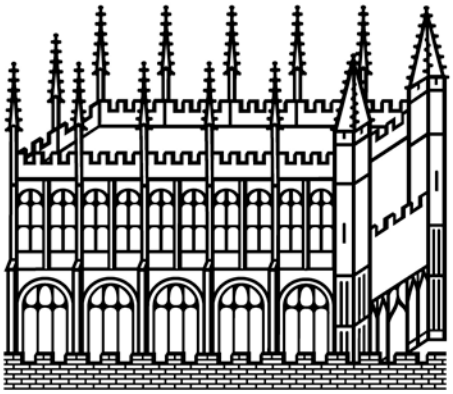

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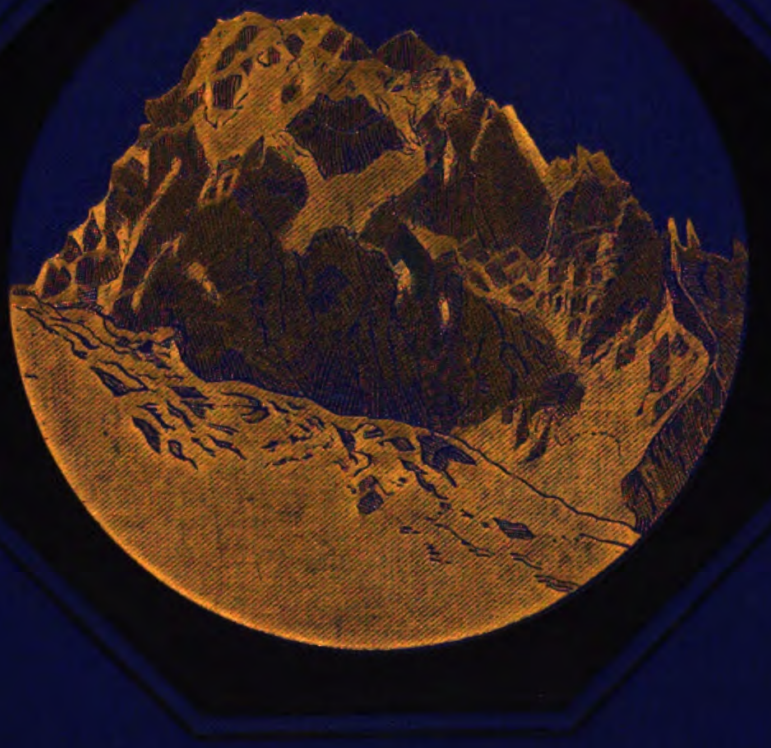

Mont Blanc

Viollet-le-Duc

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MONT BLANC

A TREATISE

ON

ITS GEODESICAL AND GEOLOGICAL CONSTITUTION;
ITS TRANSFORMATIONS;
AND
THE ANCIENT AND RECENT STATE OF ITS GLACIERS.

BY

EUGÈNE VIOLLET-LE-DUC.

WITH 120 ILLUSTRATIONS.

BIBLIOTHECA
DEC 1877
BODLEIANA.

TRANSLATED BY B. BUCKNALL.

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188. e. 78.

TRANSLATOR'S NOTE.

From the study of the architectural monuments of past times, and the analysis of the principles which guided their builders, to the examination of the older and grander monuments of Nature's Architecture, and the investigation of the laws determining their structure and ultimate form, is a natural step. In this his latest published work, therefore, M. Viollet-le-Duc gives us an abstract of his observations of mountain phenomena conducted during several summer holidays passed in the neighbourhood of Mont Blanc. Verifying his conclusions by those of other investigators, he graphically describes the configuration of the chain at the epoch of its upheaval, the successive processes by which it has been transformed from the mammillated mass it once exhibited to its present denticulated and ruined appearance, and the means by which the once deep fissure-like hollows—the ruptures occasioned by the upheaval—have been widened and shaped into the forms now presented by the environing valleys. The descriptions are aided by numerous beautiful diagrams, illustrating the crystalline structure of the rocks, the mode of their disintegration, the character and action of the glaciers, their moraines, and the

effects of drifts and torrents. Nor is the interest of the work speculative only. The author has been careful to point out the practical application that can be made of the knowlege derived from the study of the natural phenomena in question. In the last chapter he shows how the vast forces of nature may be controlled and their destructive effects obviated; how by the use of simple means—which may be said rather to aid than to oppose Nature—the dire ruin caused by avalanches may be averted, and the mountain waters be checked before they spread in disastrous floods over the plains beneath.

It is true that many of the phenomena described by M. Viollet-le-Duc have already been carefully investigated and explained by Professor Tyndall and other eminent physicists. But the special subject of this work has never before been treated in so consecutive and compendious a form; while in this not less than in his other works the author has displayed the rare talent he possesses of investing a comparatively dry subject with vivid interest. In the number, accuracy, and beauty of the diagrams, this treatise may be deemed unrivalled. It is difficult indeed to understand how mountain scenery can be properly studied without the constant aid of the pencil, since it is only by actual delineation that the peculiarities of structure and the effects of disturbing causes can be thoroughly appreciated. Only by such a close observation of the masses, details, and relations as delineation implies, can the imperfect and often illusive image left on the memory by fugitive glances be completed and corrected.

With a view to rendering the topographical knowledge he had gained while observing and sketching the

mountains of service to others, M. Viollet-le-Duc conceived the idea of mapping the district of Mont Blanc. Eight summer holidays were devoted to the work of surveying, sketching, and examining the ground. Deducting for bad weather, when out-of-doors work was impossible, this arduous portion of his labour was accomplished in a space of time scarcely exceeding eight months; and it was effected alone, without other aid than that of a guide to carry his instruments. The amount of work thus performed would appear incredible to any one not acquainted with his remarkable powers of observation, his correctness and rapidity in delineation, and last, if not least, his great physical endurance. Severe fatigue, and even risk of life, was involved in the undertaking. On one occasion, when crossing a glacier with a single guide, he slipped into a crevasse to a depth of forty feet. It was a *crevasse de fond*—that is, penetrating to the very bottom of the glacier—and his fall would have been fatal but for the existence of a block of ice, which, wedged between the walls of the crevasse at that particular spot, fortunately arrested his descent. As it was, however, he remained there nearly four hours, while his guide went for aid to extricate him from his peril. Yet even then, in spite of the dark abyss beneath him, and his sufferings from the intense cold, he occupied himself with examining some phenomena presented in the structure of the ice which his singular position enabled him to see to advantage.

All his data collected, the actual drawing of the map in his bureau in Paris occupied him barely two months; and, beautiful as is the published engraving of this map, it is but an imperfect rendering of the

delicacy and finish of the original drawing. This fine work is unique, presenting not a merely conventional, but an almost photographically-exact topographical picture of the mountains in all the details of their configuration. Not only are rocks correctly represented in form and position, but their stratigraphy is also expressed. Thus at a glance may be distinguished the granites, the schists, and the sedimentary rocks, the ancient and modern moraines, and the old glacier beds. The limits of the different zones of vegetation are also accurately marked. With this map the traveller who has had some experience of mountain climbing can ascertain beforehand the character of his route, the obstacles he will encounter, and the possibility of making his way from one part to another.

The translator has had the opportunity of personally attesting the remarkable accuracy in detail of the map in question, when, with his friends and collaborators, Mr. J. Sibree and Mr. C. Wethered, he last summer enjoyed the great advantage of visiting with M. Viollet-le-Duc many of the localities he has surveyed, and of daily listening to his interesting remarks on Alpine phenomena.

The translator desires to express his obligations to Dr. Frederick Smithe, F.G.S. (of Churchdown Vicarage) for his critical aid as a practical geologist in revising the proof-sheets, and to mention that, at his suggestion, he has endeavoured in his rendering to conform to Prof. Renevier's terminology, by designating geological subdivisions as set forth in his recent work *Les Terraines Sédimentaires etc., par E. Renevier, Professeur de Géologie à l'Academie de Lausanne* (*Lausanne*, 1874), since, from the

advantage it offers in point of definiteness and accuracy, it will be ultimately adopted by the scientific world.

In the citation of localities the translator has followed as closely as possible the nomenclature of M. Viollet-le-Duc's Map. In like manner he has retained the specific names of Alpine rocks, such, for instance, as that of *protogine*, which may be roughly designated the granite of the Alps, a primary rock whose numerous varieties are described in the note at page 114.

B. Bucknall.

Bussage, Stroud, Gloucestershire.

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MONT BLANC.

INTRODUCTION.

THE traveller who reaches an altitude exceeding 6000 or 7000 feet above the level of the sea, might suppose that the regions he was traversing were solitudes where silence, immobility, and death perpetually reign. Such, however, is far from being the case: on those plateaux covered with snow, and around those summits devoid of vegetation, where the presence of a living creature is accidental, nature is working incessantly, and as actively as in the depths of the ocean.

There, it is true, organic life has no longer any share in her works, and man feels himself isolated amid a world not made for him.

In these vast elevated laboratories man is an intruder. All that surrounds him seems to say to him: "What doest thou here? Return to thy fields and rivers and valleys; there thou wert meant to dwell; or blame thyself alone if misadventure befall thee. In these high regions we obey laws too imperious for thee, poor mortal! Go and raise dikes along the river sides or dam up the waters of the rivulets; bid promontories of stone project from thy

coasts; pierce the bases of the mountains to pass from one valley to another. Go! all this thou art permitted to do. Here thou art nothing, canst do nothing. . . . Leave us!"

And yet this restless investigating creature, man, is always endeavouring to ascend still higher,—to observe more closely the awe-inspiring phenomena which are in process of development on those summits. His intelligence assures him that in these laboratories gigantic operations are taking place, of which, after long investigation, he can barely form an elementary conception.

The wise—or those who pass for such—insist, to no purpose, that it is folly to undergo so much fatigue and risk of life, in order to visit these solitudes; a mysterious charm attracts us, and there are always to be found those who are willing to undertake this pilgrimage towards the unknown; many in spite of fatigue, danger, and privations are ever and anon recommencing it. Like gambling, it becomes a passion.

Besides the devotees who have contributed so much to science, among the Alps, are to be met regular "*ascensionnistes*," just as at Baden or Monaco may be seen the frequenters of the gaming-table. Is it the love of knowledge that impels them? No: they climb for climbing sake.

We see them in the valley, busy as bees; eagerly studying all the information they can get respecting the altitudes, inquiring for the best guides, consulting the barometer, donning the accoutrements of mountaineers, and getting up in the middle of the night to set off. . . . When they have reached a summit, do they stay there? Do they seem im-

pressed by the spectacle beneath and around them? No: they hurry down again in order to climb some other peak on the morrow.

I have had frequent opportunities of observing these sufferers from the climbing mania; and I confess that they inspire me with real sympathy.

They are seekers after the unknown.

England furnishes the largest contingent to this class of enthusiasts.

In France these Platonic lovers of mountain peaks are rare, and we cannot congratulate ourselves on the fact. Except a few French savants who have added their quota of observation to the sciences of Geology, Geodesy, and Meteorology, and who have acquired a well-merited distinction, we count among our countrymen but a small number of these amateur mountaineers, while England, Switzerland, America, and Germany can boast of thousands.

Having never failed to keep myself *au courant* with the discoveries made by observers of natural phenomena, I have always gladly availed myself of the opportunities offered me for visiting countries where these phenomena are manifested on the grandest scale.

Taking note of all the facts which the observation of the mountains brought under my notice, without knowing whether these observations would ever lead me to scientific conclusions, without any preconceived ideas, and without systematic purpose, it has resulted that in the course of years these materials have formed a collection of data from which it was possible to deduce conclusions that have appeared to me to have an interest for science.

Since the annexation to France of part of Mont

Blanc I have devoted myself to the task of preparing a complete map of the mountain, sufficiently large in scale to enable me to indicate as faithfully as possible the form and arrangement of the crystalline rocks, and the formations which compose it.

Aided by previous labours of whose results I have, through the great courtesy of the Minister of War, been able to avail myself, by Captain Mieulay's map of part of the district, the models by M. Bardin, the surveys of Mr. Forbes, and the excellent work of M. Alphonse Favre,[1] I have, in the course of eight summers, traversed every part of the mountain, with the view of completing what remained wanting in the already collected observations, and especially of accurately indicating the character of the rocks and the formations generally, the beds occupied at various epochs by the glaciers, the disposition of the moraines, their number, the form of the cones of dejection, in fact the appearance of this vast upheaved mass as it now presents itself.

I have also been able to show that the accurately mapped topography of formations throws a singular

[1] Should I say that I am acquainted with the whole of the existing Alpine cartography? I think not. That I have not mentioned any one of the maps is due to a motive which will be readily understood. I must have mentioned them all. To pass over some after having spoken of the others would have been invidious. Naming all I must have discussed all. This, for the English maps alone,—among which may be enumerated those for the Dauphiné, by Messrs. Tuckett, Wm. Matthews, and Bonney; for the Tarentaise, by Mr. Nichols; for the Graian, by Messrs. Nichols and Tuckett; and lastly—I should add that I am here speaking from memory—for the Pennines, Mr. Adams Reilly's three maps, Mont Blanc, the Val Pellina, and southern valleys of Monte Rosa,—would have involved an exegetical labour incompatible with the limits of this introduction.

light on geological phenomena which it is sometimes very difficult to explain *in situ*.

Man is so diminutive, the positions favourable for observation are so few and so inferior in elevation to the neighbouring summits, and the latter are so often difficult of access, that the masses can be scarcely appreciated as a whole, and the smallest detail assumes proportions so considerable that it withdraws our attention from the main outlines.

A good delineative map seemed to me absolutely necessary as a preliminary to all observations in detail. This therefore was the first thing to be accomplished.

