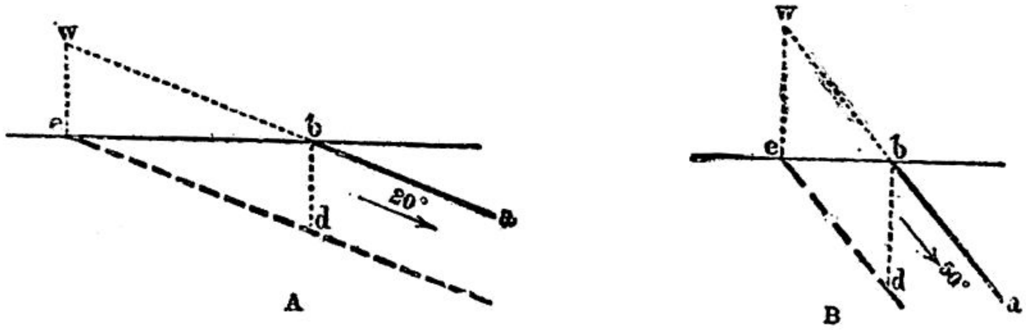


Fig. 267.—Sections to show the variation of horizontal displacement or Heave of Faults, according to the angle of inclination of strata.

the heave or horizontal shift diminishes to less than a half of what it is in A. This diminution augments with increase of inclination till among vertical beds there is no heave at all, though a fault with a horizontal thrust will cause a lateral shift even in vertical strata (see Fig. 331).

Strike-faults, where they exactly coincide with the strike, may remove the outcrops of some strata by never allowing them to reach the surface. Fig. 268 shows a plan (A) and section (B) of one of these faults, *f f*, having a downthrow toward the direction of dip. In crossing the strike, we pass successively over the edges of all the beds, except the part between the asterisks, which is cut out by the fault as shown in the section. It seldom happens, however, that such strict coincidence between faults and strike continues for more than a short distance. The direction of dip is apt to vary a little even among comparatively undisturbed strata, every such variation causing the strike to undulate, and thus to be cut more or less obliquely by the line of dislocation, which may nevertheless run quite straight.

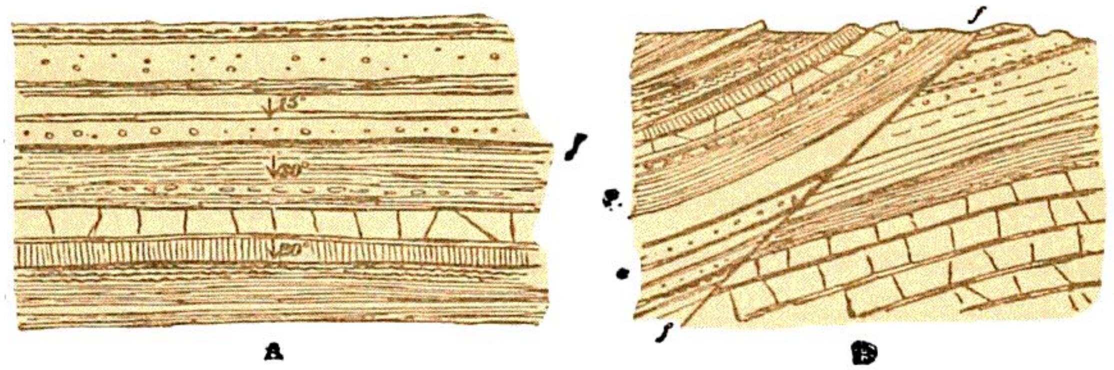


Fig. 268.—Strike-Fault.
A, Plan; B, Section across the plan in the line of the arrows.

Moreover, an increase or diminution in the throw of a strike-fault will have the effect of bringing the dislocated ends of the beds against the line of dislocation. In Fig. 269, for instance, which represents in plan another strike-fault (*f*), we see that the amount of throw increases toward the right so as to allow lower beds successively to appear

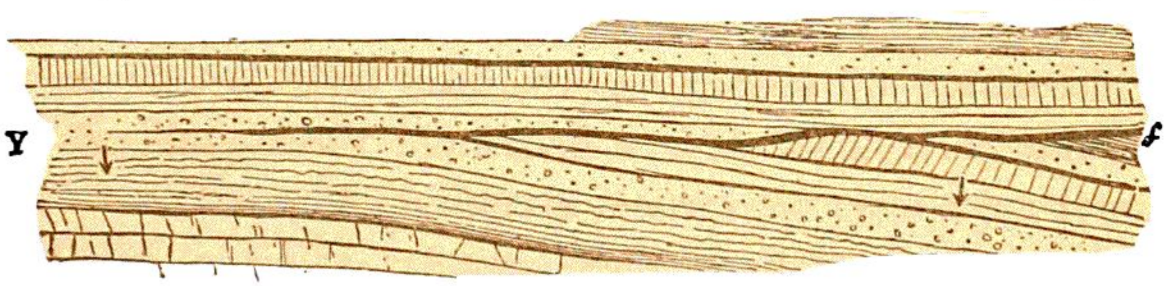


Fig. 269.—Plan of strata traversed by a diminishing Strike-Fault.

on one side, while toward the left it diminishes, and finally dies out in bed Y.

Their effects become more complicated where faults traverse undulating and contorted strata. The connection between folding and fracture has already been adverted to in the case of monoclinal bends. It sometimes happens that the plications are subsequently fractured, so that the fault may appear to be alternately a downthrow on opposite sides, according to the position of the arches and troughs which it crosses. This structure may be illustrated by a plan and sections of a dislocated anticline and syncline, which will also show clearly how the apparently lateral displacement of outcrop produced by dip-faults is due to vertical movement. Fig. 270 represents a plan of strata thrown into an anticlinal fold AA and a synclinal fold SS, and traversed

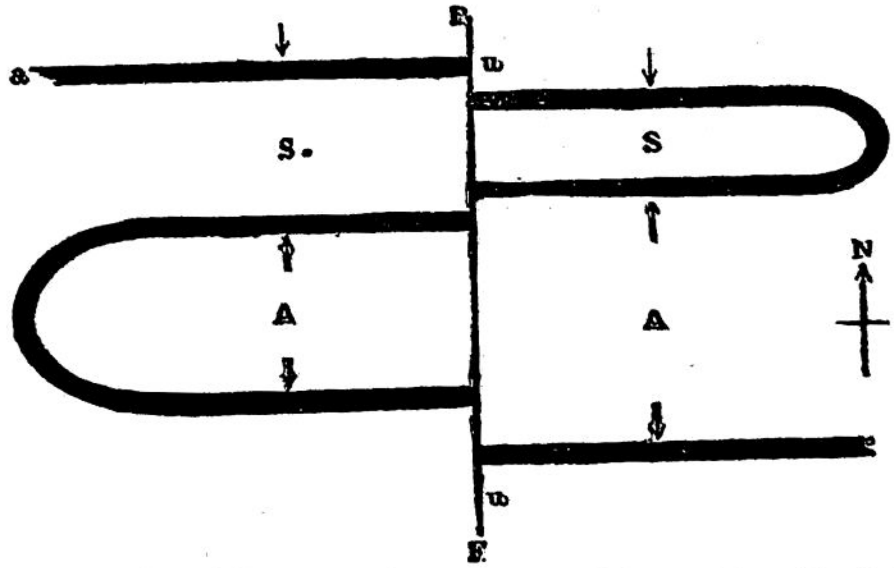


Fig. 270.—Plan of Anticline (A) and Syncline (S), dislocated by a Fault (F F).

by a fault FF, having an upthrow (*u u*) to the east. A dip-fault shifts the outcrop toward the dip on the upthrow side, and this will be observed to be the case here. On the west side of the fault, the black bed *a*, dipping toward the south, is truncated by the fault at *u*, and the portion on the upthrow side is shifted forward or southward. Crossing the syncline we meet with the same bed rising with a contrary dip, and as the upthrow of the fault still continues on the same side, the portion of the bed on the west side of the fault must be sought further south. The effect of the fault on the syncline is to widen the distance between the two opposite outcrops of a bed on the downthrow side, or to narrow it on the upthrow side. On the southern slope of the anticline A, the same bed once more appears, and again is shifted forward, as before, on the upthrow side. Hence in an anticline, the reverse effect takes place, for there the space between the two outcrops is narrowed on the downthrow side. A section along the east or upcast side of the fault would give the structure represented in Fig. 271 (1); while one along the downcast side would be

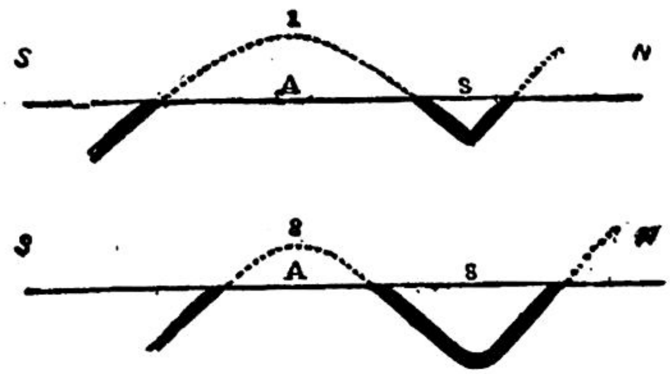


Fig. 271.—Sections along the Fault in Fig. 270.
1, Section along the upcast side; 2, Section along the downthrow side.

as in (2). These two sections illustrate how the shifting of the outcrops at the surface can be simply explained by a mere vertical movement.

Dying out of Faults.—Dislocation may take place either by a single fault, or as the combined effects of two or more. Where there is only one fault, one of its sides may be pushed up or let down, or there may be a simultaneous opposite movement on either side. In such cases, there must be a gradual dying out of the dislocation toward either end; and one or more points where the displacement has reached a maximum. Sometimes, as may be seen in coal-workings, a fault, with a considerable maximum throw, splits into minor faults at the terminations. In other cases, the offshoots take place along the line of the main fissure.

Exceedingly complicated examples occur in some coal-fields, where the connected faults become so numerous that no one of them deserves to be called the main or leading dislocation. By a series of branch-faults, the effect of a main fault may be neutralized or reversed. Suppose, for example, that a main fault at its eastern portion throws down 60 fathoms to the north, and that at intervals three

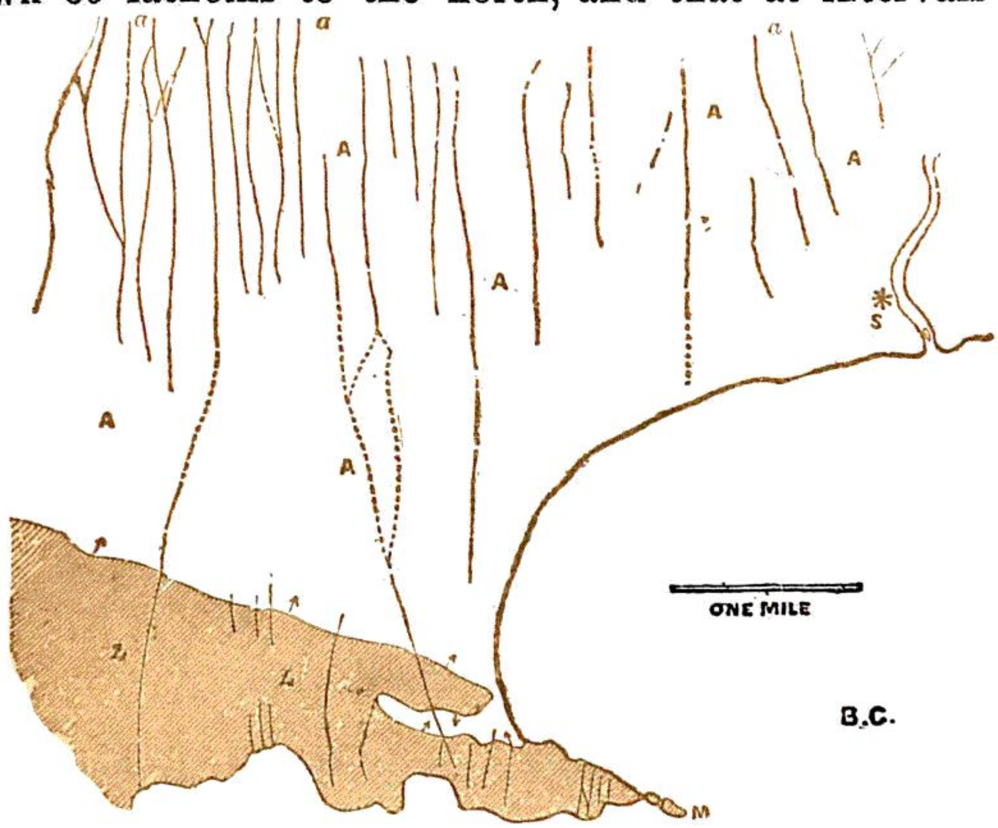


Fig. 272.—Map of part of the South Wales Coal-field.
A A, Coal-measures; L L, Carboniferous limestone dipping beneath the coal-measures as shown by the arrows; *a a*, dip-faults; S, Swansea; M, the Mumbles; B. C., Bristol Channel.

faults on the same side strike off from it, each having a downthrow of 25 fathoms to the east; the combined effect of these branch-faults will be to reverse the throw of the main fault toward its western end, and produce a downthrow of 15 fathoms to the south.

Groups of Faults.—The subsidence or elevation of a large mass or block of rock has usually taken place by a combination of faults. Detailed maps of coal-fields, such as those published by the Geological Survey of Great Britain on a scale of six inches to a mile, furnish much instructive material for the study of the way in which the crust of the earth has been reticulated by faults. In most cases, dip-faults are predominant, sometimes to a remarkable extent, as in the portion of the South Wales coal-field represented in Fig. 272. In other places, the dislocations run in all directions, so as to divide the ground into an irregular network.

It often happens that, by a succession of parallel and adjoining faults, a series of strata is so dislocated that a given stratum, which may be near the surface on one side, is carried down by a series of steps to some distance below. Excellent examples of these step-faults (Fig. 273) are to be

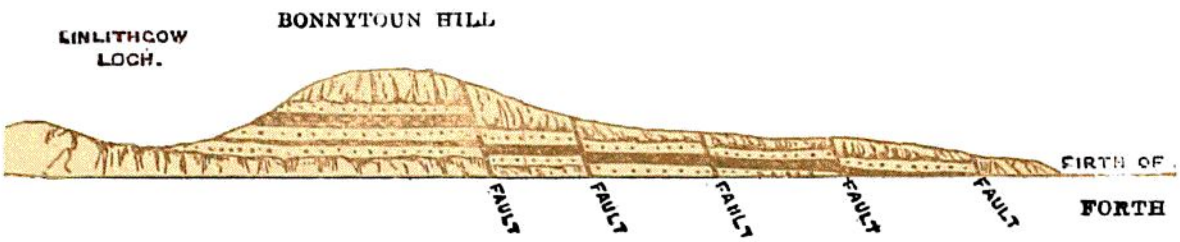


Fig. 273.—Step-Faults, Linlithgowshire.

seen in the coal-fields on both sides of the upper part of the estuary of the Forth. Instead, however, of having the same downthrow, parallel faults frequently show a movement in opposite directions. If the mass of rock between them has subsided relatively to the surrounding ground, they are trough-faults (Fig. 274), and inclose wedge-shaped masses of rock. It will be observed that the hade of these faults is in each case toward the downthrow side, and that the wedge-shaped masses with broad bottoms have risen, while those with narrow bottoms and broad tops have sunk.

The faults of a district may not have been the result of one series of movements, but of a long succession of displacements, or of renewed disturbance after prolonged quiescence. One fault sometimes displaces another. In regions of reversed faults and thrust-planes, normal faults have sometimes taken place long after the first dislocations. In northwestern Scotland, for example, the thrust-planes have been cut across and shifted, exactly as if they had been ordinary stratification-planes.

Detection and tracing of Faults.—As a rule, faults give rise to little or no feature at the surface, so that their existence would commonly not be suspected. They comparatively rarely appear in visible sections, but are apt rather to conceal themselves under surface accumulations just at

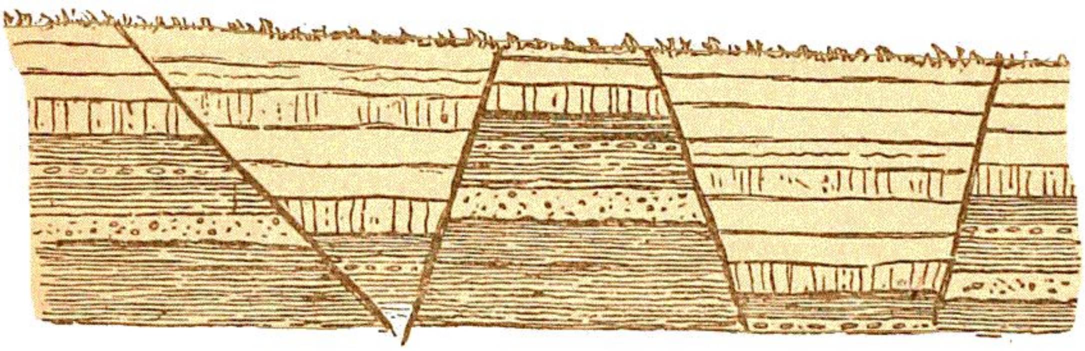


Fig. 274.—Trough-Faults.

those points in a ravine or other natural section where we might hope to catch them. Yet they undoubtedly constitute one of the most important features in the geological structure of a district or country, and should consequently be traced with the greatest care. In the majority of cases, in countries like much of central and northern Europe, where the ground is covered with superficial deposits, the position of faults cannot be seen, but must be inferred; though it must be admitted that geologists have been prone to great recklessness in this respect, introducing faults for which there was little or no actual evidence, but which were convenient for the explanation of theoretical views of the structure of a district. Experience will teach the student that the mere visible section of a fault on some cliff or shore does not necessarily afford such clear evidence of its nature and effects as may be obtained from other parts of the region, where it does not show itself at the surface at all. In fact, he might be deceived by a single section with a fault exposed in it, and might be led to regard that fault as an important and dominant one, while it might be only a secondary dislocation in the near neighborhood of a great fracture, for which the evidence would be elsewhere obtainable, but which might never be seen itself. The actual position (within a few yards) of a large fault, its line across the country, its effect on the surface, its influence on geological structure, its amount of vertical displacement at different parts of its course—all this information may be admirably worked out, and yet the actual fracture may never be seen in any one single section on the ground. A visible exposure of the fracture would be interesting: it would give the exact position of the line at that particular place; but it would not be necessary to prove the existence of the fault, nor would it perhaps furnish any additional information of importance. The existence of an unseen fault may usually be determined by an examination of the geological structure of a district. An abruptly truncated outcrop is always suggestive of fracture, though sometimes it may be due to unconformable deposition against a steep declivity. If a series of strata be discovered, in a water-course or other exposure, dipping continuously in one general direction at angles of 10° or more, and if, at a short distance, another portion of the same series be found inclined in another direction, the two thus striking at each other, a fault will almost always be required to explain their relation. If all the evidence obtainable, from the sections in water-courses or otherwise, be put upon a map (as in A, Fig. 275), it will be seen that a dislocation must run somewhere near the points marked *f f*, as there is no room for either series to turn round so as to dip below the other. They must be mutually truncated. The completed map would represent them separated by a fault (F, in B). The upthrow or downcast side of the dislocation would be determined by the ob-

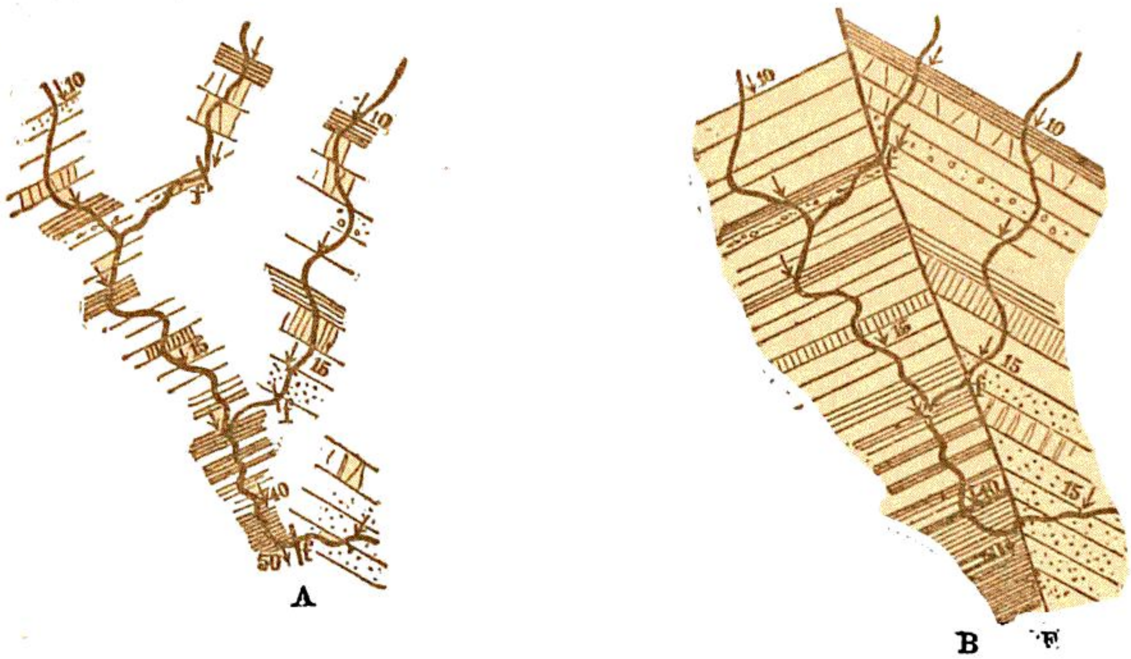


Fig. 275.—Map, illustrating the detection of an unseen Fault.
A, Field-map, showing the data actually obtained on the ground; B, completed Map, showing the geological structure of the district.

server's knowledge of the order of superposition of the respective groups of strata.

The existence of a fault having been thus proved from an examination of the geological structure of the ground, its line across the country may be approximately laid down—1st, by getting exposures of the two sets of rock, or the two ends of a severed outcrop on either side, as near as possible to each other, and tracing the trend of the dislocation between; 2d, by noting lines of springs along the supposed course of the fault, subterranean water frequently finding its way to the surface along such fissures; 3d, by attending to surface features, such as lines of hollow, or of ridge rising above hollow, the effect of a fault often being to bring rocks of unequal resistance together, so as to allow the more durable to rise more or less steeply from the fracture.[6]

PART VII. ERUPTIVE (IGNEOUS) ROCKS AS PART OF THE STRUCTURE OF THE EARTH'S CRUST

The lithological differences of eruptive rocks having already been described in Book II. (p. 269), it is their larger features in the field that now require attention—features which, in some cases, are readily explicable by the action of modern volcanoes; and which, in other cases, bring before us parts of the economy of volcanoes never observable in any recent cone, by revealing deep-seated rock-structures that lie far beneath the upper or volcanic zone of the terrestrial crust. A study of the igneous rocks

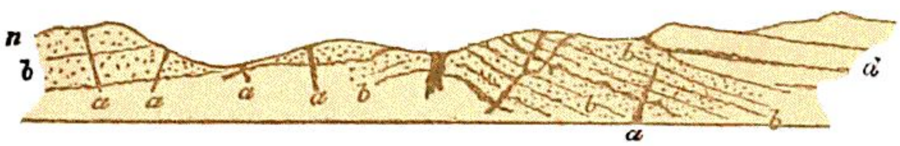


Fig. 276.—Extensively-denuded Volcanic District (*B.*).

of former ages, as built up into the framework of the crust, serves to augment our knowledge of volcanic action.

At the outset, it is evident that if eruptive rocks have been extruded from below in all geological ages, and if, at the same time, denudation of the land has been continuously in progress, many masses of molten material, poured out at the surface, must have been removed. But the removal of these superficial sheets would uncover their roots or downward prolongations, and the greater the denudation, the deeper down must have been the original position of the rocks now exposed to daylight. Fig. 276, for example,

[6] See "Field Geology," by the author, chapter x.

shows a district in which a series of tuffs and breccias (*b b*) traversed by dikes (*a a*) is covered unconformably by a newer series of deposits (*d*). Properly to appreciate the relations and history of the rocks, we must bear in mind that originally they may have presented some such outline as in Fig. 277, where the present surface (that of Fig. 276) down to which denudation has proceeded is represented by the dotted line *n s*.[1] We may therefore *à priori* expect to encounter different levels of eruptivity, some rocks being portions of sheets that solidified at the surface, others form-

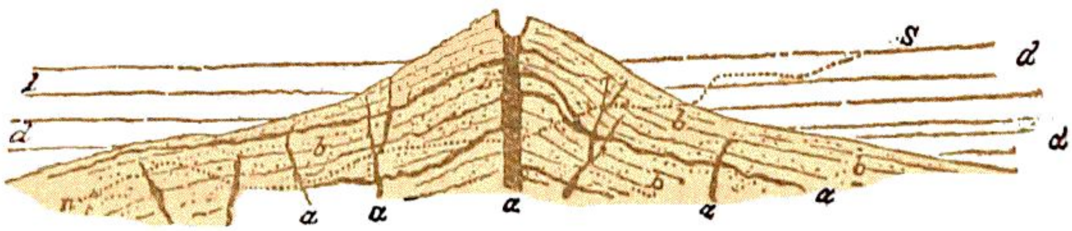


Fig. 277.—Restored outline of the original form of ground in Fig. 276 (*B*).

ing parts of injected sheets or of the pipe or column that connected the superficial sheets with the internal lava-reservoir. We may infer that many masses of molten rock, after being driven so far upward, came to rest without ever finding their way to the surface. It cannot always be affirmed that a given mass of intrusive igneous rock, now denuded and exposed at the surface, was ever connected with any superficial manifestation of volcanic action.

Now there will obviously be, as a general rule, some difference in texture, if not in composition, between the superficial and the deep-seated masses, and this difference is of so much importance in the interpretation of the history of volcanic action that it ought to be clearly kept in view. Those portions of an eruptive mass which consolidated at some depth are generally more coarsely crystalline than

[1] De la Beche, "Geol. Observer," p. 561.

those which flowed out as lava; they are likewise destitute of the cellular scoriaceous structure and the ashy accompaniments so characteristic of superficial igneous rocks. Yet even if there were no well-marked petrographical contrast between the two groups, it would manifestly lead to confusion if no distinction were drawn between those igneous masses which reached the surface and consolidated there, like modern lava-streams or showers of ashes, and those which never found their way to the surface, but consolidated at a greater or less depth beneath it. There must be the same division to be drawn in the case of every active volcano of the present day. But at a modern volcano, only the materials which reach the surface can be examined, the nature and arrangement of what still lies underneath being matter of inference. In the revolutions to which the crust of the earth has been subjected, however, denudation has, on the one hand, removed superficial sheets of lava and tuff, and has exposed the subterranean continuations of the erupted rocks, and, on the other hand, has laid open the very heart of masses which, though eruptive, seem never to have been directly connected with actual volcanic outbursts. All subterranean intruded masses, now revealed at the surface after the removal of some depth of overlying rock, may be grouped together into one division under the names Plutonic, Intrusive, or Subsequent. On the other hand, all those which came up to the surface as ordinary volcanic rocks, whether molten or fragmental, and were consequently contemporaneously interstratified with the formations which happened to be in progress on the surface at the time, may be classed in a second group under the names Volcanic, Interbedded, or Contemporaneous.

It is obvious that these can be used only as relative terms. Every truly volcanic mass which, by being poured out as a lava-stream at the surface, came to be regularly interstratified with contemporaneous accumulations, must have been directly connected below with molten matter which did not reach the surface. One part of the total mass, therefore, would be included in the second group, while another portion, if ever exposed by geological revolutions, would be classed with the first group. Seldom, however, can the same masses which flowed out at the surface be traced directly to their original underground prolongations.

It is evident that an intrusive mass, though necessarily subsequent in age to the rocks through which it has been

Fig. 278.—Section showing the relative age of an Intrusive Rock (*B.*).

thrust, need not be long subsequent. Its relative date can only be certainly affirmed with reference to the rocks through which it has broken. It must obviously be younger than these, even though they lie upon it, if they bear evidence of alteration by its influence. The probable geological date of its eruption must be decided by evidence to be obtained from the grouping of the rocks all around. Its intrusive character can only certainly determine the limit of its antiquity. We know that it must be younger than the rocks it has invaded; how much younger, must be otherwise determined. Thus, a mass of granite or a series of granite veins (*a a*, Fig. 278) is manifestly posterior in date to the plicated rocks (*b b*) through which it has risen. But it must be regarded as older than overlying undisturbed and unaltered rocks (*c*), or than others lying at some distance (*e f*), which contain worn fragments derived from the granite.