I must describe the means employed in preparing it. Independently of the maps I was able to make use of, I verified the relative position of the summits, by views drawn from numerous selected points on the ridges that surround Mont Blanc, such as the Croix de Fer above the Col de Balme, the summit of the Posettes, the Aiguilles Rouges, the Brévent, the Prarion, Mont Joly, the Crête du Poulet, the summits in the vicinity of the Bonhomme, the Cime des Fours, the Col de la Seigne, the Gramont, the Montagne de la Saxe, the Col Ferret, the Catogne and the Buet, without mentioning several intermediate points. Then setting to work on the mountain itself, I fixed on several stations on its slopes, from which I took oblique views. It will suffice to name the principal: the Col de Balme, the slope of the Glacier du Tour, those of the Glacier de l'Argentière, the névés of the Aiguille Verte, the Rachasses, Montenvers, and some points above, the Plan de l'Aiguille, the Glaciers des Pélerins, the slopes of the Aiguille du Midi, the Grands Mulets, the Pavillon de

Bellevue, the Bionassay, the slopes above Champel, the Glacier of Tré-la-Tête, the Plan Jovet, the slopes of the Grand Glacier above Les Motets, the slopes of the Italian Miage, the Italian slopes of the Grandes Jorasses, the Glacier of Mont Dolent, that of Saleinoz, and the Trient.

Then, lastly, penetrating into the body of the mountain, I succeeded in taking interior views: from the Talèfre, the Tacul, the Rocher de la Vierge, the Envers de Blaitière; the Grand Plateau, the interior parts of the Miage, Tré-la-Tête, the Aiguille de Bellaval, the Glaciers de l'Argentière, du Tour, d'Orny, du Trient, and Saleinoz, &c. Thus I obtained at least three views of the same summit. By combining these three views, I was enabled to represent the peak in horizontal plan, to estimate the inclination and the direction of its arêtes, the relative space occupied by its base, and the character of its crystalline system.

Long practice in drawing objects *in situ*, and in deducing geometrical relations from a series of perspective effects, was also useful to me in performing work of this kind.

To obtain from this examination on the spot, and the delineations resulting from it, the elements of a topographical map that should be accurate and not conventional in the drawing of the details (as is usually the case), I was obliged frequently to revisit the same point of view. In fact a particular direction of the solar rays or a recent fall of snow may enable us to discern clearly at certain moments what had not been visible a few hours before under different aspects. The extreme purity of the air on the heights, while on the one hand it facilitates graphical opera-

tions, is, on the other hand, frequently a cause of error, inasmuch as planes of distance widely separated are not distinguishable. It is therefore necessary to wait till the declining sun renders shadows visible that were previously unnoticed, and thus enables us to distinguish these planes of distance. It must also be observed that frequent sojourns on the heights give the eye a power to appreciate the real scale of objects, such as the traveller who visits the altitudes for the first time cannot possess. In this respect drawing always has an advantage over photography, or should at any rate be used to check its results; for photography reproduces the illusions to which the eye is liable amid these solitudes where there is nothing to indicate the scale—since points of comparison are wanting—and where the transparency of the atmosphere almost entirely nullifies aerial perspective.

While I had the opportunity of getting a wide range of views around the mountain, or even on its sides, or from certain points within it; it frequently happened that the shortness of the visual ray, the narrowness of the ice-valleys, the immense importance assumed by the foregrounds, compelled me to proceed by a series of drawings, either simply topographical (obtained by the help of small instruments easily carried) or perspective. After each excursion, a mass of memoranda was thus accumulated, which I hastened to arrange, to compare with existing maps, and to transfer to a general topographical delineation. But it often happened that I was obliged to return to the same localities and to verify my work by a second, a third, and even a fourth examination.

Thus I gradually succeeded in completing a polygon, and when I thought it had been accurately filled in, the topography of the neighbouring polygon often obliged me to review the first and to modify it. It was therefore only by a series of efforts that I succeeded in obtaining the exact configuration of the district.

One of my confrères, M. Révoil, conceived the idea a few years ago of applying the prism of the camera lucida to the telescope, to effect the drawing of general views at long distance and to a large scale.

Perceiving the advantages offered by the teleiconograph (as M. Révoil calls his instrument), in the study of rocks, whose general structure it is very difficult to recognize close at hand, and which can be only imperfectly seen at a distance, I had a more accurate instrument constructed by an excellent optician, M. Lefebvre, consisting of a sketching-board, on which, and parallel to it, a telescope is firmly fixed. The prism of the camera lucida being applied to the eye-glass of the telescope, distant objects are pictured on the board, always in proportion to the power of the telescope and its distance from the board. The latter is moved by means of graduated circles in a horizontal or a vertical direction, the telescope being moved with it.

By this means, exact and enlarged views can be obtained from long distances, and, if required, an entire panorama on a scale of twenty times the apparent size at a radius of eight or nine miles. The graduation of the circle also enables angles to be taken.

By means of this instrument, I was able from the

top of the Brévent, from the Grands Mulets, and the Grand-Plateau, to discern with certainty the structure and the dislocation by contraction, of the great crystals that compose the summit of the Aiguille du Midi, and to draw the curvatures that terminate this summit. From la Flégère, and from Plan-Praz, I was enabled to obtain greatly enlarged and consequently detailed representations of the Aiguille Verte, of the Grandes Jorasses, &c.; to sketch from the upper slopes of Montenvers very accurately, and on a large scale, the limestone mass that still composes the summit of the loftiest of the Aiguilles Rouges. From Plan-Praz I was also able to get detailed delineations of the Rochers Rouges, and those of la Côte, below the summit of Mont Blanc, and to mark, on the slopes of the Aiguille du Midi, the points of suture between the protogine and the crystalline schists by which it is encased at the base on the north side as with a rind that must have been pliant at the time of the upheaval, since it is moulded on the protogine, so to speak, and is not fractured.

This instrument also enabled me to draw at a great distance, and with considerable enlargement, the snows of the higher altitudes, and thus note the phenomena of the slipping and fall of these snows, which act only by their weight, as at these heights they have not yet acquired the expansive properties of ice.

The trigonometrical survey completed, maps of parts of the district prepared, the sketches collected, and the excellent photographs of M. Civiali and M. Bisson consulted, the next question was, what method should be adopted for constructing the map —for representing the configuration.

I had first thought of adopting contour lines, that being the method ensuring the greatest correctness, and the most accurate exhibition of the reliefs. Hence I have in many cases adopted it in preparing my memoranda. But it contravened the real appearance—the configuration—which I was especially anxious to render, so as to give the closest possible representation of the effect produced by nature.

With contour lines it became difficult to express the rocks—their crystalline structure, the faults, the land-slips, the moraines, and the denuded parts of glacier beds. By adopting this method I should be failing to render the map explicitly clear to the traveller,—which was my particular desire. I could not indicate the obstacle or the passage to those accustomed to Alpine exploration. It would have been impossible to express the appearance characteristic of the different varieties of formations, each of which has a physiognomy of its own. I therefore adopted that graphical method which is best adapted to express the soft and graduated configuration of the slopes, and the sharp and abrupt aspect of the rocks and peaks.

Instead of throwing the light, as is the usual practice in shaded maps, from the north-east, and according to an angle of 45°, which is never seen in nature, I adopted the shading produced by the sun at about eleven in the morning during the months of July and August. I thereby made the map agree with most of my own observations, rendered my work easier, and, as I think, brought out the position of the glaciers more distinctly, and the preservation of the névés protected by the shadow of the summits.

As regards the scale, I thought it advisable to adopt that of Captain Mieulet's map, 1/40,000th—double that of the French Ordnance Survey—that is to say, $0^{m}.025$ per 1000 metres (an inch and six-tenths to the mile).

It is with the aid of not less than 500 drawings and sketches, besides the maps drawn on the spot, that I have been enabled to commence and complete this chart.

I am very far from assuming that this work is perfect, and I have had too much experience of the difficulties of such an undertaking to believe that a photographic view of the mountains from an elevation of 10,000 yards would be identical with the topographic picture which I offer to the public. But at least I am assured that this map will not lead the Alpine traveller into error, and that it will enable him to form an exact conception beforehand of the localities he wishes to traverse.

When work of this kind has to be performed in those elevated regions, the purity of the atmosphere, the absence of any scale of comparison, the discomfort or excitement frequently experienced, add to the difficulties which the configuration of the mountain masses would of itself occasion. Certain points of observation can only be reached by eight or ten hours' walking from a spot itself very high, and to these it is necessary to return several times if the capricious mists should hide the neighbouring summits; and it requires a passion for climbing to stimulate one to recommence these ascents day after day to no purpose, for the chance of ultimately obtaining a few hours of clear weather. It must, however, be allowed that these few hours soon make

you forget the fatigue, and there is no pleasure or gratification that, in my opinion, equals that of days passed in work beneath a bright sky at an altitude of from 10,000 to 12,000 feet, commanding those vast solitudes of snow, from which shattered rocks stand out—gigantic ruins, which the imagination endeavours to restore.

It was only after I had drawn this map as faithfully as I possibly could, that I determined on compiling the observations which had been long accumulating—observations which, for the most part, only confirm the later views of geologists as to the mode in which mountains have been upheaved, their primitive form, the influence of the glacial epochs, and the present configuration of these upheaved masses, but which may perhaps also suggest some that are new.

I owe it to my readers to explain in a few words how and why an architect has from time to time put aside architecture to enter upon a domain which does not appear to belong to him.

Our globe is, in fact, only a great edifice, all whose parts are capable of rational explanation; its surface assumes forms dictated by imperious laws, following a logical order.

To analyze carefully a group of mountains, the manner in which they were formed, and the causes of their ruin; to discover the order in which the phenomena of upheaval occurred, the conditions in virtue of which they have resisted or endured the action of atmospheric agents, to note the chronology of their history, is to devote oneself to a work of methodical analysis which is, on a grander scale, analogous to that to which the practical architect

and the archæologist applies himself when drawing conclusions from the study of buildings.

My trouble will be repaid if I can arouse in others the desire to complete that which one man, dependent on his own resources and imperfect knowledge, has commenced in the way of observing phenomena of such importance, and whose study demands an unwearying patience, a certain physical aptitude, and that passion for investigation which is stimulated by the material difficulties.

Perhaps the investigators who have already discussed these subjects with such weight of authority will regard this book as not sufficiently scientific in its style.

I write, however, for the general public, and this I have always kept in view; nor do I aim at anything higher, in publishing this résumé of my observations, than imbuing the many with an ardent desire to study Nature, our common mother, whose teachings are always the healthiest and most profitable for the mind.

I.

PRIMITIVE CONFIGURATION OF MONT BLANC.

At that stage in the refrigerating process which occasioned the flexure of the earth's crust to which the primary formation of Mont Blanc is due, that crust had not yet attained the degree of hardness which it has since acquired. It still preserved a certain pliability and plasticity; either because it was composed of materials susceptible of crystallization by a process of slow cooling, or because it had received the thick deposits of the lias, the jurassic and neocomian systems in a still soft and flexible condition.

When the protogine, of which the more elevated portions of the mass consist, protruded through this crust, which, as it cooled and thickened, tended more and more to contract, it displaced the upper layers, uplifting them, not as it would have done if these layers had been inflexible and homogeneous, but folding and contorting them, as it were, or causing them to slip one over the other.

Where, however, great force was exerted, fractures would occur as in a gelatinous material; so that while there was often a decided curvature of the upheaved strata, there were also faults and wide fissures.

In fact while the folded strata preserved a con-

siderable degree of pliancy in consequence of their softness, they were not capable of expansion, as a liquid material or india-rubber would be, and of losing in thickness what they gained in extent.

Let us examine figure 1, and let A represent a section of the earth's crust before the occurrence of the flexure. To find an outlet, the protogine P (*see* B) must get rid of, or thrust aside all the part *a*, *b*, of that crust. But it must be borne in mind that this

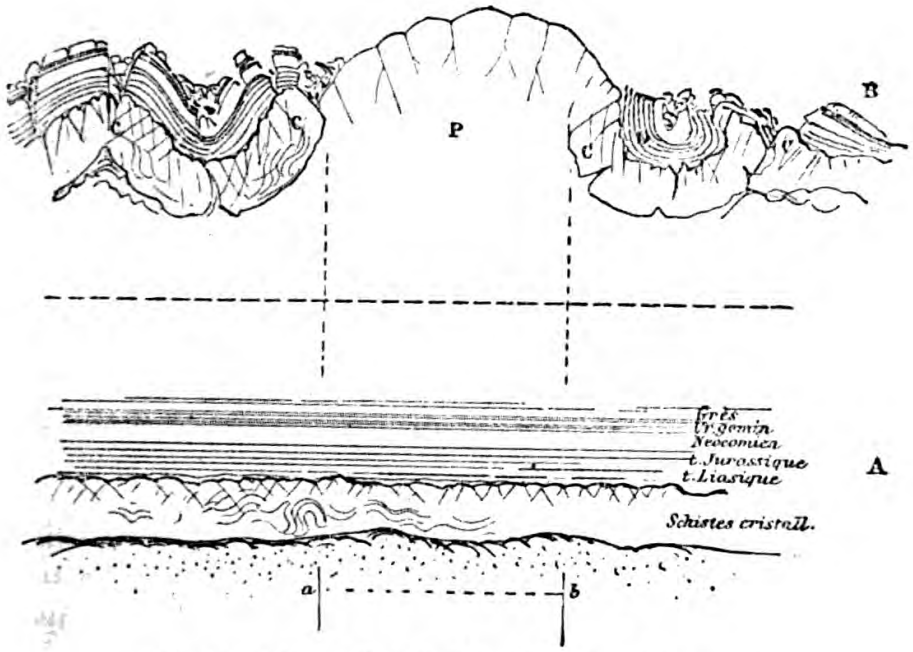


Fig. 1.—Upheaval of the Massif of Mont Blanc.

crust has a tendency to contract, that is to say, to lose in cooling a portion of its superficial extent, and that it exerts a great pressure through gravitation on the core which it envelopes.

Two forces, therefore, are acting simultaneously, and in contrary directions. The compressed interior matter tends to break its envelope, and this envelope tends more and more to compress the interior matter.

The expansive force will of necessity prevail—it upheaves the crust at a weak point, and when the limit of pliancy has been reached, the latter cracks, and from its nature tends to contract,—to widen the open gap. The protogine is upheaved, pushes aside the walls which are pressing against it, thrusts them back, and folds them over parallel to the main axis of the fissure.

The still flexible superincumbent strata that compose the crust, sometimes bend abruptly, but cannot occupy a greater extent than they had when they covered a plane surface.

Now as the surface thus folded presents a greater development than when plane, the spaces left between the portions of upheaved strata are necessarily greater in proportion to their distance from the centre. This phenomenon of flexion and thrusting back is shown in section B of Mont Blanc, taken at right angles to the valley of Chamonix and that of the Val Veni.

The protogine having protruded through the gap at P, the crystalline schists, thrust back and folded, present themselves at C, on the northern declivity, and to some extent on the southern; and the lias formation strongly depressed and folded appears at D, while on the opposite slope denudation has taken place and only fragments are visible; to such a degree, in fact, that on this side, all along the valley of Chamonix the crystalline schists are exposed. Of the jurassic, neocomian, and other systems, scarcely a vestige is to be found on that side. We shall refer again to the causes of the disappearance of these extensive *débris*.

This relative softness of the upheaved strata

enabled the protogine, which was itself in a very tough plastic condition, to mould itself among these deposits, to adhere to them, and even sometimes to protrude beyond them, as seen on the western side of the slopes of the Aiguille du Midi.

The protogine, which now assumes prismatic forms, and sometimes even a stratified appearance, presented at the time of the upheaval mammillated forms, as do still the granites of the Morvan and the Vosges. But this substance, whose external appearance is that of immense kidneys, in crystallizing by slow cooling, shrank and divided, exhibiting surfaces of contraction following certain angles which presented prismatic and pyramidal forms. These surfaces of contraction have the peculiarity of being harder than the interior mass, or, rather, of exhibiting larger crystals and fewer rents. Between them were often formed crystals which coat the planes of contraction and increase their hardness.[1]

[1] We must avoid confusion here. In contact with the environing rock most granite rocks have usually a less density than in the centre of the mass itself, especially if there is great pressure against the environing rock; but when the eruptive upheaval is very considerable, the mass undergoes a process of contraction as it crystallizes, and the crystallization is more energetic near the surfaces of contraction than in the interior of each mass; besides, the gases which escape between these surfaces of contraction coat the walls with crystals, or even fill up the fissures with veins of homogeneous and very hard quartz. But according to the observations collected by M. Delesse, in his *Études sur le Métamorphisme*, *Annales des Mines*, vol. xii., we observe that while on the one hand the granite of the Hartz at its contact with the Hornfels, presents a specific gravity of 2.608 in the interior, and 2.570 on the outside, near the embracing rock—that of Chippal, at its contact with the crystalline limestone presents on the other hand a specific gravity of 2.580 in the interior, and 2.656 at its

The highest part of the massif of Mont Blanc, therefore—consisting entirely of protogine—presented originally a mammiform surface, whose convexities were divided by planes of junction—a result which occurs when a soft substance, being subjected to lateral pressure, assumes reniform surfaces (Fig. 2).

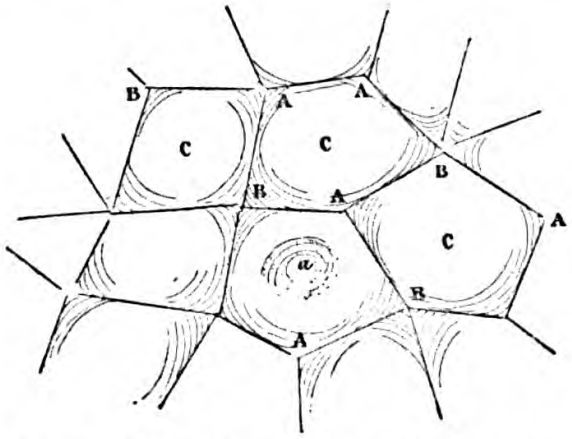


Fig. 2.—Planes of contraction of the Protogine.

In this case a depression sometimes presents itself at the centre of the reniform bodies (see *a*).

extremities. Accordingly M. Delesse adds, "It is in the granite rocks that the density varies most irregularly; it not unfrequently happens that it is greatest towards the exterior." That is to say, in contact with the embracing rock. Further on the learned author remarks, "We should also observe that the plasticity of the rock at the time of its eruption must have exerted an influence on the manner in which the density is distributed. Now, as the character of the granitic rocks shows that they were generally but slightly plastic, we can readily suppose that their specific gravity frequently fails to agree with the law of variation above stated. . . . Lastly, I would observe that molecular action has contributed more than any other cause to produce variations in the density of the eruptive rock. In fact it is easy to understand how the density should increase towards the exterior, when oxide of iron, magnesia, and the bases generally exist there in greater quantity. This would appear to have been the case especially with the granite rocks. . ."

But as the lines A, B, are only the horizontal projections of the planes of contraction, which are harder, or present masses of crystals better formed than the rest of the mammiform surface, they resisted the disintegrating causes more effectually, and formed the ridges which connect most of the existing summits, viz., the extremities of the lines of junction A, B, while the surfaces C were degraded till they formed concavities in place of the even, slightly undulating original surfaces. In Chapters III. and IV. we shall explain the principal causes of this modification of the external surfaces of the upheaved mass.

Some parts only of the culminating points of the massif of Mont Blanc have retained their original kidney shape; in particular the summit of the mountain, which, preserved by a covering of perpetual snow on the northern slope, has not perished, but retains its dome-like appearance on that side, while the southern side is incessantly disintegrating.

The aiguilles, now so sharp, which surround the principal summit of the mountain, and whose flanks exhibit masses of disjointed prisms and frequently parallel strata, are only the ruins of the general cluster of rounded eminences which the upheaval of the protogine presented. We will endeavour to explain this.

Let us take a part of the mass of protogine, comprising the summit of Mont Blanc, A, B; the Aiguille du Midi, A, C; the ridge which extends from the main summit to the Grandes Jorasses, C; the Aiguilles du Plan, D; de Blaitière E; de Charmoz, F; and de Greppont, G (Fig. 3).

At the time of the upheaval this surface would

have presented the appearance shown in Fig. 4.[2] The primitive mamelons of protogine would seem, therefore, to have been destroyed to a great extent, rather at their convexity than at their points of junction.

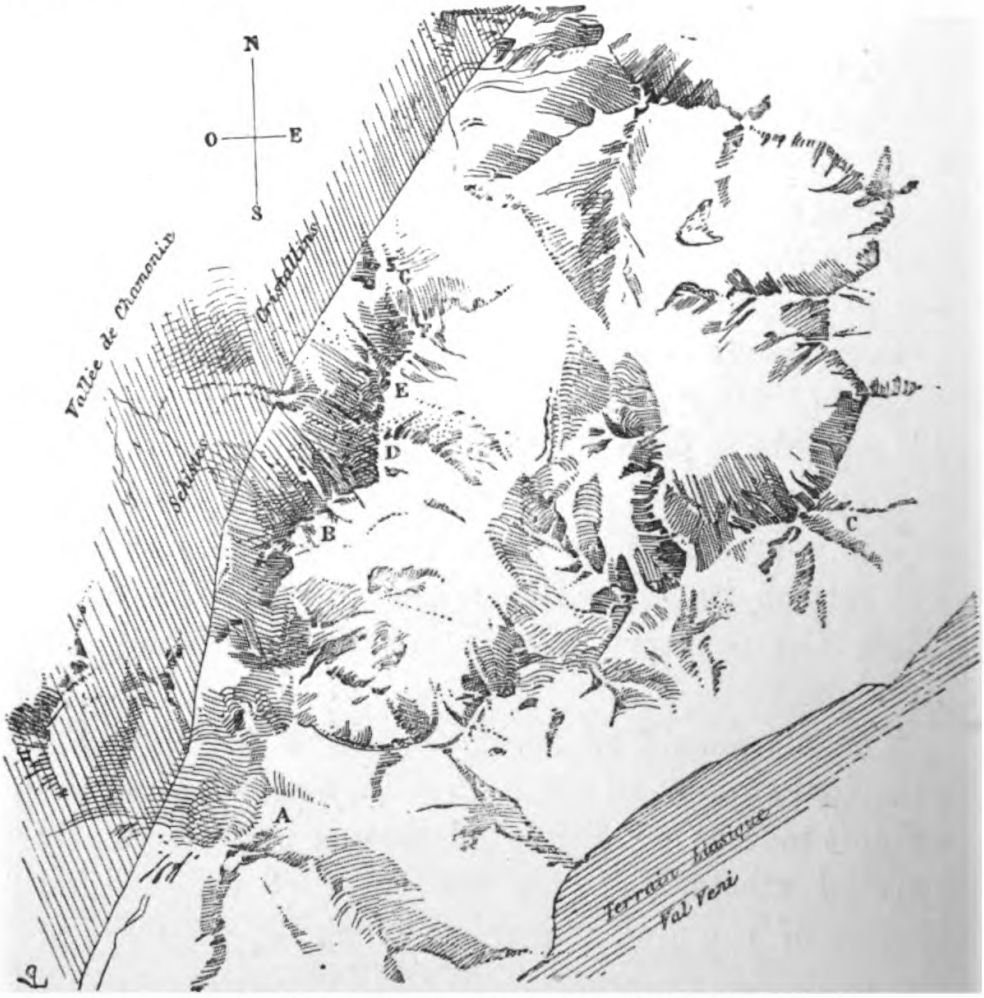


Fig. 3.—Present aspect of the middle of the Massif.

But we must inquire at the outset whether this convexity, this mammillated appearance, really existed.

[2] In this last figure the division lines of the convexities mark the existing ridges, and the summits at the junction of these ridges. For a more accurate delineation, see our large map of the *Massif*.

We have traces still visible of this mammillated form. To say nothing of the summit itself of Mont Blanc, which is concealed by the snow, but which exhibits the appearance of a dome, the actual summit of the Aiguille du Midi shows concentric layers of protogine

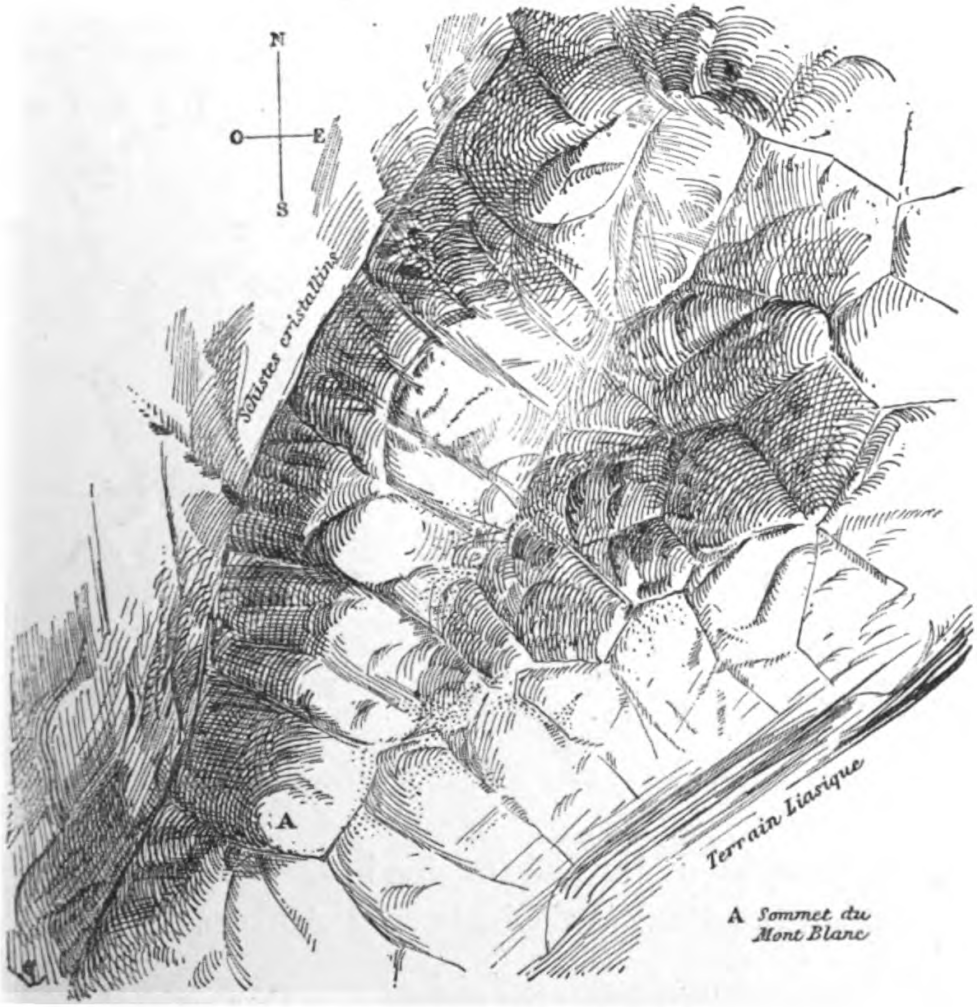


Fig. 4.—Primitive aspect of the Massif.

curving eastwards, and which in fact are only the remains of the immense lobe which once constituted its mass, and whose prolongation followed a convexity dipping towards the south-east. Fig. 5 represents the actual configuration of the Aiguille du Midi,

taken from the slopes below the Pierre-Pointue.[3] Fig. 5 *bis* gives the actual summit of that aiguille, taken from Plan-Praz.[4]

A tendency to curvature is discernible in the sharp ruined aiguilles that surround the Aiguille Verte and that of Charmoz; but we shall revert to this important question.