On the other hand, an interbedded or contemporaneous igneous rock has its date precisely fixed by the geological horizon on which it lies. Sheets of lava or tuff interposed between strata in which such fossils as *Calymene Blumenbachii*, *Leptæna sericea*, *Atrypa reticularis*, *Orthis elegantula*, and *Pentamerus Knightii* occur, would be unhesitatingly assigned by a geologist to submarine volcanic eruptions of Upper Silurian age. A lava-bed or tuff intercalated among strata containing *Sphenopteris affinis*, *Lepidodendron veltheimianum*, *Leperditia*, and other associated fossils, would unequivocally prove the existence of volcanic action at the surface during the Lower Carboniferous period, and at that particular part of the period represented by the horizon of the volcanic bed. Similar eruptive material associated with *Ammonites*, *Belemnites*, *Pentacrinites*, etc., would certainly belong to some zone in the great Mesozoic suite of formations. An interbedded and an intrusive mass found on the same platform of strata need not necessarily be coeval. On the contrary, the latter, if clearly intruded along the horizon of the former, would obviously be posterior in date. It will be understood, then, that the two groups have their respective limits determined mainly by their relations to the rocks among which they may happen to lie, though there are also special internal characters that help to discriminate them.

The value of this classification for geological purposes is great. It enables the geologist to place and consider by themselves the granites, quartz-porphyries, and other crystalline masses, which, though lying sometimes perhaps at the roots of ancient volcanoes, and therefore intimately connected with volcanic action, yet owe their special characters to their having consolidated under pressure at some depth within the earth's crust; and to arrange in another series the lavas and tuffs which, having been thrown out to the surface, bear the closest resemblance to the ejected materials from modern volcanoes. He is thus presented with the records of hypogene igneous action in the one group, and with those of superficial volcanic action in the other. He is furnished with a method of chronologically arranging the volcanic phenomena of past ages, and is thereby enabled to collect materials for a history of volcanic action over the globe.

In adopting this classification for unravelling the geological structure of a region where igneous rocks abound, the student will encounter instances where it may be difficult or impossible to decide in which group a particular mass of rock must be placed. He will bear in mind, however, that, after all, such schemes of classification are proposed only for convenience in systematic work, and that there are no corresponding hard and fast lines in nature. He will recognize that all crystalline or glassy igneous rocks must be intrusive at a greater or less depth from the surface; for every contemporaneous sheet has obviously proceeded from some internal pipe or mass, so that, though interbedded and contemporaneous with the strata at the top, it is intrusive in relation to the strata below.

The characters by which an eruptive (igneous) rock may be distinguished are partly lithological and partly geotectonic. The lithological characters have already been fully given (pp. 238, 269). Among the more important of them are the predominance of silicates (notably of felspars, hornblende, mica, augite, olivine, etc.), and of disseminated crystals of iron oxides (magnetite, titaniferous iron); a prevailing more or less thoroughly crystalline structure; the frequent presence of vitreous and devitrified matter, visible megascopically or microscopically; and the occurrence of porphyritic, cellular, pumiceous, slaggy, amygdaloidal, and fluxion structures. These characters are never all united in the same rock. They possess likewise various values as marks of eruptivity, some of them being shared with crystalline schists which were certainly not eruptive. On the whole, the most trustworthy lithological evidence of the eruptive character of a rock is the presence of glass, or traces of an original glassy base. We do not yet certainly know of any natural vitreous substance, except of an eruptive nature. The occurrence or association of certain minerals, or varieties of minerals, in a rock, may also afford presumptive evidence of its igneous origin. Sanidine, leucite, olivine, nepheline, for example, are, for the most part, characteristic volcanic minerals; and mixtures of finely crystallized triclinic felspars with dark augite, olivine, and magnetic iron, or with hornblende, are specially met with among eruptive rocks.

But it is the geotectonic characters on which the geologist must chiefly rely in establishing the eruptive nature of rocks. These vary according to the conditions under which the rocks have consolidated. We shall consider them as they are displayed by the Plutonic, or deep-seated, and Volcanic, or superficial phase of eruptivity.[2]

---

[2] As already stated (p. 220), a chronological basis has been proposed for the classification of eruptive rocks. Some writers have even gone so far as to suggest that different names should be given to eruptive rocks according to the geological formation in which they occur, as Carbophyre, Kohlephyre, Triaphyre, Juraphyre. See Th. Ebray, Bull. Soc. Geol. France (3), iii. p. 291.

Section i. Plutonic, Intrusive, or Subsequent Phase of Eruptivity

We have here to consider the structure of those eruptive masses which have been injected or intruded into other rocks, and have consolidated beneath the surface. One series of these masses is crystalline in structure, but with felsitic and vitreous varieties. It includes most of the eruptive rocks, and especially the more coarsely crystalline forms (granite, syenite, quartz-porphyry, granophyre, liparite, diorite, etc.). The other series is fragmental in character, and includes the agglomerates and tuffs which have filled up volcanic orifices.

After some practice, the field-geologist acquires a faculty of discriminating, even in hand-specimens, crystalline rocks which have consolidated beneath the surface, from those which have flowed out as lava-streams. Coarsely crystalline granites and syenites, with no trace of any vitreous ground-mass, are readily distinguishable as plutonic masses; while, on the other hand, cellular or slaggy lavas are easily recognizable as superficial outflows, or as closely connected with them. But it will be observed that such differences of texture, though furnishing useful helps, are not to be regarded as always and in all degrees perfectly reliable. We find, for example, that some lavas have appeared at or near the surface with so coarsely crystalline a structure as to be mistaken by a casual observer for granite; while, on the other hand, though an open pumiceous or slaggy structure is certainly indicative of a lava that has consolidated at or near the surface, a finely cellular character is not wholly unknown in intrusive sheets and dikes which have consolidated below ground. Again, masses of fragmentary volcanic material are justly regarded as proofs of the superficial manifestation of volcanism, and in the vast majority of cases they occur in beds which were accumulated on the surface, as the result of successive explosions. Yet cases, which will be immediately described, may be found in many old volcanic districts, where such fragmentary materials, falling back into the volcanic funnels, and filling them up, have been compacted there into solid rock; they may occasionally have been produced by explosions of lava within subterranean caverns.

The general law which has governed the intrusion of igneous rock within the earth's crust may be thus stated: Every fluid mass impelled upward by pressure from below, or by the expansion of its own imprisoned vapor, has sought egress along the line of least resistance. That line has depended in each case upon the structure of the terrestrial crust and the energy of eruption. It may have been determined by an already existent dislocation, by planes of stratification, by the surface of junction of two unconformable formations, by contemporaneously formed cracks, or by other more complex lines of weakness. Sometimes the intruded mass has actually fused and obliterated some of the rock which it has invaded, incorporating a portion into its own substance. The shape of the channel of escape has thus determined the external form of the intrusive mass, as the mold regulates the form assumed by cast-iron. This relation offers a very convenient means of classifying intrusive rocks. According to the shape of the mold in which they have solidified, they may be arranged as—(1) bosses or amorphous masses, (2) sheets, (3) veins and dikes, and (4) necks.

§ 1. Bosses

Bosses or amorphous masses consist chiefly of crystalline, coarse-textured rocks. Granite and syenite are the most conspicuous examples, but various quartz-porphyries, felsites, trachytes, diorites, gabbros, diabases, andesites, dolerites, etc., also occur. Where rocks assume this form as well as that of sheets, dikes, and contemporaneous beds, it is commonly observed that they are more coarsely crystalline when in large amorphous masses than in any other form. Pyroxenic rocks afford many examples of this characteristic. In the basin of the Forth, for instance, while the outflows at the surface have been fine-grained basalts, the masses consolidated underneath have generally been coarse dolerites or diabases.[3]

In the consolidation of an igneous rock, the more basic minerals have generally crystallized out first, and the last portions of the mass to solidify have not infrequently a notably more acid character than those which solidified first. Hence the margin of an eruptive mass may show a more basic composition than the central portions which cooled more slowly. A remarkable range of composition may thus be found within the same boss.[4] Again, if during the process of consolidation a rock should be ruptured and portions of the still liquid matter be forced into the rents, these veins or squirts will generally be found to be decidedly more acid than the rock in which they lie (pp. 384, 445, 457).

Granite.—It was once a firmly-held tenet that granite is the oldest of rocks, the foundation on which all other rocks

---

[3] Trans. Roy. Soc. Edin. xxix. p. 493, 1879.
[4] Teall and Dakyns, Quart. Journ. Geol. Soc. 1892, p. 104.

have been laid down. This idea no doubt originated in the fact that granite is found rising from beneath gneiss, schist, and other crystalline masses, which in their turn underlie very old stratified formations. The intrusive character of granite, shown by its numerous ramifying veins, proved it to be later than at least those rocks which it had invaded. Nevertheless, the composition and structure of gneiss and mica-schist were believed to be best explained by supposing these rocks to have been derived from the waste of granite, and thus, though the existing intrusive granite had to be recognized as posterior in date, it was regarded as only a subsequent protrusion of the vast underlying granitic crust. In this way, the idea of the primeval or fundamental nature of granite held its ground. From what is known regarding the fusion and consolidation of rocks (ante, p. 510 *et seq.*), and from the evidence supplied by the microscopic structure of granite itself (p. 199), it appears now to be established that granite has consolidated under great pressure, in presence of superheated water, with or without liquid carbon-dioxide, fluorine, etc., conditions which probably never obtained at the earth's immediate surface, unless, perhaps, in those earliest ages when the atmosphere was densely loaded with vapors, and when the atmospheric pressure at the surface must have been enormous (p. 70). Whether the original crust was of a granitic or of a glassy character, no trace of it has ever been or is ever likely to be found. There can be no doubt, however, that the oldest known rocks are either granites or granitoid gneisses which have probably been formed out of granite.

The presence of granite at the existing surface is, doubtless, in all cases due to the removal by denudation of masses of rock under which it originally consolidated. The fact that, wherever extensive denudation of an ancient series of crystalline rocks has taken place, a subjacent granitic nucleus is apt to appear, does not prove granite to be of primeval origin. It shows, however, that the lower portions of crystalline rocks very generally assume a granitic type, and it suggests that if, at any part of the earth, we could bore deep enough into the crust, we should probably come to a granitic layer. That this layer, even if general round the globe, is not everywhere of the highest geological antiquity, or at least has consolidated at widely different periods, is abundantly clear from the fact that in many cases it can be proved to be of later date than fossiliferous formations the geological position of which is known; that is, the granitic layer has invaded these formations, rising up through them, and possibly melting down portions of them in its progress. Granite invades and alters rocks of all ages up to late Mesozoic and Tertiary formations. Hence, it does not belong exclusively to the earliest nor to any one geological period, but has rather been extruded at various epochs, and may even be in course of extravasation now, wherever the conditions required for its production still exist. As a matter of fact, granite occurs much more frequently in association with older, and therefore lower, than with newer and higher rocks. But a little reflection shows that this ought to be the case. Granite, having a deep-seated origin, must rise through the lower and more ancient masses before it can reach the overlying more recent formations. But many protrusions of granite would, doubtless, never ascend beyond the lower rocks. Subsequent denudation would be needed to reveal these protrusions, and this very process would remove the later formations, and, at the same time, any portions of the granite which might have reached them.

Granite frequently occurs in the central parts of mountain-chains; sometimes it forms there a kind of core to the various gneisses, schists, and other crystalline rocks. It appears in large eruptive bosses, which traverse indifferently the rocks on the line of which they rise, and commonly send out abundant veins into them. Sometimes it even overlies schistose and other rocks, as in the Piz de Graves in the upper Engadine, where a wall-like mass of granite, with syenite, diorite, and altered rocks, may be seen resting upon schists.[5] In the Alps and other mountain ranges, it is found likewise in large bed-like masses which run in the same general direction as the rocks with which they are associated.

Reference has already been made (p. 273) to some of the more marked varieties of texture and structure in granite bosses. To a few of these further and more detailed remarks may be appropriately inserted here. The patches or inclosures in granite, which differ in color, texture, and composition from the general mass of the rock, may be grouped in two divisions: 1st. Angular or subangular fragments, probably in most cases derived from the rocks through which the granite has been protruded. These are sometimes tolerably abundant toward the outer margin of a boss. They usually show considerable contact-metamorphism, due no doubt to the influence of the eruptive rock in which they are inclosed. 2d. Globular or rounded concretions, due to some process of segregation and crystallization, in the original still unconsolidated granite. Examples of this nature occur in the Cornish and Devon granite, as in

---

[5] Studer, "Geologie der Schweiz," i. p. 290.

Fig. 279, which was long ago cited by De la Beche as showing a central cavity (*a*), not quite filled with long crystals of schorl surrounded with an envelope of quartz and schorl (*b*), outside of which lies a second envelope (*c*) of the same minerals, the schorl predominating, the whole being contained in a light flesh-colored and markedly felspathic granite (*d*). But more remarkable concretionary forms have since been observed in many granites, some of them presenting an internal radial concentric arrangement, and recalling the orbicular structure of some diorites (Napoleonite) (Fig. 8). Such concretionary aggregations are generally more basic than the surrounding granite.[6]

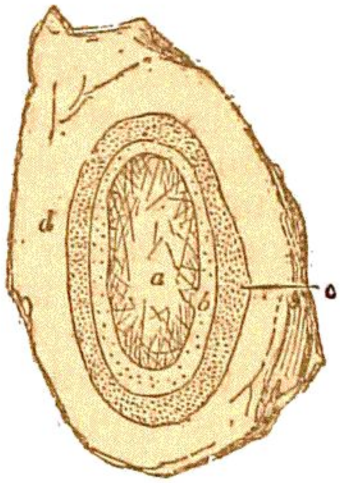


Fig 279.—Crystalline geode in granite, Dartmoor (*B.*).

Of more importance, as affecting a much larger proportion of a granite boss, are the differences of texture and of structure not infrequently traceable from the margin to the centre. Like most intrusive rocks, granite is apt to be more close-grained at its contact with the surrounding strata than in the centre of its mass, though it does not show this contrast so strikingly as the more basic rocks such as gabbro, diabase, and dolerite. Certain characteristic varieties of texture and even to some extent of composition may, however, be recognized in many granite areas. In particular the marginal portions not infrequently present a remarkable foliated arrangement which simulates the structure of gneiss, the folia being rudely parallel to the margin of contact and either vertical or dipping at high angles away from the core

[6] Besides the papers of Phillips, Brögger and Hatch, cited on p. 276, see on inclosures in the Shap granite Harker and Marr, Quart. Journ. Geol. Soc. xlvii. 1891, p. 280; on gradation of granite into basic rocks, Teall and Dakyns, cited on p. 937.

of granite. In some granite bosses a striking gradation can be traced even into picrites and serpentines.