The granites and the syenites often present the same phenomenon on the outer face. We find a

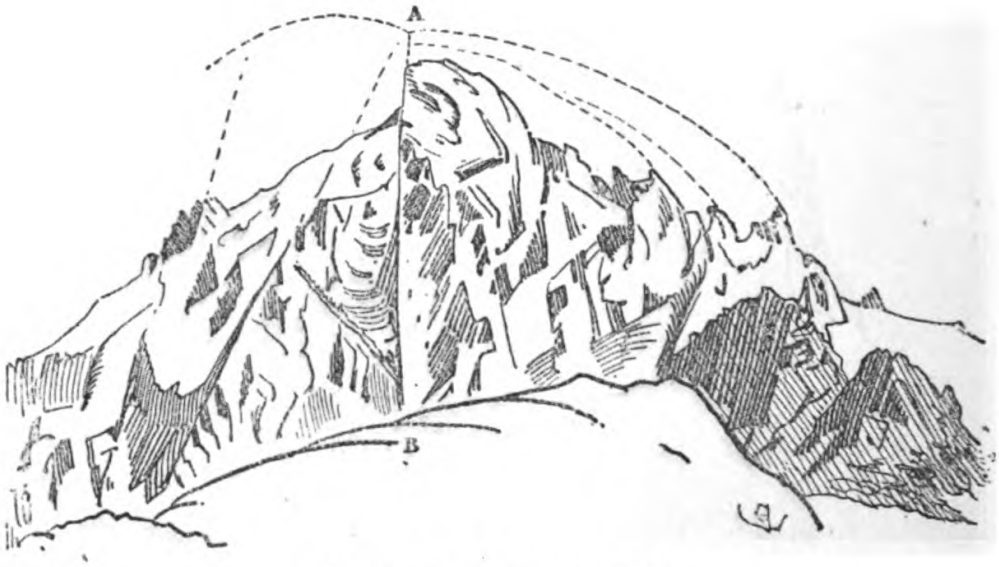


Fig. 5.—The Aiguille du Midi.

very remarkable instance of this in the gorge situated between the Pont du Diable and Andermatt,[5] Fig.

[3] The dotted lines denote the prolongation of the perished beds of the protogine, and the line A, B, the great separating plane of contraction. The etched part denotes the environing crystalline schists.

[4] This figure was obtained by the help of the teleiconograph. Saussure had already remarked the concentric configuration of the planes of contraction of the protogine at the summit of the Aiguille du Midi.

[5] Above the tunnel of the St. Gothard route.

5 ter. There the syenites were dislocated in great vertical planes (see A). But the external surface of the protruded rock presents beds evidently concentric.

To return to the massif of Mont Blanc, the

Fig. 5 *bis.*—Summit of the Aiguille du Midi.

Aiguilles du Plan, de Blaitière, de Charmoz, and de Greppont formed a series of protuberances, some dipping towards the valley of Chamonix, the others towards the Vallée Blanche, as shown in Fig. 4,

connected by planes of contraction which now constitute the summits and ridges of these aiguilles.

Between the mammillated summits of Charmoz, and of the Aiguille Verte a depression existed. The Aiguille Verte itself consisted of a mammillated group, inclining west, north, south-east, and south, and of which only débris remain; although the summit of the Aiguille Verte exhibits the original culmination

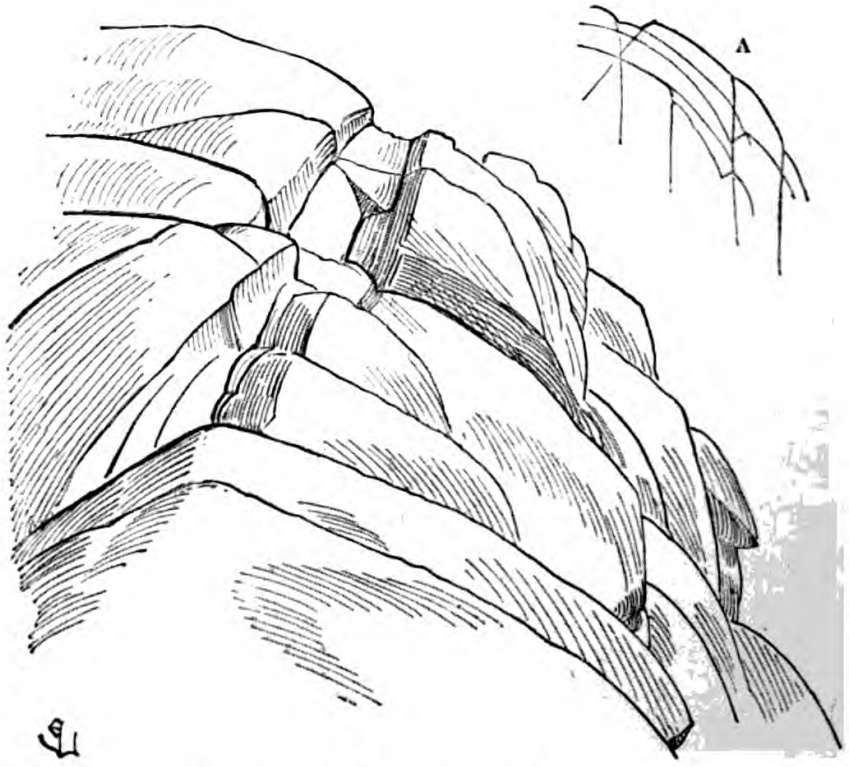


Fig. 5 *ter.*—Syenites above Andermatt.

of the group which is now divided into several aiguilles, i. e. besides the principal one, those named le Dru, le Moine, and part of the Droites.

On the other slope of Mont Blanc, a series of rounded eminences extended in a north-easterly direction with a declivity towards the south-south-east, and towards the north-north-west, as far as

the point which is now occupied by the Grandes-Jorasses. Thence, the culminating points of junction followed a zigzag line in uniting with the summit of the Aiguille Verte group.

We have endeavoured to give as clear an idea as possible of these masses of protogine presenting a mammillated surface divided by lines which are none other than the planes of contraction of the cooled and crystallized mass: and these are the lines which now form those sharp and jagged ridges, while it is their conjunction which constitutes what are called the aiguilles,—that is, the culminating points protruding through the névé.

But an examination of these Figures 3 and 4 gives occasion to other important remarks.

It will be observed (Fig. 4) that the most elevated part of the massif—the summit of Mont Blanc—is found precisely at the point where the environing rocks approach each other more closely, and where consequently they offered greater resistance to the protogine; which was urged by a force acting upwards, and forcibly confined by lateral pressures, whereas in those portions where the environing rocks are wider apart, there has been a central subsidence of the upheaved mass of protogine. Towards the north-east the schists reappear, also embracing the protogine on that side, so that the whole upheaved mass presented a general configuration as follows (Fig. 6.)

A, being the summit of Mont Blanc, the crystalline schists rise rather abruptly towards the north-west, and south-west, and rest on the mass of protogine which, protruding as through a wide button-hole, fell back on the liassic strata on the east and

south-east without uplifting them along its escarpment on that side, but violently overturning them.

This mass which, in a plastic condition and at a more or less elevated temperature, first constituted a sort of rounded plateau, sank in cooling along the widest part of the upheaval, as dough would, separated into lobes, which subdivided in consequence of the contraction of a slow crystallization,

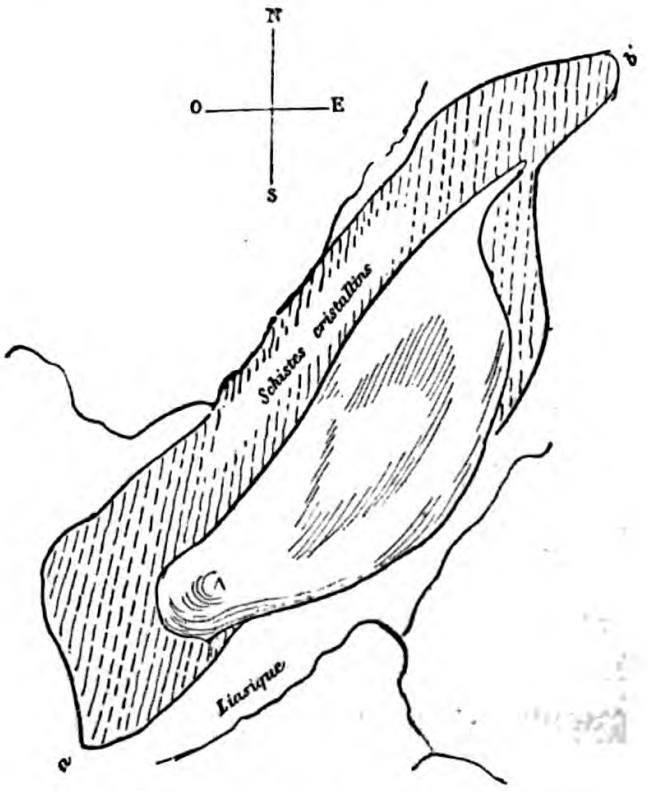


Fig. 6.—General form of the upheaved Massif.

and left around the depressed part a lip whose highest point would be that at which in consequence of the narrowness of the orifice no movement of subsidence had occurred. It was the point A, therefore, the summit of Mont Blanc, which from the beginning of the cooling must have been the most elevated, as it still is; although when the upheaval

took place, and before the protogine had hardened, the profile from *a* to *b* must have been that represented at B in course of transition to section C, which gives its appearance after the complete refrigeration and the subsidence of the broader parts (Fig. 6 *bis*).

The preceding figures might seem to favour the supposition that the mass of protogine, which differs in composition from the mass of the crystalline schists, and which has protruded through the schists and the lias, would, in presence of atmospheric agencies, and the action of the névé, ice, and water, be affected quite otherwise than those environ-

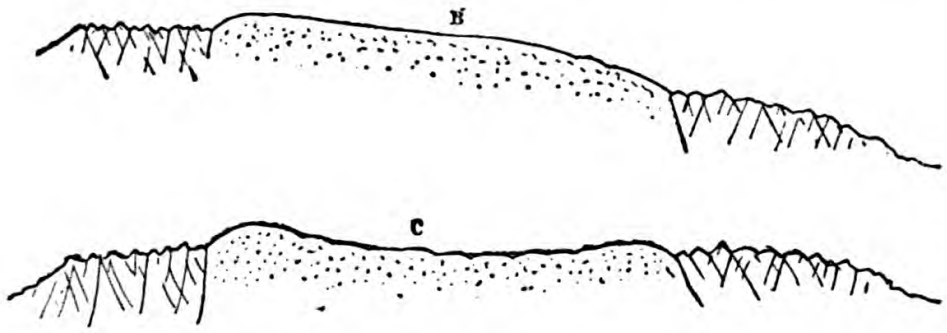


Fig. 6 *bis*.—General form of the upheaved Massif.

ing crystalline rocks, and present quite a different general aspect of ruin in its disintegration. Nothing of the kind. The system of crystallization and contraction which obliged the protogine to assume certain forms, and determined the ridges and summits, prevailed in general, if not in detail, through every part of the environing rocks; so completely as to compel the inference that when the disturbing movement took place these environing rocks were in a state of plasticity or incomplete development, which permitted normal metamorphism and con-

formity to the laws of contraction and crystallization, to which the protogine itself was subjected. It is only by minute examination that we can detect a difference in the mode of disaggregation between the crystalline schists and the protogine. But we shall have occasion to enlarge upon these facts later on. To the foregoing a few remarks must be added to indicate the various agencies which produced the original form of the massif after its complete refrigeration.

It is evident that the point A (Fig. 6) being maintained at a higher level in consequence of the narrow limits between which it was compressed and its being thus hindered from subsiding, must have exerted a pressure on the neighbouring parts which were themselves tending to subside.

Accordingly it is observable that the planes of contraction of the protogine are inclined at right angles to that pressure. In fact from the top of le Buet we remark that the planes of contraction of Mont Maudit, of Mont Blanc du Tacul, of the Aiguilles du Midi, du Plan, de Blaitière, and even de Charmoz, present the inclination Fig. 7.[6] This effect diminishes as we advance northwards, i. e. in going from the summit of Mont Blanc towards the summits of the Glacier du Tour. In that direction the planes of contraction are vertical, and even tend to incline the contrary way, in consequence of the pressure exerted by the environing rocks of the northern extremity of the massif. So that, referring to section C, of Fig.

[6] This is what many competent observers—Saussure at their head—regard as a stratified structure.

6 *bis*, the planes of contraction of the protogine present the direction shown in Fig. 8; a result moreover of the subsidence of the central part M.

On the other hand, in the direction of the transverse section of the group, the planes of contraction

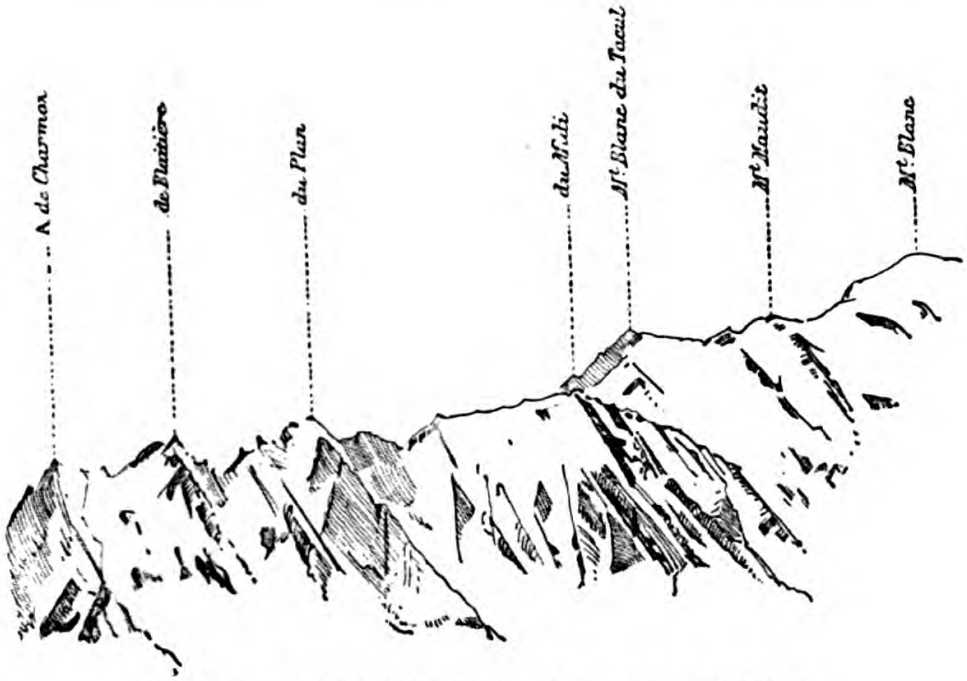


Fig. 7.—View of the Massif from the summit of the Buet.

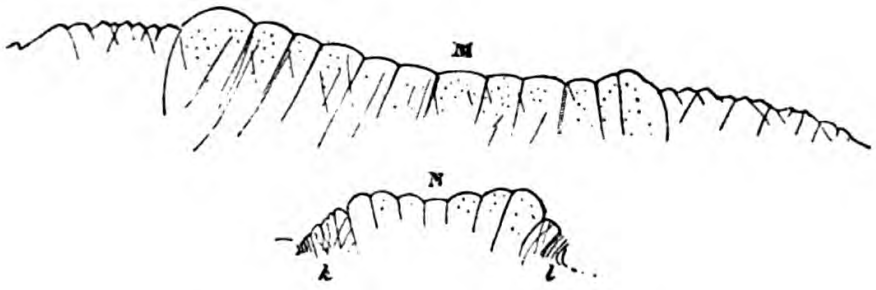


Fig. 8.—Longitudinal and transverse sections of the Massif.

(see N) exhibit a fan-like arrangement, the radiation being from the centre of the group, which is similarly explained by the lateral pressure exerted by the environing rocks, *k*, *l*.

This is the fan-like structure remarked by many geologists. We shall here give only a very summary view of the various opinions enunciated by the learned observers, M. A. Favre having given a most lucid exposition of these views in his *Recherches géol.* (*Savoie, Piémont et Suisse*, vol. iii. p. 123 et seq.)

The general inference from these observations is that if the fan-like structure is incontestable, and the stratified appearance, as shown in our Fig. 7 is not less so, there is something contradictory in these two results. In fact, if the stratification is parallel to any given plane, planes perpendicular to the former cannot be regarded as a stratification. They may be planes of contraction, but not stratification.

Suppose the mass to be entirely formed by a juxtaposition of rhombohedrons, for example, there will be found six planes of stratification in this mass, intersecting at certain angles. This is pretty nearly what the planes of contraction of the protogine exhibit. Consequently the term *stratified* seems hardly applicable to the case.

With regard to the primitive condition of the protogine at the time of its extrusion when urged by their pressure it outflanked the crystalline schists, geologists are hitherto not agreed.

Some contend that the protogine was upheaved in a plastic state, others in a solid condition.

This latter opinion seems hardly tenable.

If the protogine had been upheaved in a solid state such as we now find it, it would not have filled up the enormous *boutonnière* through which it has protruded; it would have presented vast faults, and occasioned far greater disturbances in the environing rocks than those observed. It

would not have exhibited those concentric layers that are so frequently discernible in the neighbourhood of the existing summits (see Fig. 5), and it would not have moulded itself as it has done among the environing rocks.

Respecting the state of softness which the protogine might have presented, M. Sainte-Claire Deville wrote to the author in Nov. 1869, as follows: "*A priori*, and in default of experiment and observation sufficient to enable me to form a decided opinion on the question, I think that certain rocks, even those most compact externally, might be supposed to be internally in a state of softness sufficient to enable their crystallization by stratification to take place after a movement determined by any cause of metamorphism. Suppose a gelatinous condition of any kind at great depths—a softened state effected by heat—and the phenomenon you consider possible really becomes so. . . ."

M. Bischoff of Bonn, as pointed out by M. Elie de Beaumont (*Système de Montagnes*, pp. 1, 231), has shown that the rocks regarded as eruptive,—such as granite,—undergo a contraction which M. Ch. Deville has succeeded in measuring. M. Delesse thinks that the earth's radius has diminished through the formation of the crystalline rocks which appear at its surface.

M. Delesse, it may be observed, does not attribute to the presence of granite the metamorphism of the crystalline rocks that generally environ it. "If," says he (*Études sur le Métamorphisme*, *Annales des Mines*, vol. xii.), "metamorphism generally accompanies the crystallization of granitic rocks, it does not appear always to result from their direct action. In

fact, one is struck, in glancing at a geological map, by the small extent of the eruptive granitic rocks as compared with the metamorphic rocks. Sometimes even gneiss, mica-schist, slaty schist, and various crystalline schists are largely developed, while no granitic or even eruptive rock is visible in their neighbourhood. It may therefore be reasonably doubted whether these metamorphic rocks were formed by direct action of the granitic rocks. The latter seem to have merely participated in their crystallization. Their condition is the result of a general action and not that of contact. In a word, they have been modified by normal metamorphism."

M. Lory appears to have explained the fan-like structure presented by the contracting planes of the protogine and the granitic rocks.

"It must," says he (*Descript. géol. du Dauphiné*, p. 180; see in M. A. Favre's work cited, the diagrams accompanying this extract from M. Lory's book), "be supposed that, thrust back by tremendous pressure, the strata of the crystallized formations underwent a very considerable flexure, and were ruptured by the excess of curvature (see our Fig. 1). In this way, the granite, which was situated at a great depth below the surface, under talcose schists and gneiss, presents itself in the centre of the protruded mass. But the chain thus produced being elevated above all the others, the upper parts of the tilted-up strata experienced only a slight lateral pressure, while the deeper parts of the same beds were forcibly compressed by the reaction of the neighbouring less salient flexures—by the general compression which produced the entire series of these folds. As a result the rocks of the principal

chain were subjected at the level of the base of the neighbouring less elevated chains, to a *constriction* which did not occur in its culminating parts. They assumed some such arrangement as that of the straws in a tightly-bound sheaf of corn."

But the susceptibility to pressure supposes a condition of softness in the matter compressed.

Upheaved masses of basalt, in fact, very often exhibit this fan-like appearance. The extruded matter diverges, and the planes of contraction present the appearance of a sheaf.

But while the protogine of Mont Blanc was powerfully compressed at the base in the transverse direction of the formation, it could not be so in the direction of its length, since the embracing rocks,—the ends of the button-hole shaped aperture—reach the higher level of the mass of protogine. Lengthwise it was the external surface of the upheaved mass itself that was subjected to the pressure; which moreover would exert considerably less force in the direction of the longer than of the shorter axis. The fan-like structure, therefore, does not appear in the direction of the length; or rather, this structure is reversed, in consequence of the pressure exerted by the highest and narrowest part of the eruptive mass. (See Figs. 7 and 8.)

As regards the subsidence of the central part of the upheaved mass, Baron Leopold von Buch, speaking of the beds that dip into the interior of the masses of pyroxenic porphyry which seem to have upheaved them, thus expresses himself: "It is possible that the expansion of the pyroxenic masses at the time of their upheaval was considerable; and their contraction, slow and continuous, may have

forced the neighbouring beds (those which are in immediate contact with the pyroxenic porphyries) to follow the vacuum which was gradually forming, and to incline in that direction, that is to say, towards the interior of the mountain." (*Annales de Chimie et de Physique*, xxiii. 286.)

This subsidence is owing in many cases as much to the contraction of plastic masses as to the forcing back caused by the embracing parts. And in reference to this we will quote a passage which appears to us highly important, and which we deem conclusive, from M. Alphonse Favre (*Recherches géol. dans la Savoie*, vol. iii. p. 138): "The study of the fan-like structure naturally leads us to some considerations respecting the origin of the mountains, which cannot be explained by an *upheaval*. We would not thereby suggest that the rocks of a lofty summit have been deposited at the height where they are now found. It is evident that they have been elevated, but their elevation cannot be ascribed to an upheaval—that is, to a force acting vertically upwards; and for this reason. Let us examine a mountain having the form of an unruptured vault . . . . " In fact, M. Favre demonstrates that if the impelling force had been exerted vertically upwards the vault would have been fractured, and its débris thrown right and left: that consequently, where the strata have a vaulted form, there must have been folding, depression, subsidence, rather than upheaval. And if this is incontestable in regard to the examples cited by the learned geologist, it must be admitted that the materials which have been extruded—the granite, protogine, porphyry, &c.—have fractured this crust and made a button-hole-

shaped aperture in the earth's rind. This is the case with Mont Blanc. To avoid confusion resulting from the use of terms, it must be understood that when we speak of upheaval, the action in question may be the effect of a compression, thrusting back and lateral subsidence—folding in fact—but the thrusting back, by occasioning flexures, does not the less cause an upheaval of certain parts of the crust above the existing level, while the neighbouring parts sink down.

Referring to Figs. 3 and 4, we see that the planes of contraction form polygons, exactly as clays do on losing their humidity, and even basalts. These chief planes of contraction which circumscribe the great convexities, are not the only ones; and it must not be supposed that in the interspaces the crystalline mass was compact and homogeneous, as an amorphous substance would be. These polyhedrons formed by the chief planes of contraction are subdivided by other planes, intersecting at certain angles, which usually tend to form rhombohedrons; and the surfaces of these secondary planes of contraction are also harder than are the intermediate parts, though not possessing the density of the crust of the principal planes.

It was the structure characterizing the protogine and likewise the crystalline schists which led to their disintegration; but that disintegration necessarily followed certain laws which we proceed to point out. Let Fig. 9 be a section of two great masses of protogine after cooling and crystallization. Let A B, C D, be the chief planes of contraction separating the convexities.

The secondary lines indicate the curved fissures and

secondary planes caused in the masses themselves by the process of contraction. When atmospheric agents—congealed snows (*névés*), and ice—begin to act upon the rock, since the surfaces of the principal planes present a greater degree of hardness and resistance than the mass generally, the mammillations will in consequence of the disintegration and gradual removal of the less resisting parts, be replaced by a jagged and hollowed-out surface, as shown in the shaded section.

So that the points A and C, which presented furrows or lines scarcely perceptible on the surface, will

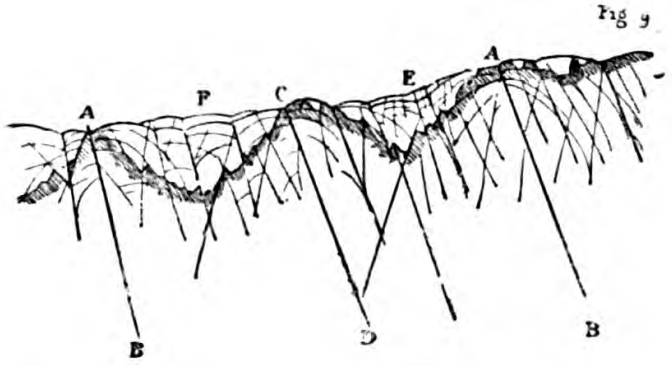


Fig. 9.—Disintegration of the surfaces of the Protogine.

constitute the crests of the group; and the external surface F, E, which was rounded, undulating and scored with furrows or even ribs faintly marked at first, will be replaced by a series of sharp serrated and prominent ridges. And what we here see on a grand scale is repeated indefinitely in each of the masses, secondary, tertiary, &c. That is to say, the planes of contraction always resist, while the mass itself is decomposed and scooped out, leaving high projecting ridges which are only the planes of contraction.

This leads to the inference that the protogine in being extruded, as in section B, Figs. 6 and 6 *bis*, first

underwent a subsidence in the middle of the upheaved mass, in consequence of refrigeration, and perhaps also the escape of gas; that in continuing to cool it was divided into large polyhedrons, whose visible external faces were generally convex, as proved by the still existing remains of summits (see Fig. 3); that the gases continuing to escape from the contracting mass formed solid crystalline crusts upon the primary surfaces of contraction, and that this phenomenon was repeated indefinitely, invariably in accordance with the same laws, in each great polyhedron, in proportion as the cooling proceeded and the crystallization was completed.

Where, in fact, do we find the finest quartz crystals for example? Precisely in those parts of the formation where the surfaces of contraction are the most definite and even; where the protogine is purest; where the phenomenon just described took place with the greatest regularity. In a word it is in the very centre of the formation,—at le Talèfre, les Droites, at the bottom of the Glacier de l'Argentière, at les Courtes, and at the Aiguille du Triolet.[7] It is there we meet with fine geodes, but especially with planes of contraction, completely coated with magnificent crystals of quartz, white, smoke-tinted, and amethyst. The crust which serves as a base for these crystals is extremely hard to a depth of a few inches, then the protogine gradually softens. A secondary surface of contraction presents the same phenomenon, but in a less marked degree.

There cannot then be a doubt that the mass which constitutes Mont Blanc, and which now presents a surface consisting of ridges uniting at

[7] See the general map of the formation.

certain points to form polygons whose sides project and whose middle parts are hollow, originally presented, on the contrary, a bossed surface of convex polygons, with sides more or less marked by depressions,—in short a kind of plateau slightly uneven, as shown in Fig. 8.

But what had become of the strata which this upheaved mass had pierced, gneiss or crystalline schists, the triassic, liassic, jurassic, neocomian, urgonian, and other groups? Rent, folded, and thrust back, the harder and thicker inferior strata—the gneiss and the crystalline schists—resisted, while the upper strata, except at some points where they were held fast, were removed by the névés and ice which soon overspread these heights. If, previous to their displacement, the liassic and jurassic deposits, though not yet hardened, exhibited horizontal strata—water having been the prime agent in their formation—what was the structure of the subjacent crystalline schists and gneiss?

This is a difficult question to answer. These rocks now exhibit parallel and obliquely crossing planes of contraction which tend to divide the mass into more or less regular rhombohedrons.