A detailed study has been made by Dr. Charles Barrois of the granulites (*i.e.* granites with two micas) of the Morbihan in Brittany. He has shown that the large bosses measuring some hundreds of square kilometres present certain well-marked modifications not only of structure but of composition as they are traced from the centre to the periphery, while the smaller bosses show no such modifications and are to be regarded merely as apophyses from those of large size. The modifications along the contact do not arise from any exchange of substance between the granite and the surrounding rock, but solely from the influence of cooling which has affected the orientation of the minerals, their grouping and their order of crystallization. Where the granite has risen parallel to the strike of the adjacent strata it usually passes from its ordinary granular into a porphyroid structure, with its large constituents arranged parallel as in flow-structure; where, on the other hand, it breaks across the bedding it has assumed a finely granular massive character (aplite) with its crystalline constituents showing regular geometric forms. These variations are thus proved in this particular instance to depend on the influence of the surrounding envelope, which, though chemically inactive, offers considerable diversity as a conductor of heat and of pressure. The crystallization of the constituents of the rock took place progressively from the outside inward, that is, from a mass still in motion across a magma that had come to rest and which shows now no trace of flow. But besides this marginal band of "porphyroid granulite," the external portions of the southern flanks of the bosses present a remarkable schistose structure which, likewise limited to a peripheral zone, resembles that of gneiss, both fine-grained and glandular (angen-gneiss). Examined in detail the mica-flakes of this gneissic band are found to be torn and drawn out, the felspar crystals deformed, broken, and blunted, indicating the powerful mechanical forces which have affected the rock. These crushed constituents have subsequently been recemented by membranes and fibres of white sericitic mica, sometimes of black mica, and by sheets of secondary granular quartz, formed out of the triturated débris of the older ingredients. Considering the gradual passage of these schistose selvages into the ordinary granular rock, and the further fact that the schistose structure occurs only on the southern flanks of the granitic bosses of the Morbihan, Dr. Barrois attributes this structure to a powerful lateral pressure which has acted in a direction from south to north.[7]

Relation of Granite to contiguous Rocks.—From an early period the attention of geologists has been given to the evident mineralogical change which has taken place among stratified rocks as they approach a mass of granite. This change is developed within a ring or areola which encircles the granite, and varies in breadth from a few yards to two or three miles. The most intense alteration is found next the granite, while along the outer margin of the areola the normal character of the rocks is resumed. In some cases, however, no perceptible trace of alteration can be detected next a mass of granite. Of the European examples of contact-metamorphism, those of Devon and Cornwall, Ireland, Scotland, the Harz, Vosges, Pyrenees, and Norway have long been known. The nature of the metamorphism thus superinduced upon rocks is more particularly discussed at p. 1007.

The southeast of Ireland supplies an admirable illustration of the relation between granite and its surrounding rocks (Fig. 280). A mass of granite 70 miles in length and from

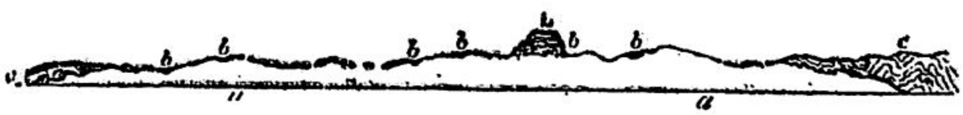


Fig. 280.—Section across part of the granite belt of the southeast of Ireland. *a*, Granite; *b b*, patches of Lower Silurian rocks lying on the granite at various distances from the main Lower Silurian area, *c c*.

7 to 17 in width there stretches from northeast to southwest, nearly along the strike of the Lower Silurian rocks. These strata, however, have not been upraised by it in such a way as to expose their lowest beds dipping away from the granite. On the contrary, they seem to have been contorted

[7] Ann. Soc. Geol. Nord, xv. 1887, pp. 1–40.

prior to the appearance of that rock; at least they often dip toward it, or lie horizontally or undulate upon it, apparently without any reference to movements which it could have produced. As Jukes showed, the Silurian strata are underlain by a vast mass of Cambrian rocks, all of which must have been invaded by the granite before it could have reached its present horizon. He infers that the granite must have slowly and irregularly eaten its way upward through the Silurian rocks, absorbing much of them into its own mass as it rose. For a mile or more, the stratified beds next the granite have been altered into mica-schist, and are pierced by numerous veins from the invading rock. Within the margin of the granitic mass, belts or rounded irregular patches of schist (*b b*) are inclosed; but in the central tracts, where the granite is widest, and where therefore we may suppose the deepest parts of the mass have been laid bare, no such included patches of altered rock occur. From the manner in which the schistose belt is disposed round the granite, it is evident that the upper surface of the latter rock, where it extends beneath the schists, must be very uneven. Doubtless the granite rises in some places much nearer to the present surface of the ground than at others, and sends out veins and strings which do not appear above ground. If, as Jukes supposed, a thousand feet of the schists could be restored at some parts of the granite belt, no doubt the belt would there be entirely buried; or if, on the other hand, the same thickness of rock could be stripped off some parts of the band of schist, the solid granite underneath would be laid bare. The extent of granite surface exposed must thus be largely determined by the amount of denudation, and by the angle at which the upper surface of the granite is inclined beneath the schists. Where the inclination is high, prolonged denudation will evidently do comparatively little in widening the belt.[8] But where the slope is gentle, and especially where the surface undulates, the removal, for some distance, of a comparatively slight thickness of rock, may uncover a large breadth of underlying granite. Portions of the metamorphosed rocks left by denudation upon the surface of the granite boss, are relics of the deep cover under which the granite no doubt originally lay, and, being tougher than the latter rock, they have resisted waste so as now to cap hills and protect the granite

[8] See Jukes's "Manual of Geology," 3d ed. p. 243.

below, as at the mountain Lugnaquilla (L in Fig. 280), which rises 3039 feet above the sea.

Recent observations by Prof. Hull and Mr. Traill, of the Geological Survey of Ireland, have shown that in the Mourne Mountains, a mass of granite has in some parts risen up through highly inclined Silurian rocks, which consequently seem to be standing almost upright upon an underlying boss of granite. The strata are sharply truncated by the crystalline mass, and are indurated but not otherwise altered. The intrusive nature of the granite is well shown by the way in which numerous dikes of dark melaphyre are cut off when they reach that rock.[9] The accompanying dia-

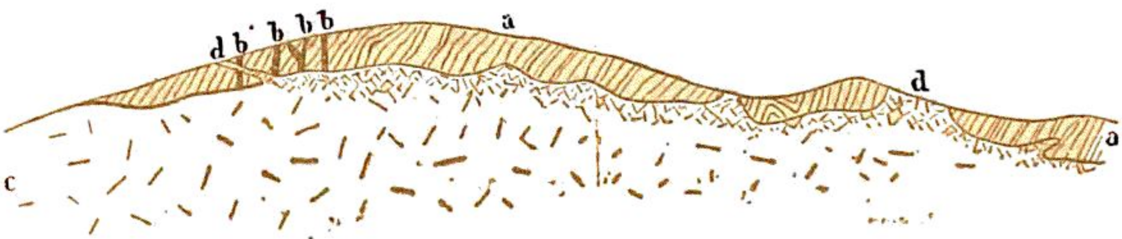


Fig. 281.—Section of Slievenamaddy, Mourne Mountains.

a a, Lower Silurian strata dipping at high angles; *b b*, Dikes of basalt (melaphyre), cutting these strata but truncated by the granite *c*, which along the outer margin and in extruded veins passes into a quartz-porphyry, *d d*.

gram (Fig. 281) is taken from one of the sections in which this structure is portrayed by these observers.

In the Lower Silurian tract of the south of Scotland several large intrusive bosses of granite occur (Fig. 282). The strata do not dip away from them on all sides, but with trifling exceptions maintain their normal N.E. and S.W. strike up to the granite on one side, and resume it again on the other. The granite indeed has not merely pushed aside the strata so as to make its way past, but actually occupies the place of so much Silurian graywacke and shale, which have disappeared, as if they had been pushed or blown out or had been melted up into the granite. There is usually a metamorphosed belt of about a mile in width, in which, as they approach the granite, the stratified rocks assume a thoroughly schistose character. Numerous small, dark, often angular patches or fragments of mica-schist may be observed in the marginal parts of the granite. Occasionally granite-veins protrude from the main masses; in the metamorphosed zone which surrounds the Criffel granite

---

[9] Horizontal Section No. 22, Geol. Surv. Ireland.

area in Kirkcudbright, hundreds of dikes and veins of various felsitic or elvanitic rocks occur (see p. 959).[10]

Similar features are presented by the granite bosses of Devon and Cornwall, which have risen through Devonian and Carboniferous strata. The Dartmoor mass is specially instructive. As shown by the early work of De la Beche, it passes across the boundary between the Devonian and Carboniferous areas, extending chiefly into the latter, so that it cuts across strata of different ages. In doing so it has risen irresistibly through the crust, without seriously affecting the general strike of the rocks. It cuts volcanic bands, as well as grits and shales into which it sends veins.[11]

Connection of Granite with Volcanic Rocks.—The manner in which some bosses of granite penetrate the rocks among which they occur strongly recalls the structure of volcanic necks or pipes (p. 969). The granite is found as a circular or elliptical mass which seems to descend vertically through the surrounding rocks without seriously disturbing them, as if a tube-shaped opening had been blown out of the crust of the earth, up which the granite had risen. Several of the granite masses of the south of Scotland, above referred to, exhibit this character very strikingly (Fig. 282). That granite and granitoid rocks have probably been associated with volcanic action is indicated by the way in which they occur in connection with the Tertiary volcanic rocks of Skye, Mull, and other islands in the Inner Hebrides. Jukes suggested many years ago that granite or granitoid masses may lie at the roots of volcanoes, and may be the source whence the more silicated lavas proceed.[12]

---

[10] Explanation of Sheet 9, Geological Survey of Scotland. The contact-metamorphism of these granite bosses is described on p. 1008.

[11] De la Beche, "Report, Devon and Cornwall," p. 165. J. A. Phillips, Q. J. Geol. Soc. xxxiv. p. 493. Compare the action of the Tertiary granites of Skye, Trans. Roy. Soc. Edin. xxxv. 1888, Fig. 56, p. 170.

[12] "Manual of Geology," 2d ed. p. 93; Geikie, Trans. Geol. Soc. Edin. ii. p. 301; Trans. Roy. Soc. Edin. xxxv. 1888, p. 150; Judd, Quart. Journ. Geol.

While the instances are few where any satisfactory connection can actually be traced between granitic masses and true lava-form or volcanic rocks, the close relationship between granite and the crystalline schists has long been recognized. It was formerly believed by many geologists that some granite is of metamorphic origin, that is to say, may have been produced by the gradual softening and recrystallization of other rocks at some depth within the crust

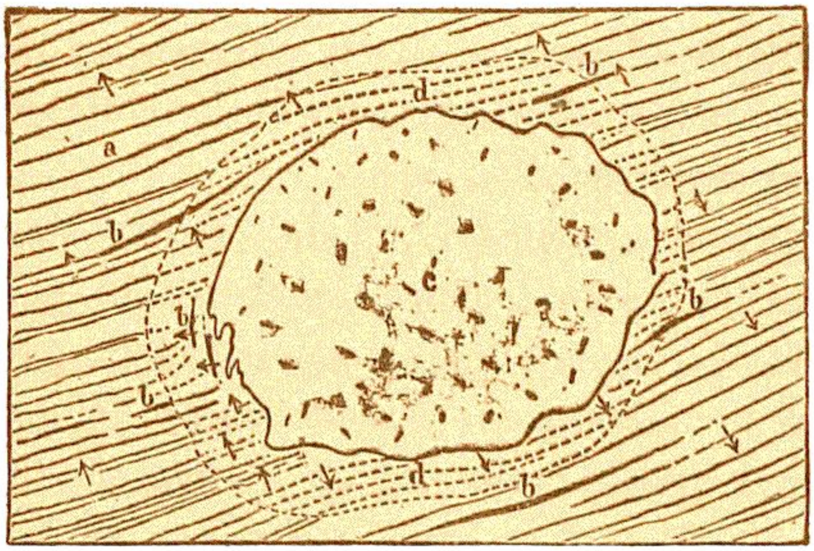


Fig. 282.—Plan of granite boss, Cairnsmore of Fleet, Scotland.

The granite area (*c*) is from 7 to 10 miles in diameter, rising through highly inclined Lower Silurian strata (*a*), among which are some conspicuous bands of black anthracitic and graptolitic shales (*b*). The arrows show the direction of dip; the parallel lines that of the strike. The ring within the dotted line round the granite defines the belt of metamorphism.

of the earth. As gradations can be traced from gneiss through less distinctly crystalline schists into unaltered strata, the granite into which such gneiss seems to pass was by some looked upon as the extreme of metamorphism, the various schists and gneisses being less advanced stages of the process. Prof. Dana has described a series of hornblendic, hypersthenic, augitic, micaceous, and olivine rocks in the valley of the Hudson River, which, as varieties of granite, syenite, diorite, norite, etc., he describes as masses

Soc. xxx. p. 220; Reyer, Jahrb. Geol. Reichsanst. 1879, p. 405, and his "Beitrag zur Physik der Eruptionen."

that have been reduced to a fused or plastic condition through metamorphic action."[13] The tendency of modern inquiry is to regard granite as an eruptive and not as a metamorphic rock, and to look upon the gradations between it and various schists as phases in the deformation and alteration of the original granite. Many cases are now known where under great mechanical stresses the component minerals of granite have been drawn out, as in the fluxion structure of lavas, and the rock has assumed the laminar structure of gneiss. Many gneisses are almost certainly only varieties of granite in which a foliated structure has been superinduced.[14]

Diorite, etc.—On a smaller scale usually than granite, other crystalline rocks assume the condition of amorphous bosses. Diorite, syenite, quartz-porphyry, gabbro, and members of the diabase and basalt family have often been erupted in irregular masses, partly along fissures, partly along the bedding, but often involving and apparently melting up portions of the rocks through which they have made their way. Such bosses have frequently tortuous boundary-lines, since they send out veins into or cut capriciously across the surrounding rocks.. In Wales, as shown by the maps and sections of the Geological Survey, the Lower Silurian formations are pierced by huge bosses of different crystalline rocks, mostly included under the old term "greenstone," which, after running for some way with the strike of the strata, turn round and break across it, or branch and traverse a considerable thickness of stratified rock. In central Scotland, numerous masses of dolerite

---

[13] Amer. Journ. Sci. xx. 1880, p. 219.

[14] See, for an early statement of this view, Dr. Lehmann's work on the granulite region of Saxony, cited ante, p. 272. The gneisses of the northwest of Scotland are believed to be essentially crushed and foliated eruptive rocks.

or diabase have been intruded among the Lower Carboniferous formations. One horizon on which they are particularly abundant lies about the base of the Carboniferous Limestone series. Along that horizon, they rise to the surface for many miles, sometimes ascending or descending in geological position, and breaking here and there abruptly across the strata.[15] There can be little doubt that they have actually melted down some parts of the stratified rocks, particularly the limestone.[16] Considerable petrographical differences occur among them, which may perhaps be in some measure due to the incorporation of such extraneous material into their mass. Gaps occur where these intrusive rocks do not rise to the surface, but as they resume their position again not far off, it may be presumed that they are really connected under these blank intervals. In the Inner Hebrides huge bosses of gabbro occur as well as granophyre and other acid rocks in the midst of the Tertiary volcanic series.