This form of structure must have been produced when these masses crystallized after slow refrigeration. It might be supposed, however, that the outer surface of the crystalline schists, previous to the deposit of the strata which covered them, was uneven, and presented a series of more or less decided furrows, like wrinkles.

A proof of such structure exists at the summit of the loftiest of the Aiguilles-Rouges. On the summit a specimen of the trias and of the jurassic limestone

has kept its place, whose beds preserve their normal horizontal position, while the crystalline schist on which these beds lie, exhibits a denticulated upper surface. Consequently this denticulated upper surface had its present form before the deposit of the strata in question—the trias and the jurassic limestone.

Figure 10 clearly explains what we have been describing.[8]

The primitive terrestrial crust already cooled, previous to the time when the water could deposit the earliest strata, was therefore of unequal thickness, rugged and perhaps already split by planes of contraction, resulting from an earlier refrigeration, without having acquired its final hardness. This is a phenomenon difficult to explain. Had these rocks or had they not at that time undergone the action of normal metamorphism, which at a later period, when the great lateral thrustings occurred, would be produced by the intensely energetic emanation of gases from within making their way through the not yet indurated primary crust ?[9] It is possible

[8] The view of this summit is taken from above the Lacs Blancs, at the south-east of the loftiest of the Aiguilles Rouges.—See also *Recherches géologiques dans les parties de la Savoie voisines du Mont Blanc*, A. Favre, t. ii. p. 324.

[9] M. Delesse seems to us to have perfectly defined, in his able investigations (*Études sur le Métamorphisme*, *Annales des Mines*, t. xii.), the metamorphic action produced by embracing on eruptive rocks, and by the latter on the former—an action limited in its effect. This metamorphism of contact, whose effect was so restricted, must not be confounded with normal metamorphism, which has modified enormous masses of deposits. But it still remains a very difficult problem to determine whether the two processes were simultaneous, or whether these masses had already experienced normal metamorphism; since the great disturbances that have supervened in the crust of the earth, have, in their turn

that this conformation of the surface of the crystalline schists was only accidental, and that the presence of this calcareous fragment on the summit in question is simply owing to that denticulated bed keeping it in the position in which we still see it; for in many cases we observe the coal measures, the liassic beds, the argillaceous schists and the jurassic deposits succeeding one another parallel to the even surface of the crystalline schists which served as their base.

It is none the less certain that after an earlier—at

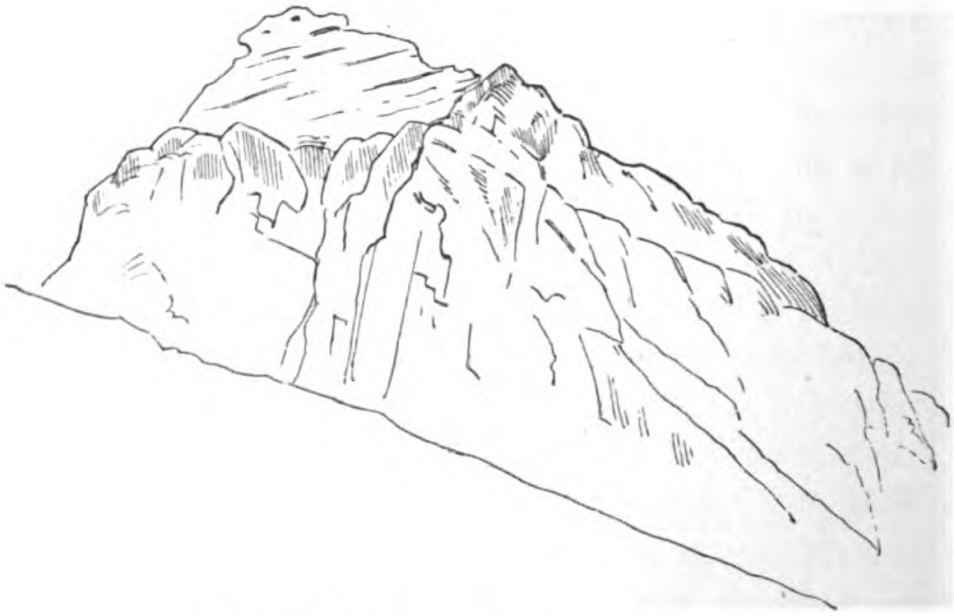


Fig. 10.—The highest of the Aiguilles Rouges.

least an accidental disturbance of the crystalline schists at a lower level, the sandstone and calcareous strata were deposited horizontally, and that subsequently the whole was folded and crumpled up.

It should, however, also be observed that the crystalline schists through which the protogine of

produced a partial metamorphic action at the contact of the eruptive with the environing rocks.

Mont Blanc protrudes, on the north-western slopes of the group, appear to have been upheaved in a condition far from solid, since between them and the protogine there exists a complete adherence and sometimes even a commingling.

Admitting the slipping of the protogine in a plastic state along the crystalline schists, if the latter had acquired their present degree of hardness, there would have been ruptures and discontinuities of adherence between the two classes of material—discontinuities and ruptures which are not observed. It should also be remarked that the protogine which is generally compact in appearance and fissured by innumerable planes of contraction causing the débris to assume prismatic or pyramidal shapes, partly loses this appearance in approaching the south-eastern declivity of the group. On that side the protogine is often laminated, and its aspect approximates that of the schist with which it sometimes alternates, as it also does with porphyry and serpentine.

It would appear therefore that the upheaval of the massif took place slowly—from north-west to south-east, its north-western slope being much less abrupt than the south-eastern. The protogine then would seem to have upheaved these crystalline schists less suddenly on one side than on the other;[1] to have even overlapped them on the south-eastern slope, scarcely permitting them even to crop out; and perhaps it is to the enormous pressure it has undergone on this side that we must attribute its laminated appearance, and the presence of substances foreign

[1] See Figure 1.

to it, but which it carried with it and which suffered a process of metamorphism.

With regard to the crystalline schists and the gneiss, their stratified appearance would seem to be due to pressure and to contraction.

Did this apparent stratification take place horizontally or obliquely, or even vertically, according to the processes which were acting on the materials at the time of their refrigeration?

At that time the contraction of the earth's crust which still remained thin, must have produced phenomena of flexure whose extent and importance it is impossible to appreciate; and this crust, unequal in thickness, would form, as it cooled, a terrestrial surface of extreme rugosity, exhibiting deeply furrowed undulations and wrinkles. The superincumbent strata which were deposited on the surface of this unequal crust necessarily filled up and levelled these rugosities; then, as the crust continued to cool, the great mountainous flexures occurred, accompanied by the eruption of granite or of protogine.[2] These disturbances, in the nature of the case, took place where the underlying crust presented the greatest tenuity or inequalities. We must therefore not be surprised if in mountain masses the gneiss and the crystalline schists exhibit disturbances in their structure. These dis-

[2] The term eruption must not be understood here as it is when applied to basalts, or more particularly to lava. With M. Delesse, and other distinguished observers, we think that the crystalline constituents of the earth's crust may have been formed in a moist state, and that the granite, syenite, protogine, and serpentine rocks may have been upheaved in a plastic condition at a temperature considerably below that of fusion.

turbances are not the *consequence* of the flexion and accidental rupture of the parts which occasioned the appearance of the so-called eruptive rocks at the surface, but they may have been the *cause*.

II.

ACCESSORY CAUSES OF THE ACCUMULATION OF THE SNOWS.

SUBSEQUENT to the upheaval of Mont Blanc there must have been a long period of repose.

The upheaved protogine and crystalline schists could not have attained that state of complete crystallization, except by a very slow process of refrigeration.

Gases must have been emitted from these materials during a long space of time. The still heavily charged terrestrial atmosphere allowed the watery vapours to become snow only at an extreme altitude, and in descending this snow melted before it reached the highest summits or on touching them. Their surface might have been affected by the action of water, but not by that of frost.

Those earlier diluvian rains aided in denuding the slopes of the smaller débris that covered them, and, collected in reservoirs with the materials borne away, formed those pudding-stones and conglomerates of comparatively recent period, which, mingled with fossils of the quaternary period, are frequently found in the lower parts of certain valleys, particularly in that of the Rhine.

It seems scarcely doubtful at present that after

the successive upheavals of the Alps there was an anteglacial period of mild temperature (the Pliocene) during which water alone might have modified the surface of the upheaved mass. This period witnessed the growth of the quaternary fauna and flora whose remains we find beneath the glacial deposits, and sometimes even mingled with those deposits. The diluvial rains that preceded the first glacial epoch would, however, merely collect in the bottom of the hollows left between the upheaved beds, and form deep, long lakes, generally finding an outlet only at a considerable height, or bursting a dam of no great strength to diffuse their waters lower down. Thus the valleys were first roughly shaped, and then a part of the non-crystalline formations, being upheaved, might be carried away, reduced to rounded pebbles, and constitute deposits mingled with organic detritus.

It would be exceeding our limits to quote here the numerous opinions advanced by distinguished savants respecting the causes that produced the glacial epochs.[1] On this subject we shall imitate the reserve of the learned professor of Geneva, M. Favre. But while attention has been absorbed by the investigation of the primary causes of the phenomena, accessory or secondary causes that may

[1] See Agassiz, *Actes, Soc. helvét*, Zurich, 1841, p. 63; Lartet *Comptes rendus de l'Académie*, 1865, 21 Août; Ch. Martins, *Revue des Deux Mondes*, 1867, 1er Mars; De Charpentier, *Essai*; Lecoq, *Des Glaciers et des Climats;* La Rive, *Actes de la Soc. helvét*, Archives, 1865, xxiv. 48; Frankland, *On the Physical Cause of the Glacial Epoch*, Philosoph. Mag., May, 1864; A. Favre, *Causes et Effets de l'ancienne extens. des Glaciers; Recherches géol. dans la Savoie voisine du Mont Blanc*, t. ii.; Tyndall, *Glaciers of the Alps; Heat considered as a mode of motion* (Lect. VI.).

have had a considerable influence on the extent and intensity of the glacial periods may not have been sufficiently observed and allowed for.

And here we are no longer in the field of hypothesis; but remain within the domain of observation from which we are by no means inclined to depart; for, as M. Favre so justly observes, "The time has arrived when, in geology, it is better to attempt no explanation, but to leave questions in abeyance, than to construct hypotheses resting on unsound bases."

In the preceding chapter we endeavoured to present a picture of the primary configuration of the upheaved mass of Mont Blanc before the action of atmospheric agents had been able to exert an influence on the surfaces of the mass.[2]

Apart therefore from the general causes that may have occasioned the accumulation of snow on the upheaved protuberances of the earth,—causes which have not yet been scientifically verified,—we shall limit ourselves to such observations of detail and locality as have a considerable importance.

The jagged forms now presented by the summits of the Mont Blanc mass, the wide and deep openings of its upper valleys, and its amphitheatre-shaped concavities did not originally exist. The mass exhibited a kind of undulating plateau, whose average height was about 13,000 feet.[3] But on

[2] What may appear hypothetical in this sketch, is more fully developed in Chapter VII.

[3] Heights: Mont Blanc, 15,780 feet; Mont Maudit, 15,650; Mont Blanc du Tacul, 13,930; Aig. du Midi, 12,610; Dôme du Goûté, 14,210; Bosses du Dromadaire, 14,940; Aig. blanche de Peuteret, 13,390; peak des Flambeaux, 11,590; summit south of

referring to Fig. 6, and the general map of the group, it will be perceived that this plateau was depressed in the centre, and that its edges attained a uniform height, except at the S.S.-Western extremity, where the summit rose considerably higher. On the plateau, the atmosphere, which was doubtless greatly charged with moisture, would deposit the snow in thick masses, since it could only fall away along the escarpments that formed the perimeter of the plateau. The environing crystalline schists had been raised to nearly the same altitude as the protogine, especially towards the S.S.-Western extremity,[4] so that on a surface of about 150 square miles,[5] the snows accumulated without being able to discharge themselves, except on the N.E. and S.W. walls of the plateau, for at the N.E. and S.W. extremities the group is bordered by very lofty peaks.

Granting that the general height of the plateau did not greatly exceed that of the existing summits,[6] say about 13,000 feet, the vapours that rise much higher in the atmosphere, deposited layers of snow

the Aig. du Geant, 12,720; Grandes Jorasses, 13,800; Aig. de l'Eboulement, 11,840; Aig. du Talèfre, 12,290; Aig. du Triolet, 12,730; Mont Dolent, 12,570; Aig. Verte, 13,540; Aig. de Blaitière, 11,590; Aig. du Plan, 12,050; Aig. du Chardonnet, 12,540; Aig. de l'Argentière, 12,470; le Darrey, 12,730; le Tour Noir, 12,610.

[4] The summit du Bionnassay, 13,320; Aig. du Gouté, 12,710; Tête-Carrée, 12,140; Aig. de Trè-la-Tête, 12,890; Aig. de Saussure, 12,580. This last aiguille, to which M. Ch. Martins has given the name of *Saussure*, to which we give the preference, is usually designated the *Aiguille du Glacier*, a denomination not sufficiently specific, and which gives rise to mistakes.

[5] The length of the plateau is twenty-five miles; its average breadth, six miles.

[6] See Figures 3 and 4.

upon it, which annually increased the thickness of the bed, since they could not descend in avalanches, and did not lose in summer what they gained in winter.[7] This deposit reached and probably exceeded a depth of 3000 feet in the course of several centuries. Taking account of the quantities discharged on the two sides of the plateau, this mass had a solid content of more than 400,000 millions of cubic yards. There was no reason why this deposit should not have reached the limit of the vapours, if it was not tending more and more, by its very accumulation, to discharge itself into the hollows that bordered the massif, the chief of which now form the vales of Chamonix, Veni, and Ferret. These depressions were subsequently quite filled up.

A drawing will enable the reader to understand what has just been stated. Fig. 11 represents the section of the massif from west to east through the summit of Mont Blanc, with the contour resulting from the upheaval.

The line A B exhibits the accumulation of snow to a mean depth of 3000 feet on the plateau, or the actually existing summit which we consider not to have been altered; it is evident that these masses of

[7] Even at the present day the névés at great heights do not lose by melting the volume acquired in winter; and if they did not slide, their mass would reach an enormous thickness. The layers of compressed névé, after the summer melting, exhibit a mean annual thickness of nearly 20 inches. On Mont Blanc du Tacul this thickness was at least doubled during a very moist period. In 1000 years, therefore, the névés might have reached a depth of 3300 feet on the great plateau of the group, very probably much more; for melting takes place to a much less extent on plane surfaces at a height of 13,000 feet than on slopes and in a drier atmosphere.

snow must have discharged themselves in avalanches into the hollows and filled them up.

Since snows do not possess, like ice, any expansive force of dilatation, but are in a powdery condition at an elevation of 13,000 feet, they could produce no effect on a plateau except by their weight—by the discharges resulting from their accumulation and elevations of temperature. Falling into the cavities at the bottom of the hollows of the mountain and so reaching a lower level, part of them was melted, and thus formed névés. It was then that the disintegrating process commenced.

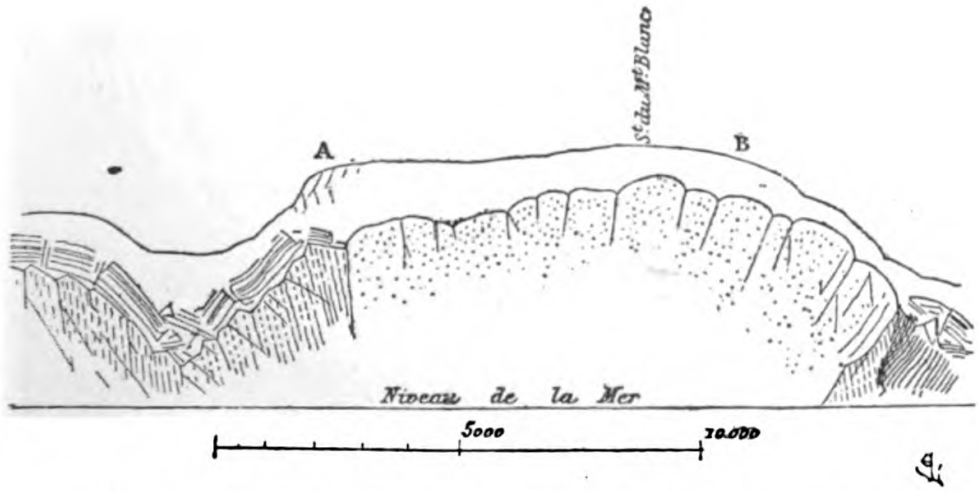


Fig. 11.—Accumulation of Snow on the Massif in its primitive state.

It should be observed that in consequence of the upheaval, there remained between the parts of the crust that had been raised, sunk spaces—a kind of basins without issues. This primitive configuration has left traces still visible, and the valley of Chamonix presents us an example, Fig. 12.[8] On the col de Balme side to the N.N.W., the schists and

[8] See the general map.

coal-measures still rise to an elevation of 7260 feet, but these deposits have been partly carried away by ice, while the village of les Houches, the lowest point of the valley on the south, stands on an eleva-

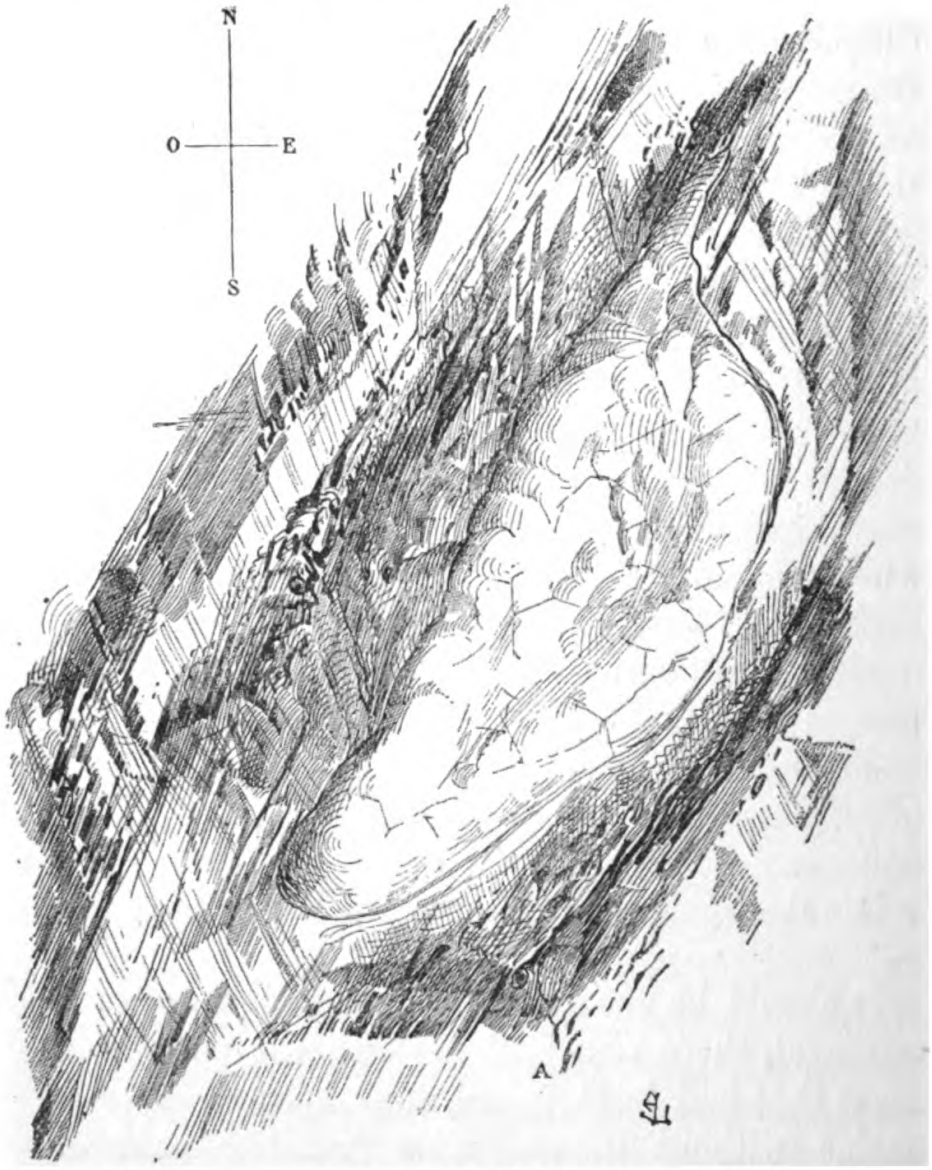


Fig. 12.—Topographical aspect of the Massif after the upheaval.

tion of 3300 feet. It is evident that this point was much lower before the accretions that have levelled the bottom of the valley of Chamonix. Above les

Houches, on the south, le Prarion rises 6500 feet, and was, as also the col de Balme, much higher before the glacial epoch. Le Prarion was joined with l'Aiguillette, west of les Houches, and thus formed a dike which left the thalweg of the vale of Chamonix as now existing more than 3300 feet below. On the Italian side, the col de la Seigne is 8400 feet high on the south, and the col Ferret 8480 feet on the north. These two *cols* have lost in height, while the village of Entrèves, at the lowest point where the two vales, Veni and Ferret, unite in the same line, is at a height of 4280 feet, built on accretions at least 1650 feet at that point. On this side, therefore, the vales of Veni and Ferret formed a deep trench 5000 feet below the lowest part of its edges, except perhaps in the direction of Cormayeur, where the upheaval presented a weak point and a rupture. This area, shown in Fig. 12, was, moreover, covered with the enormous débris of the upheaved deposits, of which at present we find only fragments. The snows accumulated on the plateau of the massif, and on the peaks that surround it, rolling down into these cavities, naturally carried with them the greater part of the fragments of the upheaved deposits, precipitating them to the bottom of the hollows, which were thus roughly filled in. Subsequently these masses of snow were penetrated with water resulting from the meltings, and produced immense glaciers that found no outlet, and whose volume was not less than 50,000 million cubic yards in the vale of Chamonix before reaching the lowest crests of the mountain mass, and 15,000 millions of cubic yards in the vales of Veni and Ferret, before they could pass the least elevated

ridges. The expansive force of these glacial accumulations could exert itself only on the barriers that enclosed them, and, not being able to break through them, the glacier rose in height. On the Italian side, finding a weak point—perhaps a fault at A—in an interior angle of the massif, the glacial masses found their way out, and began to descend into the valley of Aosta. But on the Italian side, the range of the Alps presents much more abrupt declivities than on the north and west, consequently much less extensive reservoirs of snow. Thus the glaciers that descended on that side, independently of the aspect, which favoured their ablation, were much shorter than those following a north and west direction, and sooner reached the level at which they necessarily melted; which would explain how, even during the glacial period, the pliocene fauna might continue its existence on the southern Alpine slope, in the neighbourhood of these glaciers. On the Chamonix side the only vulnerable point was le Prarion and its junction with the Aiguillette de Merlet. There the lias, the coal measures, and the trias, not possessing the consistency of the crystalline schists, could not dam up the ice reservoir, which, bearing down the summits of this part of the mass as soon as it had attained their level, passed the barrier, and spread along the valley of Sallanches.

The elevations that surrounded the massif of Mont Blanc reached a greater altitude than at present, presented surfaces which were level compared with those they now exhibit, and long preserved on their summits and gentler declivities deep and extensive outlying portions of subsequent beds that had

been upheaved, which increased their height; so that the upheaved strata that environed the massif reached, and at some points—as for example, at the Aiguilles Rouges, at le Brévent, le Buet, and the mountains of Saxe—exceeded the mean height of the plateau of protogine.

Two principal conditions, therefore, were favourable to the accumulation of the névés; the configuration of the eruptive mass of Mont Blanc, forming as it did an undulating plateau, at a mean height of 13,000 feet, with an area of nearly 10,000 acres; and all round this mass, a less regular tract of upheaval, but reaching nearly the same altitude, and moreover deeply excavated hollows,—cavities without an outlet; in which the snow accumulated as in immense ice-reservoirs.

A very moist state of the atmosphere and the local configuration just described were causes sufficient to occasion an immense accumulation of water in the state of snow, névé, or ice. Their effect was increased by the fact that the greater the extent and depth of the snow masses, the lower did the temperature of the atmosphere tend to become over a larger area; the more considerable was the evaporation during the summer, the more frequent were the storms, and the more effective did the causes of accumulation become. It must be understood that we are concerned only with the purely local causes, which the examination of the phenomena as they now present themselves, and of the district itself, enables us accurately to estimate.

A property of water, when in a freezing state, is to absorb humidity from the air in a liquid state, and appropriate it. Every one knows that around a

decanter of ice the moisture contained in the air condenses in drops, and would unite with the ice, if the glass did not hinder it. The glacier has the same effect on the large scale as the decanter; it absorbs the water in a state of vapour, takes its heat, and is proportionately melted, or it freezes the water.

If the glacier is small in extent as compared with the volume of water it is able to absorb, it tends to diminish; but if its bulk is very considerable as compared with the volume of water it attracts to it, it freezes it, and is proportionately fed and increased in bulk.

We here merely refer to a phenomenon respecting which we shall have more to say further on, but which must have assumed a considerable importance during the increase of the névés, and have contributed to the further augmentation of the immense primitive "glacières" (ice-accumulations) beneath a very moist atmosphere. We designedly use the term "glacières," because, in fact, the first accumulations of névé in the depth of the furrows of upheaval, which have since become valleys, could only have behaved as glaciers when they had filled those hollows, passed over or burst through their confines, and commenced a regular progress. But it can be imagined that before reaching this stage the accumulations of ice must have attained a force such that at its greatest extent the production of glaciers extended to enormous distances from the upper plateaux. Especially, as what we are here describing as existing in one corner of the Alps presented itself over the whole surface of this vast area of upheaval, and those dikes and wallings-in of

valleys without issue existed everywhere; and as soon as a glacière had passed its banks, and, setting itself in motion, was becoming a glacier, this glacier would find another glacier below which arrested its course, until the united masses made an effort to descend lower. In fact, between Sallanches and Cluses, the upheaval of the Neocomian and Valengian systems constituted a dam whose ridge rose to a height of more than 3000 feet above the bed of the valley of Sallanches, now to a great extent filled up, and which presented a second hollow without issue, much more considerable than that of Chamonix. This hollow was bounded on the south by the extremity of the massif of Mont Blanc, on the east by the great upheaved plateau of the limestone and lias groups which extends from Mont Joli to Mont Vergys, and on the west by the other part of that upheaved district whose ridge begins at les Fis and ends above la Frasse. This elevated calcareous mass, which presented and still presents a relatively even general surface, notwithstanding the profound ravines that now furrow it, then formed two plateaux of a mean height of 10,000 feet, peculiarly favourable to the accumulation of snow.

Having passed the barrier of le Prarion, therefore, the "glacière" of the valley of Chamonix would fall into another and somewhat lower "glacière," but which would be supplied by the snows accumulated on the upheaved surfaces above mentioned.

The combined force of these two masses of ice had to find an issue, and it naturally forced a passage at the weakest and lowest point, namely, through the Neocomian, Valengian, and schistose lime-

stone series which now border the gorge of Cluses.

In the valley of Bonneville this primary glacier again found a barrier at the level of Faucigny and Sentrier; for a glance at the geological map of Upper Savoy[9] will show that the plications of the upheavals are generally parallel to the massif of Mont Blanc, except in the district just referred to, where there has been a rupturing, disturbance, and intersection of the parts upheaved. The primary glacier, which, descending from the valley of Chamonix, reached as far as the southern extremity of the lake of Geneva, had therefore, in making its way, taken advantage of these faults, irregularities, and weaker and more fractured parts of the upheaved district. The same phenomenon is exhibited on a still grander scale in the valley of the Rhone.