Mr. G. K. Gilbert has described, under the name of "laccolite," a structure in the Henry Mountains in Southern Utah, which is probably not uncommon in denuded volcanic districts. Large bosses of trachytic lava have risen from beneath, but instead of finding their way to the surface, have spread out laterally and pushed up the overlying strata into a dome-shaped elevation (Fig. 283). Here and there, smaller sheets proceeding from the main masses have been forced between the beds, or veins have been injected into fissures, and the overlying and contiguous strata have been considerably metamorphosed.[17]

---

[15] Trans. Roy. Soc. Edin. xxix. p. 476.

[16] See Dr. Stecher's papers, quoted postea, pp. 937, 1013.

[17] "Geology of the Henry Mountains," U. S. Geog. and Geol. Survey, Washington, 1877. A similar structure was figured and described by C Mac-

Effects on Contiguous Rocks.—The contact-metamorphism around bosses of diorite and other rocks includes alteration of the texture and even the mineralogical composition of the rocks through which intrusive material has been erupted. The amount and nature of the change produced vary with the character and bulk of the eruptive mass, as well as with the susceptibility of the surrounding materials to alteration. Diorite, diabase, melaphyre, basalt, felsite, and other eruptive rocks are not

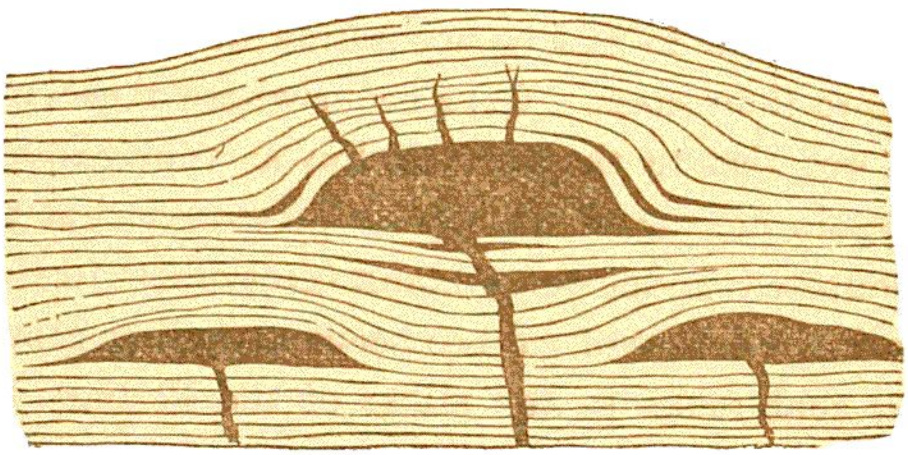


Fig. 283.—Ideal section of three "Laccolites," after Gilbert.

infrequently accompanied by considerable metamorphism of the adjacent strata, though the change seldom approaches the intensity of that around large areas of granite. These phenomena are manifested also by intrusive sheets, dikes, veins, and necks. They belong to the series of changes embraced under the head of contact-metamorphism, and are grouped together for description in Part VIII.

Effects on the Eruptive Mass.—Allusion has been made above to the displacement of rocks by eruptive bosses as if the original material that filled the present area

---

laren, "Geol. of Fife and Lothians," 1839, pp. 100, 101. The gabbros of Skye have been injected in this way into the sheets of the great basalt-plateau. Trans. Roy. Soc. Edin. xxxv. 1888, p. 122. See also J. D. Dana, Amer. Journ. Sci. xlii. 1891, p. 79.

of these bosses had been blown out, pushed up, or melted down into the advancing column of the igneous magma. If any serious amount of material were incorporated by fusion into an eruptive mass we should expect to be able to detect some change in the chemical composition or crystalline structure of the rock so affected. The observations and deductions of Dr. Stecher on the change in the composition of intrusive sheets (Book IV. Part VIII.) deserve full consideration, for they appear to indicate that considerable differences may be induced on an igneous mass by the incorporation into its substance of portions of the surrounding rocks.

Connection with Volcanic Action.—There can be little doubt that in regard to eruptive masses, particularly of the dioritic, gabbro, and doleritic or basaltic series, though the portions now visible consolidated under a greater or less depth of overlying material, they must in many cases have been directly connected with superficial volcanic action. Some of them may have been underground ramifications of the ascending molten rock which poured forth at the surface in streams of lava, though these superficial portions have been removed by denudation. Others may mark the position of intruded masses which were arrested in the unsuccessful attempt to open a new volcanic vent. The gabbro and granophyre bosses of the Inner Hebrides were undoubtedly a part of the general Tertiary volcanic phenomena of that region.

Connection with Crystalline Schists.—In some regions masses of diorite, gabbro, diabase, etc., associated with crystalline schists, have undergone such a rearrangement of their component minerals as to pass into amphibolites and hornblende-schists. These changes are well developed in the Saxon Granulitgebirge and in the North of Scotland. They are further referred to at p. 314, and Book IV. Part VIII.

§ 2. Sheets, Sills

Eruptive masses have been intruded between other rocks, and now appear as more or less regularly defined beds. In many cases, it will be found that these intrusions have taken place between the planes of stratification. The ascending molten matter, after breaking across the rocks, or rather, after ascending through fissures, either previously formed or opened at the time of the outburst, has at last found its path of least resistance to lie along the bedding-planes of the strata. Accordingly it has thrust itself between the beds, raising up the overlying mass, and solidifying as a nearly or exactly parallel cake, sheet, or sill.

It is evident that one of these intercalated sheets must present such points of resemblance to a subaerial stream of lava as to make it occasionally a somewhat difficult matter to determine its true character, more especially when, owing to extensive denudation, or other cause, only a small portion of the rock can now be seen. Intrusive sheets are marked by the following characters, though these must not be supposed to be all present in every case. (1) They do not rigidly conform to the bedding of the rocks among which they are intercalated, but sometimes break across it, and run along on another platform. (2) They catch up and involve portions of the surrounding strata. (3) They sometimes send veins into the rocks above and below them. (4) They are connected with dikes or pipes which, descending through the rocks underneath, have been the channels by which the sills were supplied. (5) They are commonly most close-grained at their upper and under surfaces, and most coarsely crystalline in the central portions. (6) They are rarely cellular or amygdaloidal. (7) The rocks both above and below them are usually hardened and otherwise more or less altered.

As a well-known and (from its association with the Huttonian and Wernerian disputes) classical example of this structure, the mural escarpment called Salisbury Crags at Edinburgh may be described (Fig. 284). This is a sill of crystalline diabase (dolerite), which can be traced for a distance of 1500 yards, lying among the red and gray sandstones, shales, and impure limestones which form the base

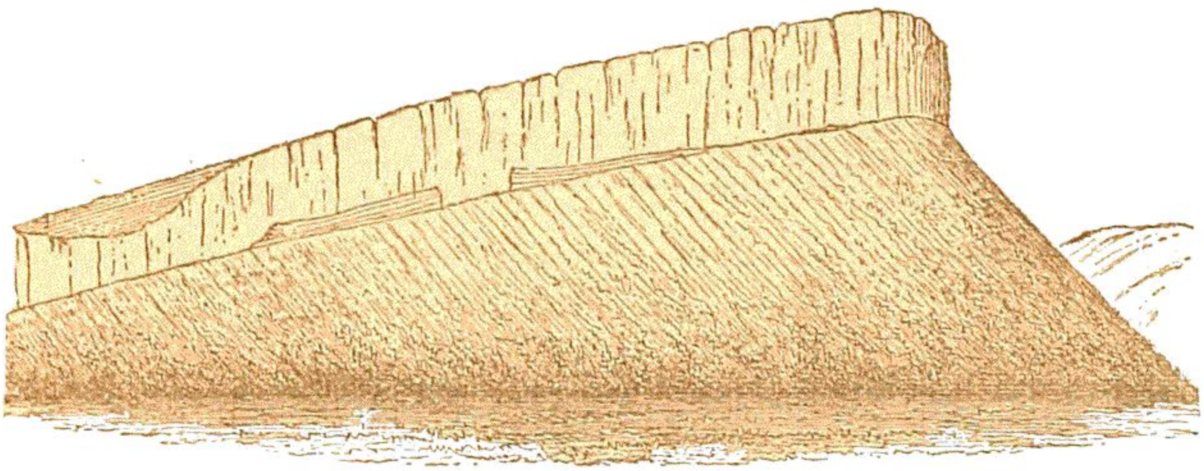


Fig. 284.—Diagrammatic view of Salisbury Crags, Edinburgh—a sill in Carboniferous sandstones and shales.

of the Carboniferous system of central Scotland. As the general dip of the rocks is northeasterly, the sill forms a lofty cliff facing west and south, from the base of which a long grassy slope of débris stretches down to the valley in front. Its thickness at the highest part is about 80 feet, but at a distance of 650 yards to the north this thickness diminishes to less than a half. At first, the diabase might be taken for a conformable sheet, regularly interposed between the sedimentary strata. But an examination of the beds on which it rests shows that it transgressively passes over a succession of platforms, and eventually comes to rest at the east end on strata somewhat lower in geological position than those at the north end. Moreover, another parallel intrusive sheet intercalated in a lower portion of the sandstone series gradually approaches the rock of Salisbury Crags. They are both transgressive across the strata, and they appear to unite in a large mass called Samson's Ribs.

On the west front, a large dike-like mass of the diabase descends vertically through the sandstones, and has been regarded as not improbably a pipe or feeder, up which the molten rock originally rose (Fig. 284). Along the southern face of the escarpment, several instructive exposures show the behavior of the diabase to the strata through which it has made its way. In Fig. 285, for example, a portion of the underlying strata having been carried away, the diabase has wedged itself below one of the remaining broken ends. Again, veins and threads of the eruptive rock have been injected into fragments of the strata caught up in its mass (Fig. 286). The strata in contact with the diabase have

Fig. 285.—Section at base of south front of Salisbury Crags, showing portion of strata cut out by intrusive diabase. *a*, sandstones, shales, etc.; *b*, diabase. Length of section, 22 feet.

been much hardened, the shales being converted into a kind of porcellanite, and the sandstones into quartzite.[18] The diabase in the centre of the bed is a coarse-grained rock, in which the component minerals can readily be detected with a lens, or even with the unassisted eye. But as it approaches the sedimentary beds, above and below, it becomes finely crystalline. I have had sections cut for the microscope, showing the actual junction of the two rocks (Fig. 287). In these it is interesting to observe that the diabase, for about the eighth of an inch inward from its edge, consists mainly of an altered glass in which lie well-formed crystals of triclinic felspar and numerous opaque tufted microlites, which may be of augite. An inch back from

[18] Mr. Sorby has observed in specimens from this locality sliced by him for microscopic examination that the fluid cavities in the quartz-grains have been emptied.—Address, Quart. Jour. Geol. Soc. xxxvi. Address, p. 82. But see Dr. Stecher's papers quoted p. 937, 997. This author gives a detailed account of the contact phenomenon of the Carboniferous sills in the basin of the Firth of Forth.

the edge, the glass and the microlites have alike disappeared, and the rock is merely a crystalline diabase, though finer in grain than in the central portions of the bed. Numerous steam- or gas-vesicles occur in the vitreous part, some of them empty, but mostly filled with calcite or a brown ferruginous earth. There can be little doubt that the vitreous structure of this marginal film was originally that of the whole rock. The thinness of the glassy crust is in harmony with all that is known as to the feeble thermal conductivity

Fig. 286.

Fig. 287.

Fig. 286.—Mass of sandstone and shale (*a*) imbedded in the diabase (*b*) of Salisbury Crags, and injected with veins and threads of it.

Fig. 287.—Junction of intrusive Diabase with Sandstone, Salisbury Crags, Edinburgh. Magnified 20 Diameters.—The granular portion at the bottom of the drawing is sandstone, a part of which is involved in the diabase that occupies the rest of the slide. The darker portion next the sandstone is a vitreous substance which has been serpentinized. It contains crystals of plagioclase and vapor vesicles drawn out in the direction of flow. Above the darker part the glassy condition rapidly passes into ordinary but minutely crystalline diabase. The rock has been considerably altered, calcite occupying many of the vesicles and fissures.

of lava. When the rock was intruded, it was no doubt a molten glass containing much absorbed vapor, the escape of which at its high temperature was probably the main agent in indurating the adjacent strata. In a number of slices cut from different parts of the central portion of the diabase, I have failed to detect any of the steam-holes so marked in the outer vitreous edge.[19]

[19] One of the most remarkable examples of an intrusive sheet is the Whin Sill of Northumberland, of which an account by Messrs. Topley and Lebour will be found in Q. J. Geol. Soc. xxxiii. 1877, p. 406. See also J. J. H. Teall, op. cit. 1884.

This greater closeness of texture at the surfaces of contact forms one of the distinguishing marks of an intrusive as contrasted with a contemporaneous sheet (pp. 952, 979). Microscopic examination of these marginal parts from many of the intrusive sheets in central Scotland, shows that even where no distinct glass remains, the rock is crowded with black opaque microlites arranged in a delicate geometric network. Back from the surface of contact, the microlites disappear, and the magnetite or titaniferous iron assumes its ordinary crystalline and often indeterminate or imperfect contours. These bodies, developed along the marginal portions of the intrusive mass, probably belong to conditions of rapid cooling.[20]

Another lithological characteristic of the intrusive, as compared with the interbedded sheets, is the considerable variety of composition and structure which may be detected in different portions of the same mass. A rock which at one place gives under the microscope a crystalline-granular texture, with the mineral elements of diabase, will at a short distance show a coarsely crystalline texture with abundant orthoclase and free quartz—minerals which do not belong to normal diabase—or may be traversed by veins of fine-grained siliceous material. These differences, like those above referred to as noticeable among amorphous bosses, seem to point to successive stages in the consolidation of a molten magma of which the more basic constituents separated first. But sometimes they suggest that great intrusive sheets have here and there involved and melted down portions of rocks, and have thus acquired locally an abnormal composition.[21]

[20] See Fouqué and Michel-Lévy, "Synthèse des Minéraux."

[21] Trans. Roy. Soc. Edin. xxix. p. 492. Clough, Geol. Mag. 1880, p. 433. See also J. J. H. Teall, Q. J. Geol. Soc. xl. p. 247, xlviii. p. 104. Stecher, paper cited on p. 937.

Effects on Contiguous Rocks.—Admirable examples of the alteration produced by eruptive masses are not uncommonly presented at the contact of intrusive sheets with the surrounding rocks. Induration, decoloration, fusion, the production of a prismatic structure, conversion of coal into anthracite, of limestone into marble, and other alterations, may be observed. The nature of these changes is described in Book IV. Part VIII.

Connection with Volcanic Action.—Many volcanic rocks occur in the form of intrusive sheets, as felsite, quartz-porphyry, diorite, melaphyre, diabase, dolerite, basalt, trachyte, and others. The remarks above made regarding the connection of intrusive bosses with volcanic action may be repeated with even greater definiteness here. Intrusive sheets abound in old volcanic districts, intimately associated with dikes and surface-outflows, thus bringing before our eyes traces of the underground mechanism of volcanoes. They frequently occur among the rocks that lie beneath a mass of ejected lavas and tuffs, or traverse the lower, sometimes even the upper parts of the volcanic mass. They then appear to mark some of the later stages of eruption when the orifices of discharge had become choked up and the subterranean energy only sufficed to inject the magma between the bedding of the rocks below ground but not to impel it to the surface. It is observable that later intruded masses are often more acid than the lavas previously erupted.[29]

Among the Palæozoic and Tertiary volcanic regions of Britain numerous illustrations of such sills are to be found. Some of the most striking are those that emerge from be-

[29] Trans. Roy. Soc. Edin. xxxv. 1888, p. 143 Quart. Journ. Geol. Soc. xlviii. 1892, Address, p. 177.

neath the great erupted masses of Arenig and Bala age in North Wales. Admirable examples occur among the Carboniferous volcanic rocks of the basin of the Forth.[23] The Tertiary sills injected among Carboniferous and Cretaceous rocks of Antrim and the Jurassic rocks of the Inner Hebrides are likewise conspicuous for size and abundance.[24]

§ 3. Veins and Dikes

The term "vein" is rather vaguely employed by geologists. It is used as the designation of any mass of mineral

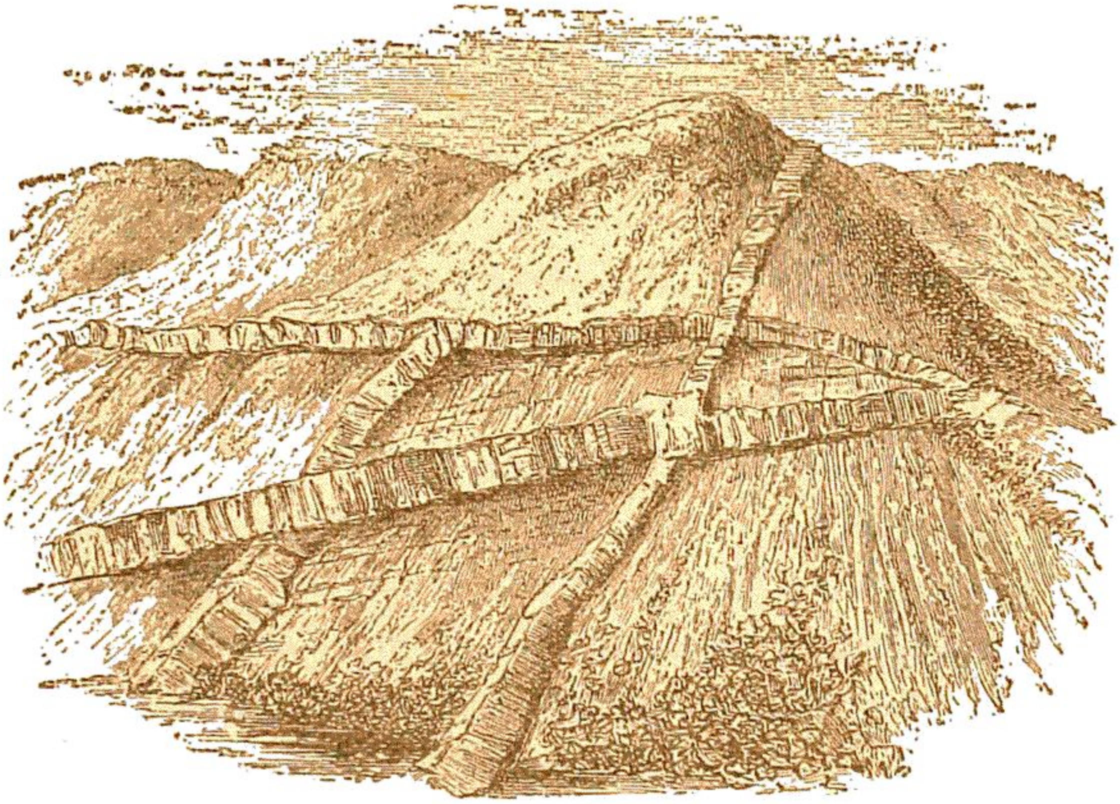


Fig. 288.—Intrusive Veins and Dikes of Porphyrite in Tuff of a Volcanic "Neck," Renfrewshire.

matter which has solidified between the separated walls of a fissure. When this mineral matter has been deposited from aqueous solution or from sublimation, it forms what is known as a *mineral vein* (Pt. IX.). When it has been

[23] See Trans. Roy. Soc. Edin. xxix. p. 474.
[24] Op. cit. xxxv. 1888, p. 111.

injected in a molten or pasty state into some other rock, it forms an *eruptive vein*, or, if it forms a vertical wall-like mass, a *dike*. When it forms part of the igneous rock in which it occurs, but belongs to a later period of consolidation than the portion into which it has been injected, it has been called a *contemporaneous vein*. When it has crystallized or segregated out of the component materials of some still unconsolidated, colloid, or pasty rock, it is called a *segregation-vein*.

Eruptive or Intrusive Veins and Dikes are portions of once-melted, or at least pasty matter, which have been injected into rents of previously solidified rocks. When traceable sufficiently far, they may be seen to swell out and merge into their parent mass, while in the opposite direction they may become attenuated into mere threads. Sometimes they run for many yards or miles in tolerably straight lines. When this takes place along vertical or highly-inclined stratification, they look like beds, but they are of course really intrusive sheets. They may frequently be found to break across the bedding in a very irregular manner.

No rock exhibits more instructively than granite the numerous varieties of form assumed by Veins.[25] Three distinct kinds of granite veins may be observed. (1) Protrusions of the ordinary granite extending from the main masses into the surrounding rocks and demonstrating the intrusive character of the granite (Figs. 289, 290). These, varying in breadth from several feet or many yards down to fine filaments or threads, are often remarkably abundant and markedly irregular in the manner in which they branch and intersect. Where they are several yards broad their texture, at least in the central parts, may not sensibly differ from that of the main granite mass, though it is apt to

[25] On granite veins, see Prof. H. Credner, Zeitsch. Deutsch. Geol. Ges. 1875, p. 104; 1882, p. 500. E. Kalkowsky, op. cit. 1881, p. 629.

become finer especially as the veins diminish in breadth. Round some bosses of granite the adjacent rocks are injected or impregnated with such an abundance of minute threads or veins of granite substance, like layers or leaves

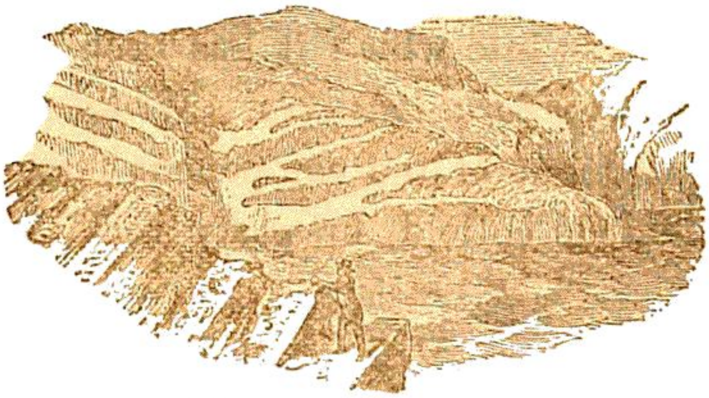


Fig. 289.—Granite Veins.

parallel with the stratification or foliation, that they are said to be "granitized." [26]

Besides greater closeness of texture, these intrusive veins sometimes present considerable differences in mineralogical

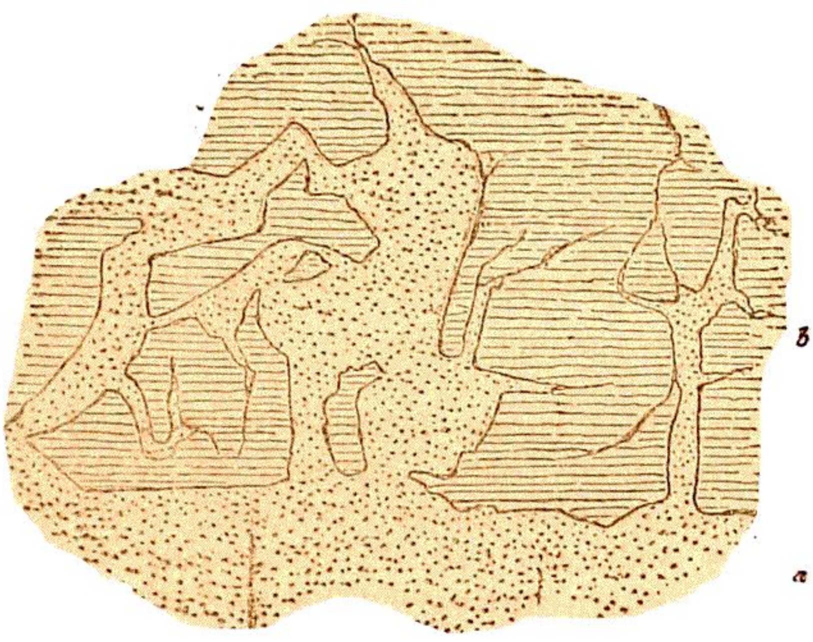


Fig. 290.—Section of granite (*a*), sending a network of veins into slate (*b*); Cornwall (*B.*).

composition. The mica, for example, may be reduced to exceedingly minute and not very abundant flakes, and may almost disappear. The quartz also occasionally assumes a subordinate place, and the rock of the veins passes into

---

[26] Michel-Lévy, Bull. Soc. Geol. France, ix. 1881, p. 187.

one of the varieties of felsite, quartz-porphyry, elvanite, aplite or eurite.[27]

It is in the metamorphosed belt, already (p. 946) described as encircling an intrusive boss of granite, that eruptive veins are typically developed and most readily studied. In Cornwall, for example, the slates around the granite bosses are abundantly traversed by veins or dikes of granite and of quartz-porphyry (*elvans*), which are most numerous near the granite (Fig. 291). They vary in width from

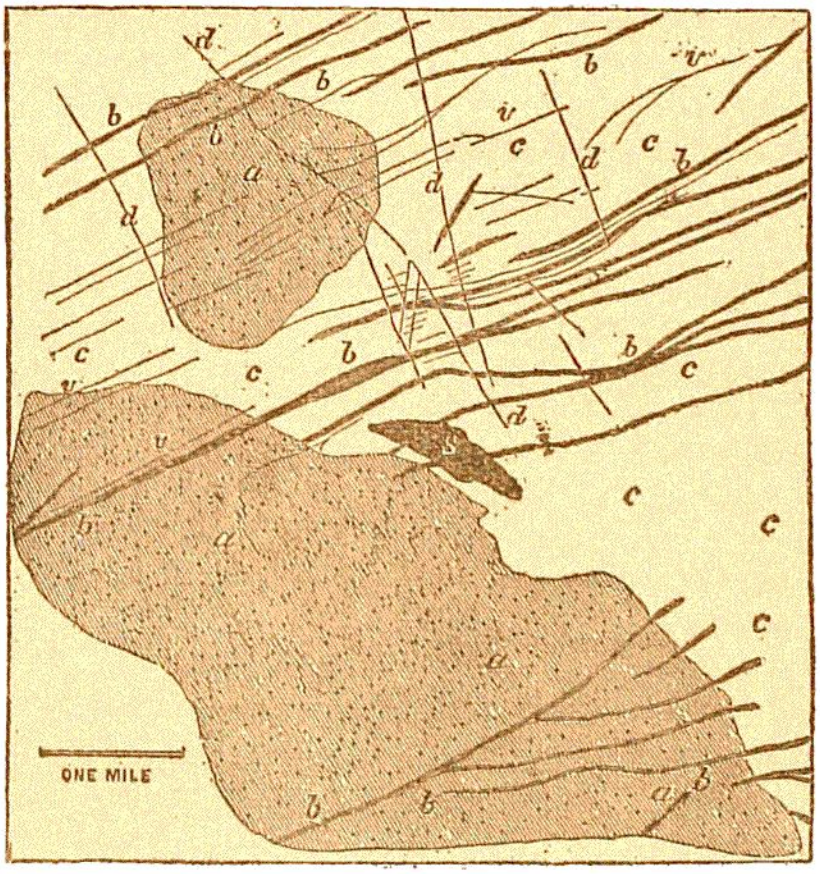


Fig. 291.—Map of part of the Mining District of Gwennap, Cornwall (*B.*). *a a*, Granite; *c c*, Schistose rocks; *b b*, Elvan dikes; *s*, "Greenstone"; *v v*, *d d*, two intersecting series of mineral-veins.

a few inches or feet to 50 fathoms, their central portions being commonly more crystalline than the sides. They frequently inclose angular fragments of slate (p. 940). In the great granite region of Leinster, Jukes traced some of the elvans for several miles running in parallel bands, each only a few feet thick, with intervals of 200 or 300 yards between them. Around some of the granite bosses of the south of Scotland similar veins of felsite and porphyry

[27] See a reference to the Bodegang, ante, p. 277; also Hawes, Amer. Journ. Sci. xx. 1881, p. 244.

abound. The granite of the Wahsatch Mountains in Utah, which rises through the Upper Carboniferous limestones, converting them into white marble, sends out veins of granite-porphyry and other crystalline compounds. In short, all over the world it is common for eruptive bosses of this rock to have a fringe of intrusive veins (*Apophyses*).

(2) Veins in the granite itself. These must be regarded as later than the rock which they traverse, but they may represent lower, still liquid portions of the granitic magma which have been forced by earth-movements into rents in the partially or wholly solidified granite. They are generally finer in grain than the granite around them, and differ more or less from it also in composition, especially in their greater acidity (Fig. 30).

(3) Pegmatites. These are distinguished by the manner in which their component minerals, notably the quartz and felspar, are intergrown (see p. 175). Much discussion has arisen as to the origin of such veins. They evidently cut the ordinary granite and in so far may be regarded as intrusive veins. But it is difficult to conceive that they could have been injected in their present crystalline condition. They may have been squeezed up from some lower, still liquid part of the granitic magma, but their remarkable crystalline structure would seem to have been afterward superinduced by some process of segregation or rearrangement and crystallization of their materials.

Many other eruptive rocks (diorite, diabase, melaphyre, basalt, etc.) present admirable examples of intrusive (even pegmatitic) veins. These are generally distinguished from those of granite by the much less metamorphism with which they are attended.

The "Contemporaneous Veins" of older writers included those veins in crystalline rocks which, though differing sufficiently from the surrounding material to be easily distinguished, resembled it so closely as to indicate that they were probably a part of it. The veins above described under No. 2 are examples. But they are not confined to granite, since they may not infrequently be observed in sheets of gabbro, diorite, dolerite, diabase, and other eruptive rocks. They are more particularly to be seen in sills and bosses. They run as straight, curved, or branching ribbons, usually not exceeding a foot in thickness. They are finer in texture than the rock which they traverse. Close examination of them shows that, instead of being sharply defined by a definite junction line with the inclosing rock, they are welded into that rock in such a way that they cannot easily be broken along the plane of union. This welding is found to be due to the mutual protrusion of the component crystals of the vein and of the surrounding rock—a structure sometimes admirably revealed under the microscope. Veins of this kind evidently point to some process whereby, into rents formed in the deeply buried and at least partially consolidated or possibly pasty or jelly-like mass, there was an injection of similar material from some still unsolidified part of the mass with a transfusion or exosmosis of some of the crystallizing minerals along the mutual boundaries. Such veins are to be distinguished from the true Segregation-veins, which are irregular bands usually of more coarsely crystalline material not infrequently to be seen in intrusive sheets, wherein the constituent minerals have crystallized out in a much more conspicuous form than in the main mass of the surrounding rock along certain lines or around particular centres. These are probably due to some kind of segregation from the surrounding mass, though the conditions under which it took place have not yet been satisfactorily explained.[28] Segregation-veins occur among the crystalline schists and even in sedimentary rocks which have been crushed and metamorphosed, as in the felspathic Torridon Sandstone of Loch Carron.

---

[28] For some illustrations see Trans. Roy. Soc. Edin. xxxv. 1888, pp. 113, 115, 118, 131.

Along the margin of segregation-veins in granite a foliated structure of the rock may be occasionally observed, as in some of the large granite quarries near Aberdeen (Fig. 292). Coarse pegmatite veins abounding in large plates of muscovite, black tourmaline, and quartz, with occasional crystals of beryl and other minerals, merge into the sur-

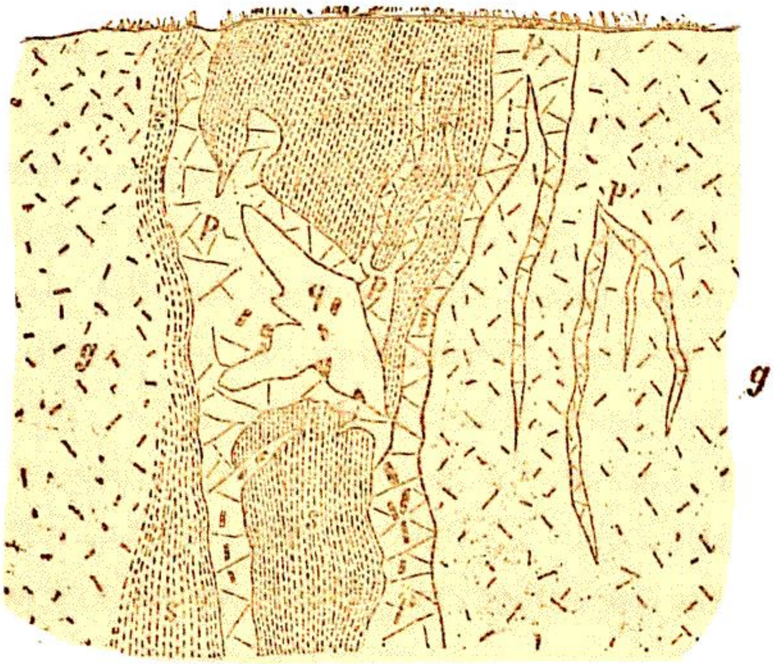


Fig. 292.—Pegmatite Vein associated with foliated granite. Rubislaw Quarry, Aberdeen.

g g, Ordinary granite of the mass; *p p*, coarse pegmatite veins; *s s*, foliated granite passing insensibly into *g*; *q*, mass of quartz. The black patches in *p* and *q* are nests of schorl.

rounding granite which for a few inches along the contact has a foliated structure precisely resembling that of a fine gneiss. This foliation may indicate motion of the granite mass along the line of fissure, while the rock itself or the material forced up into the fissure was still capable of molecular rearrangement. It is in veins in granite that the remarkable structure known as *graphic granite* occurs.[29]

[29] For an able discussion of Pegmatite veins see Prof. W. C. Brögger's great work "Die Mineralien der Syenitpegmatitgänge," in Groth's Zeitsch. Krystallographie, xvi. 1890; at p. 215 *et seq.* a historical résumé of the discussion will be found.

Dikes are veins of eruptive rock, filling vertical or highly-inclined fissures, and are so named on account of their resemblance to walls (*Scotice*, dikes). Their sides are often as parallel and perpendicular as those of built walls, the resemblance to human workmanship being heightened by the numerous joints which, intersecting each other along the face of a dike, remind us of well-fitted masonry. Where the surrounding rock has decayed, the dikes may be seen projecting above ground exactly like walls (Fig. 294); indeed, in many parts of the west of Scotland they are made use of for inclosures. The material of the dikes has in other

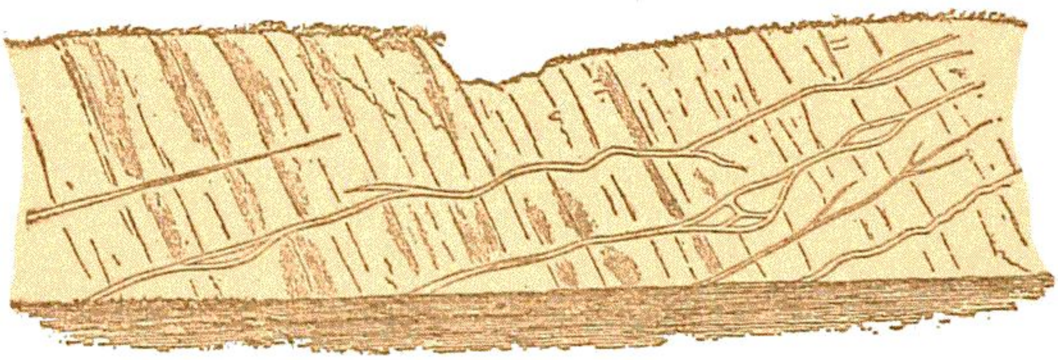


Fig. 293.—"Contemporaneous Veins" in diabase.

cases decayed, and deep ditch-like hollows are left to mark their sites. The coast-lines of many of the Inner Hebrides and of the Clyde Islands furnish numerous admirable examples of both kinds of scenery.

The term dike may be applied to some of the wall-like intrusions of quartz-porphyry, elvanite, and even of granite, but it is more typically illustrated among the basic and intermediate igneous rocks such as basalt, diabase, andesite, diorite, etc., while occasionally dikes may be observed of even tuff and volcanic agglomerate.[30] Veins have been in-

[30] Some remarkable examples of sandstone-dikes have been described from various districts of North America, ranging from a mere film to eight feet broad and varying from 200 yards to upward of nine miles in length. They have been

jected into irregular branching cracks; dikes have been formed by the welling upward of liquid or plastic rock in vertical or steeply inclined fissures, though obviously there is no essential difference between the two forms of structure. Sometimes the line of escape has been along a fault. In Scotland, however, which may be regarded as a typical region for this kind of geological structure, the vast major-

Fig. 294.—Dikes in volcanic tuff of a "neck"; shore, Elie, Fife.

ity of dikes rise along joints or fissures which have no throw, and are therefore not faults. On the contrary, the dikes may be traced undeflected across some of the largest faults in the midland counties.

Dikes differ from veins in the greater parallelism of their sides, their verticality, and their greater regularity of breadth and persistence of direction. They sometimes occur as mere plates of rock not more than an inch or two

ascribed to the infilling of fissures with sand from below by earthquakes acting on wet sandstone strata underground. J. S. Diller, Bull. Geol. Soc. America, i. 1890, p. 411.

in thickness, at other times they attain a breadth of twelve fathoms or more. The smaller or thinner dikes can seldom be traced more than a few yards; but the larger examples may be followed sometimes for many miles. Thus, in the south and west of Scotland, a remarkable series of basalt and andesite dikes can be traced across all the geological formations of that region, including the older Tertiary basalt-plateau. They run parallel to each other in a general northwest and southeast direction for distances of twenty and thirty miles, increasing in numbers toward the northwest, and they have been assigned to the great volcanic activity of Tertiary time. A dike of the same series crosses the north of England, from near the coast of Yorkshire for about 100 miles inland. A complex system of massive pre-Cambrian dikes occurs in N.W. Scotland.

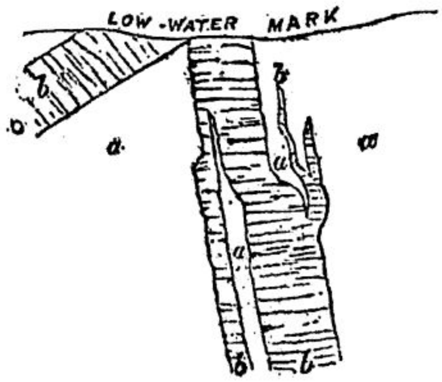


Fig. 295.—Plan of dikes (*b b*) cutting sandstone (*a a*); shore, Gourock, Renfrewshire.

Though the wall-like form is predominant among dikes, it may readily pass into vein-like ramifications and intrusive sheets (Figs. 284, 288). The molten material took the channels that happened to be most available. If the fissure bent off at an angle from its previous trend, or if another adjacent fissure happened to be more convenient, the eruptive rock might change its course. Again, while the ascending lava, under the hydrostatic pressure of the mass below, rose in one main fissure, portions of it might find their way into neighboring parallel rents, and inclose wall-like portions of rock within the dike, as in Fig. 295, where the total breadth of the main dike, including the sandstone between the two arms, is about thirty feet, the sandstone being gently inclined, and the portions inclosed between the arms of the dike having been greatly indurated.

It must be kept in mind, however, that irregular expansions and contractions of dikes may sometimes be caused by subsequent movements of the terrestrial crust. The dikes, for instance, may be plicated together with the rocks among which they have been intruded, and the folds may afterward be pressed in such a way as to give rise to alternate or irregularly distributed enlargements and constrictions, or a similar effect may be produced by shearing or by faulting.[81] Mr. Clough has found that in a great system of dikes traversing the crystalline schists of Argyllshire frequent attenuations of the dikes are produced by faults.

In internal structure, considerable differences may be detected among dikes. The rock may appear (*a*) with no definite structure of any kind beyond irregular jointing; (*b*) columnar, the prisms striking off at right angles from the walls, and either going completely across from side to side, or leaving a central non-columnar part in which they branch and lose themselves; when the side of a dike having this structure is laid bare, it presents a network of polygonal joints formed by the ends of the prisms which, if the dike is vertical, lie of course in a horizontal position, whence they depart in proportion as the dike is inclined: occasionally the prisms are as well-formed as in any columnar bed of basalt; (*c*) jointed parallel with the walls, the joints being sometimes so close as to cause the rock to appear as if it consisted of a series of vertical plates or strata: this platy character is due doubtless to contraction in cooling between parallel walls, and when it occurs in basalt-dikes is best de-

[81] Compare the structure illustrated by Fig. 312. See also Harker, Geol. Mag. 1889, p. 69, and the account of the pre-Cambrian rocks in Book VI. Part I.

veloped near the margins; (*d*) vesicular or amygdaloidal, lines of minute vesicles having been formed parallel with the walls, and attaining their greatest number and size along the centre of the dike.

As a rule, the outer parts of a dike of crystalline rock, like the upper and under surfaces of an intrusive sheet, are finer grained than the centre. Occasionally, the external surface has a vitreous structure. Basalt veins, for example, have not infrequently an external coating or crust of glass (tachylite, hyalomelan, etc.). It occasionally happens also that the central portions of a basalt or andesite dike are glassy, of which structure several cases have been observed in Scotland; perhaps in these instances the dike has opened along its centre, and a fresh uprise of more glassy material has risen in the fissure.[32]

Effects on Contiguous Rocks.—These are similar to the changes produced by intrusive sheets and other eruptive masses. Induration is the most frequent kind of alteration. Remarkable examples have been observed where limestones in contact with dikes have had a saccharoid crystallization of the calcite superinduced upon them, and where even new crystalline silicates have been developed (pp. 545, 998).[33]

§ 4. Necks

Under this term are included the filled-up pipes or funnels of former volcanic vents. Every series of volcanic sheets poured out at the surface must have been connected either with fissures, or with orifices probably opened in lines of fissures. On the cessation of the eruptions, these orifices

---

[32] See Proc. Roy. Phys. Soc. Edin. vol. v. 1880, p. 241.
[33] On the Mechanism of Dikes see Mallet, Q. J. Geol. Soc. xxxii. 1876, p. 472.

have remained filled with lava or with fragmentary matter. But unless subsequent denudation has removed the overlying cone, a vent lies buried under the materials which came out of it. So extensive, however, has been the waste of the surface in many old volcanic regions that the vents have been laid bare. In Fig. 296 two volcanic funnels are represented, one of them still buried under overlying formations, the other partially exposed by denudation. The study of volcanic Necks brings before us some of the more deep-

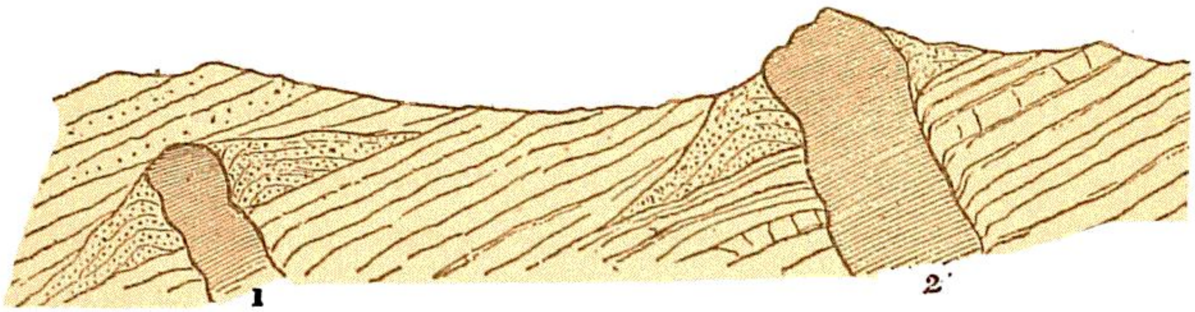


Fig. 296.—Diagram-section to show the structure of old volcanic vents, and how they may be concealed and exposed.

1, Tuff cone with basalt plug still buried under sedimentary accumulations; 2, Tuff cone and basalt plug partially exposed by denudation.

seated phenomena of volcanic action, that cannot usually be seen at a modern volcano.

A Neck is circular or elliptical in ground-plan, but occasionally more irregular and branching, and may vary in diameter from a few yards (Fig. 297) up to two miles, or even more. It descends into the earth perpendicularly to the stratification of the formation with which it is chronologically connected. Should rocks originally horizontal be subsequently tilted, a neck associated with them would of course be thrown out of the vertical (Fig. 296). As a rule, however, the vertical descent of necks into the earth's crust appears to have been comparatively little interfered with. In external form, necks commonly rise as cones or dome-shaped hills (Fig. 298). This contour, however, is not that of the original volcanoes, but is due to denudation. Occasionally the rocks of a neck have been so worn away that a great hollow, suggestive of the original crater, occupies their site. (Fintry Hills, Stirlingshire.)[34]

It might be supposed that necks should always rise on

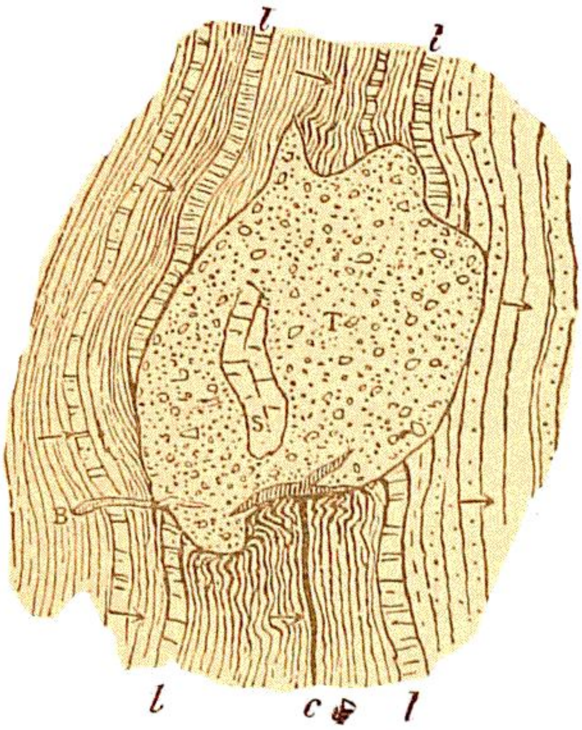


Fig. 297.—Plan of Neck, shore, near St. Monans, Fife.

l l, beds of limestone; *c*, thin coal-seam; B, basalt veins; S, large bed or block of sandstone. The Neck, T, measures about 60 by 37 yards. The arrows mark the dip of the strata.

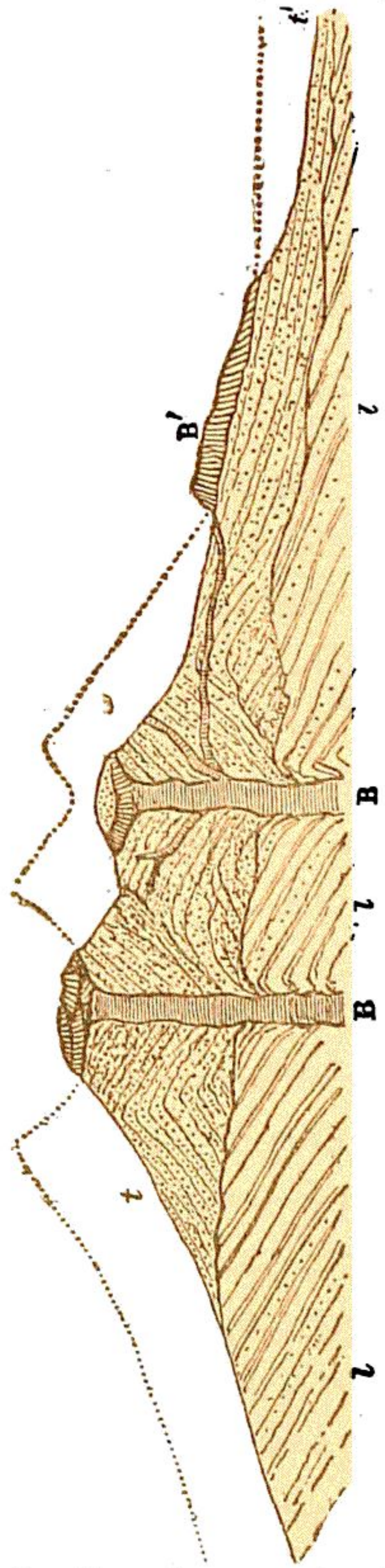


Fig. 298.—Section of the volcanic neck of Largo Law, Fife.

l l, Lower Carboniferous strata; *t*, tuff of cones; *t′*, tuff of area around the cones; B B, basalt filling central pipes of the vents and lateral veins; B′, basalt, which may have flowed out at the surface. The dotted lines are suggestive of the original outline of the hill.

lines of fissure. But in central Scotland, where they abound in rocks of Carboniferous age, it is quite exceptional to find one placed on a fault. As a rule, they seem

[34] For some striking views of denuded volcanic necks see Captain Dutton's Report on Mount Taylor and the Zuñi Plateau, 6th Ann. Rep. U. S. Geol. Survey, 1884–85. Compare also Trans. Roy. Soc. Edin. vol. xxxv. 1888, p. 100.

to be independent of the structure of the visible part of the crust through which they rise.

The materials filling up ancient volcanic orifices may be (*a*) some form of lava, as granophyre, felsite, gabbro, diabase, porphyrite, basalt; or (*b*) the fragmentary materials which fell back into the throat of the volcano and finally solidified there. In many instances, both kinds of rock occur in the same neck, the main mass consisting of agglomerate or tuff with a central pipe or numerous veins of lava. Among the Palæozoic volcanic districts of Britain, necks not infrequently are filled with some siliceous crystalline rock, such as a quartz-porphyry or felsite, even where the surrounding lavas are basic. The great vent of the Braid Hills near Edinburgh, belonging to the time of the Lower Old Red Sandstone, is filled with felsite-tuff containing 70 per cent of silica, while the lavas which flowed from it are porphyrites and diabases with not more than 50 per cent of this acid. Again, at Largo in Fife, strings of quartz-felsite occur in one of the necks, though all the surrounding lavas are basalts.[35]

In some necks composed of eruptive rock, the material appears arranged in successive spherical shells, which may be supposed to be due to the protrusion of successive portions of the pasty or viscous mass one within the other, the outer layers thinning away over the crown of the dome as they were attenuated by the ascent of fresh material from below.[36] Or we may suppose that the top of the plug some-

[35] Necks of agglomerate and fine tuff abound among the Carboniferous and Permian volcanic regions of Scotland, and are laid bare in so many admirable sections, that these regions may be regarded as typical for this kind of geological structure.

[36] Scrope, "Geology and Extinct Volcanoes of Central France," 2d edition, p. 68. See E. Reyer, Jahrb. Geol. Reichsanst. xxix. 1879, p. 463; and ante, p. 421; A. G., Trans. Roy. Soc. Edin. xxxv. 1888, p. 161.

times solidified, and that subsequent emissions of lava rose through rents in the crust, and flowed down the outside of the vent.

The fragmentary materials in necks consist mainly of different lava-form rocks imbedded in a gravelly *peperino*-like matrix of more finely comminuted débris of the same rocks; but they also contain, sometimes in abundance, fragments of the strata through which the necks have been drilled. When occasionally, as in some of the Maare of the Eifel, these non-volcanic fragments constitute most of the débris (p. 417), we may infer that after the first gaseous explosions, the activity of the vent ceased, without the rise of the lava-column or its ejection in dust and fragments to the surface. So unchanged are many of the pieces of sandstone, shale, limestone, or other stratified rock in the necks, that they have evidently never been exposed to any high temperature. In some cases, however, considerable alteration is displayed. Dr. Heddle, from observations in Fife, concluded that the altered blocks in the tuff there must have been exposed to a temperature of between 660° and 900° Fahr.[37]

Among the numerous vents of central Scotland, pieces of fine stratified tuff not infrequently appear in the agglomerates. This fact, coupled with the not uncommon occurrence of a tumultuous, fractured, and highly-inclined bedding of the tuff with a dip toward the centre of the neck (Figs. 298, 299), appears to show that the pipes were partly filled up by the subsidence of the tuff consolidated in beds within the crater and at the upper part of the funnel. Further indication of the probable subaerial character of the

[37] Trans. Roy. Soc. Edin. xxviii. p. 487.

tuff is furnished by abundant pieces of inclosed coniferous wood, which may have belonged to trees or brushwood that grew upon the dry slopes of the cones; for these fragments are seldom to be seen in the estuarine and marine strata, out of which the necks rise.

It is common to find among necks of tuff numerous dikes and veins of lava which, ascending through the tuff, are usually confined to it, though occasionally they penetrate the surrounding strata. They are often beautifully columnar, the columns diverging from the sides of the dikes and being frequently curved.

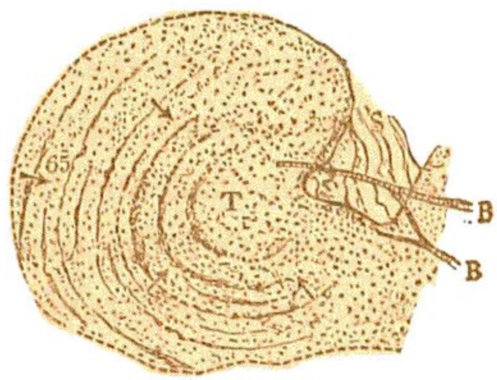


Fig. 299.—Plan of Neck, on shore, at Elie, Fife.
T, tuff; the arrows marking the inward dip; S, sandstones through which the Neck has been blown open; B B, basalt dikes.

Proofs of subsidence round the sides of vents may often be observed. Stratified rocks, through which a volcanic funnel has been opened, commonly dip into it all round, and may even be seen on edge, as if they had been dragged down by the subsidence of the materials in the vent. Beautiful examples occur along the shores of the Firth of the Forth.[38] (Figs. 300, 301). The fact of subsidence beneath modern volcanic cones has been already referred to (pp. 395, 418).

Effects on Contiguous Rocks.—The strata round a neck are usually somewhat hardened. Sandstones have acquired a vitreous lustre; argillaceous beds have been indurated into porcellanite; coal-seams have been fused, blistered, burned, and rendered unworkable. The coal-workings in Fife and Ayrshire have revealed many inter-

[38] Trans. Roy. Soc. Edin. xxix. p. 469. For an excellent example from New Zealand, see Heaphy, Q. J. Geol. Soc. 1860, p. 245.

esting examples of these changes, which may be partly due to the heat of the ascending column of molten rock or

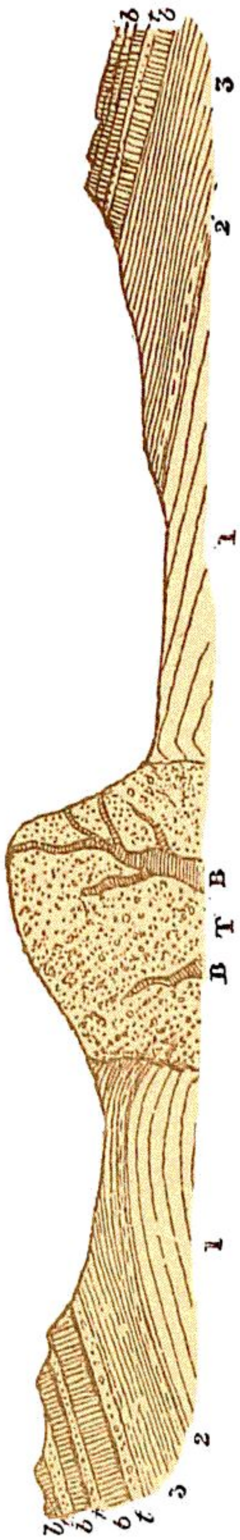


Fig. 300.—Section across the Binn of Burntisland, Fife.
1, Sandstones; 2, Limestone; 3, Shales, etc.; *b b*, Interstratified basalts; *t t*, Bedded tuffs, etc.; T, Tuff of the great neck of the Binn; B, Basalt veins.

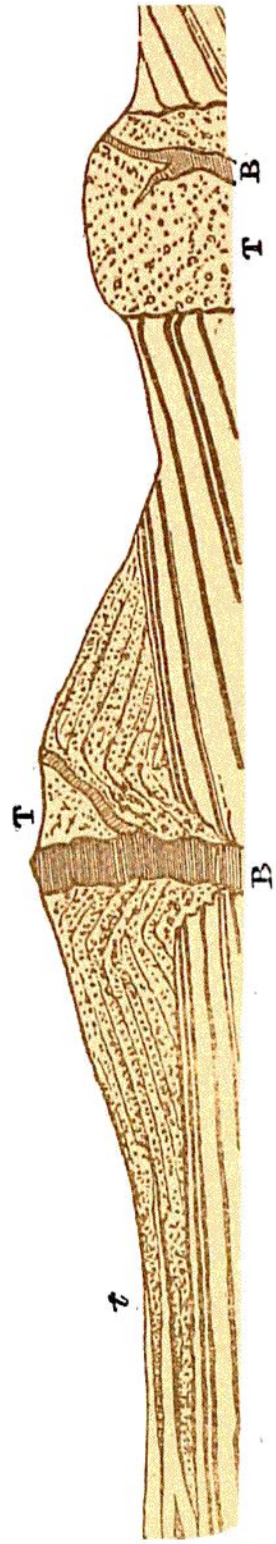


Fig. 301.—Section across the Saline Hills, Fife.
T, Tuff of necks; *t*, Continuation of tuff of cone intercalated with the contemporaneously formed sedimentary strata; B, Basalt. The thick parallel lines are coal-seams, which have been charred round the smaller eminence (Knock Hill), while they can be worked for some way under the larger, or Saline Hill.

ejected fragments, partly to the rise of heated vapors, even for a long time subsequently to the volcanic explosions. Proofs of a metamorphism, probably due to the latter cause, may sometimes be seen within the area of a neck. Where the altered materials are of a fragmentary character, the nature and amount of this change can best be estimated. What was originally a general matrix of volcanic dust has been converted into a crystalline and even porphyritic mass, through which the dispersed blocks, though likewise intensely altered, are still recognizable. Such blocks as, from the nature of their substance, must have offered most resistance to change—pieces of sandstone or quartz, for example—stand out prominently in the altered mass, though even they have undergone more or less modification, the sandstone being converted into vitreous quartz-rock.[39]

---

[39] For a detailed account of the structure of some volcanic necks, the student may consult a monograph by the author on the Carboniferous volcanic rocks of the Basin of the Forth, Trans. Roy. Soc. Edin. xxix. p. 437.

END OF SECOND PART OF "TEXT-BOOK OF GEOLOGY"