The immense glacier which made its way on that side, filling the bed of lake Leman and passing it, followed the course of a vast fault, the hollows, ruptures, and subsidences occurring between the principal chain of the Bernese Alps, Mont Blanc, the Simplon, St. Gothard, and Monte Rosa. But not to carry our investigation to a tedious length, we shall remark that, on the other hand, the tributary glaciers which fall into the two great principal glaciers of the Rhone and Arve valleys, followed the upheaved strata, and descended principally towards the south-west, where the upheaved region is more regularly parallel to the main axis of Mont Blanc. The glacier of the valley of the Rhone, again, which, at the altitude of Martigny, took an

[9] See the geological map of the neighbouring parts of Savoy, Piedmont, and Switzerland, by A. Favre, 1862.

abrupt turn towards the N.N.-West, regained, at the altitude of lake Leman, a direction parallel to the main axis of the massif of Mont Blanc, and consequently to the folds which the upheaval of that mass had occasioned in the earth's crust.

But there cannot be a doubt that where the accumulation of névés has taken place, those causes of it which are attributable to the primitive configuration of upheaved eminences can be only secondary; they would not suffice to account for the relatively considerable accumulations of névés on far less elevated chains, such as the Jura and Vosges mountains.

On the massif of Mont Blanc itself, and on the mountains that border it, declining northwards and westwards, this deposit of névé was so considerable that during many ages the whole of this area was covered with an immense mantle of snow, inert by its very mass, and incapable of powerfully affecting the form of the upheaved eminences, which it protected from the action of the weather.

But natural phenomena are complex. Nature never attains a result, or what we regard as a result, except by a series of gradual efforts, interrupted and resumed.

There can be no question that the glacial epoch was divided into two periods, with an interval between, during which the present fauna and flora, mingled with a few extinct varieties, took possession of the Alps. This inter-glacial period has left incontestable traces in those deposits of lignite and bog-turf, mingled with fossils, that are met with in the earlier *roches moutonnées*, and which are, in their turn, covered with moraine deposits,—the work of

the second glacial period. This latter would appear to have been more extended than the former, and to have been followed by a very marked refrigeration of the atmosphere; since the arctic flora was prolonged far into the period of the diminution of the great glaciers.[1]

During the first glacial period, the inchoate valleys had been further developed; but they were still in process of formation; some basins were already filled up, or were occupied by marshes that have left their traces in the inter-glacial peat-bogs. The process that caused the disintegration of the higher plateaux, and gave a definitive form to the valleys, was recommenced, not at the top but from below, at the decline of the second and great glacial period. This we shall endeavour to explain. But it will be necessary first to define exactly the nature and action of the névé, as well as that of the ice.

[1] See E. Desor's *Paysage morainique, son Origine glaciaire, &c.* Paris, 1875.

III.

THE SNOWS AND THE NÉVÉS.

At the present day the substance on which we tread at or above a mean height of 8000 feet, is not ice, neither is it snow at all like that which covers our plains during winter. On the highest points it is a dust of fine sparkling crystals, and in the amphitheatres where the snow has accumulated during the winter, an agglomeration of granules of ice to which we give the name of *névé*. These deposits consist of successive layers compressed and consolidated, of an opaque saccharoidal appearance, of a greyish white in fracture, and but slightly pervious when once formed.

For when the sun shines intensely the water resulting from the melting of the crystals at the surface sinks in, slowly causing the subjacent crystals to freeze again in the form of transparent granules, but whose union has only the translucency of sugar.

The elevated "cols" and upper plateaux are covered with fields of snow whose delicate crystals of sparkling appearance, not welded like those of the névé, are easily carried away by the gusts of wind in dust-like whirls. During winter, with a temperature always below freezing-point, this snow preserves its

mobility, and is drifted by the winds into the hollows, gorges or amphitheatres. As soon as warm weather returns, its surface only melts and forms a shining glaze, which prevents the subjacent mass from being borne away by the wind; but this mass remains none the less incoherent, enabling the frigid air of the nights to keep it in a state of floury powder. In the neighbourhood of the summits, however, the snow not yet passed into the state of névé sometimes absorbs water in the interior of its mass; when, for instance, snowy slopes are exposed to the direct rays of the sun, and are sheltered from the north-east winds; or again when they are exposed to the south-east wind (Föhn). We have seen the névés of the Aiguille Verte, which had been perfectly hard in the morning, become very soft in a few minutes beneath the influence of the wind and the early solar rays. Every foot-print became filled with water.

This fact was remarked by M. Desor when he ascended the Schreckhorn. Then, during the night, this snow becomes ice without passing through the condition of névé.

The névé is more compact at the bottom than near the exterior surface, in consequence of the pressure to which it has been subjected. It apparently adheres to the perpetually frozen rocks beneath.

The névé is merely a state of transition from snow to ice, and we must distinguish, as Agassiz has rightly observed, the snow-fields from the areas of névé, inasmuch as it is the latter which directly feed the glaciers.[1] The accumulation of the névé takes

[1] "As the snow fields abut on the névé, it might be inferred that they nourish them. There could not be a more erroneous

place in accordance with certain conditions imposed by the wind, the nature and configuration of the rocks, and the laws of gravitation.

It is these laws also that dictate the forms assumed by the detached and slipping masses.

What was the prevailing direction of the winds during the glacial epoch? We cannot tell; but an examination of the débris as they now present themselves inclines us to believe that at that time the prevailing winds were from the W.S.W., and that the deposits of névé on the plateau and the slope facing that aspect were very considerable.[2]

supposition. In all the amphitheatres the snow-fields unquestionably mingle their ice with that of the névé; but it does not thence follow that they supply them. The heights of the Schreckhorn furnish a very considerable proportion of this ice. Its northern face, from the Abschwung to the col de Lauteraar, is completely overspread with snow-fields, which by four different affluents convey their contributions to the névé of the Lauteraar, which is below. The quantity of ice they discharge there is no doubt very great, and yet the space it occupies in the common bed, at the foot of the Abschwung is inconsiderable; the four affluents together (that from the Schreckhorn, the two from the Lauteraarhorn, and that from the Abschwung) scarcely equal a fourth of the width of the great arm of the Lauteraar. Were these sources entirely cut off, the glaciers would still exist, in fact, would lose only a fourth of their volume. . . ." (*Système glaciaire, ou Recherche sur les Glaciers*, p. 52. L. Agassiz, 1847, Leipzic.) See in the same work, chap. v. "*De la neige, des névés*, &c."

[2] At that time, previous to and after the glacial period, the Adriatic sea bathed the southern declivities of the Alps, and the whole of Lombardy was a vast gulf of inconsiderable depth. M. Charles Martins had called our attention to the existence of fossils of gasteropoda at the base of the frontal moraines of Camerlata, and M. Desor has lately published a description of those fossil shells found at Bernate in the "*Paysage morainique.*" We deem it worth while to quote some passages relating to this important discovery (page 33).

In fact, on the Italian side, although the traces of the glacial epochs are visible, indeed incontestable,

"The interior of the mound consists of quite loose materials, sand and gravel, mixed with larger fragments; all these materials appear as if washed, and have no adherence, the usual result of rolling by waves or drifting by currents. Every blow of the pick-axe brought down, with the gravel loosened from the mound, a quantity of whitened shells, principally gasteropoda. . .

"The composition of the ground was not less characteristic. The materials consisted of erratic Alpine débris, very various in dimensions as well as in character, heaped together without the slightest stratification or regularity of arrangement, the largest fragments being scattered among the smallest. But what most struck us was finding on many of these stones, particularly those of the Alpine limestones, streaks and scratches distinctly marked and crossing each other in every direction, like those seen on erratic débris collected near existing glaciers—evidently testifying to the action of ancient glaciers. It should also be observed that among the limestones many were found perforated by the holes made by pholades." Here follows the catalogue of the fossil shells, of species of which not less than twenty-two are still living in the Mediterranean.

"It is therefore certain," adds M. Desor, "that we find at Bernate, in the very midst of a moraine district, a distinctly marked pliocene fauna, side by side with smoothed and striated stones, indicating that the glaciers once extended as far as the southern extremity of the lake of Como, where they met the sea."

If M. Desor's observations are not disputed, the conclusions he draws from them have not been accepted without discussion; but the learned geologist in the work from which we have extracted this passage, appears to us to have answered in the most satisfactory manner the objections urged against his views.

That expanse of shallow water must have produced a considerable amount of vapour, which tended to charge the atmosphere along these acclivities with moisture, and to increase the volume of névé on the northern slope and the elevated plateaux. The lakes of Lugano and Como were veritable glacial fiords, like those met with on the shores of Iceland and Sweden. M. Agassiz considers the vicinity of a marine climate one of the causes of

the erosive demolitions of the slopes are on a less gigantic scale than on the opposite slopes, and the mountain sides have been broken down far more by atmospheric agents than by the discharges of névé and the passage of ice. The escarpments are more broken, more abrupt, towards the south than towards the north, where it is evident that an immense glacier current has carried away enormous sections of deposits over a very extensive area, widening the valleys, removing asperities, paring down formidable obstacles, and rounding inferior summits—that of le Salève, for instance; so completely in fact, that towards the north, at the culmination of the glacial epoch, few summits emerged, whereas on the southern slope, numerous crests appeared between the glaciers which were undergoing a continual process of disintegration from the action of the weather.

The configuration of the upheaved tract was likewise favourable to this difference in the effects of glacial action. On the Italian side the Alps present declivities considerably more abrupt than on the French side or in that of the Jura. The massif of Mont Blanc exhibits this conformation. Towards the valley of Chamonix the slope presents a general gradient of 20°, whereas towards Cormayeur the general gradient is 40°. Observe, moreover, that the upper plateau of the massif (see Fig. 11), presented an undulating surface, slightly inclined to the north-west. Every circumstance, therefore,

the extension of glaciers. "The glaciers of the Alps," says he, "would be larger than they are if they were affected by sea-winds." (*Syst. glaciare*, p. 37.)

favoured the accumulation and retention of snow on this plateau: the configuration of the massif, the aspect and—as we shall see—the conditions of the deposit of névé.

Referring to Fig. 12, we see that the highest part of the plateau is on the margin of the protogine, towards the south-east, and that this mass of protogine and environing rocks assumes an elongated form, presenting the largest front to the north-west. The winds conveying the vapours from the south, the west, and the north-west, thus found a surface well adapted for collecting and retaining the snows.

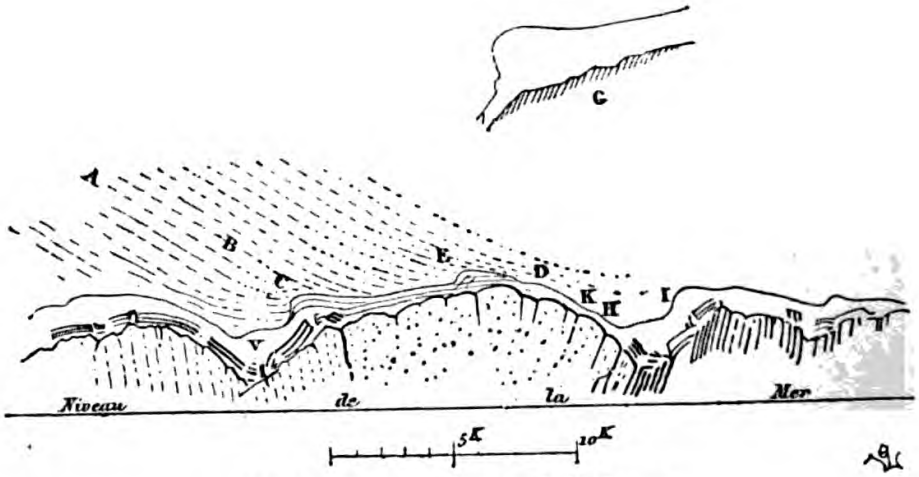


Fig. 13.—Accumulation of the Snows.

Was the accumulation of the snows parallel to the surface of the plateau? No: they would, under the circumstances in question, be deposited on that surface as they now are on planes that present analogous sections, and whose aspect is similar; that is, the accumulation was effected conformably with the outline given in the section Fig. 13.[3]

[3] Section from West to East through the summit of Mont Blanc.

The direction of the wind being represented by A B, the successive layers of snow are deposited more thickly where there is a projection than where the slope approaches the horizontal. The current of air only grazes the flat parts and deposits but little snow on them; while it rebounds and whirls about where there is a more decided slope, and deposits a layer of greater thickness, as shown at C and E.

At D the wind strikes off at a tangent, and sweeps the snow, which is only thinly deposited. So marked is this difference in the deposit that under analogous conditions we observe the snow forming rolls, as shown in section G; and the more decided the projection the greater is its tendency to augment in bulk.

Masses of snow, such as G, naturally broke away at last in enormous avalanches which filled the valley of Chamonix, V, already partly filled with névés.

On the Val Veni side, at H, the same phenomenon occurred. The snows accumulated at I, while they left only a comparatively thin deposit at K, along the steep declivities facing the south-east. Hence these declivities were more exposed to the action of the weather than those of the north-west, and disintegration would begin in the former long before it affected the latter; only, however, at the decline of the glacial epoch; for at the culmination of that epoch a thick capping of snow covered the entire surface of the upheaved mass.

When a mountain section presents a steep declivity facing the wind charged with snow, and on the reverse side a slightly-inclined plateau, the deposit exhibits a section different from that presented in Fig. 13.

Suppose a mountain presenting the section A B, Fig. 14. The direction of the winds charged with ice-crystals, being that of the line C D, the snows form a thick mound at E. The current, in fact, finding an obstacle, F, rises, whirls about, and amasses on the crest G a much greater quantity of ice-dust than it can on the slope G B, which it sweeps in passing. The greater the augmentation of the snow-ridge, the more decided is the tendency to accumulate ice-crystals on its surface. Having called attention to these two general facts, we must

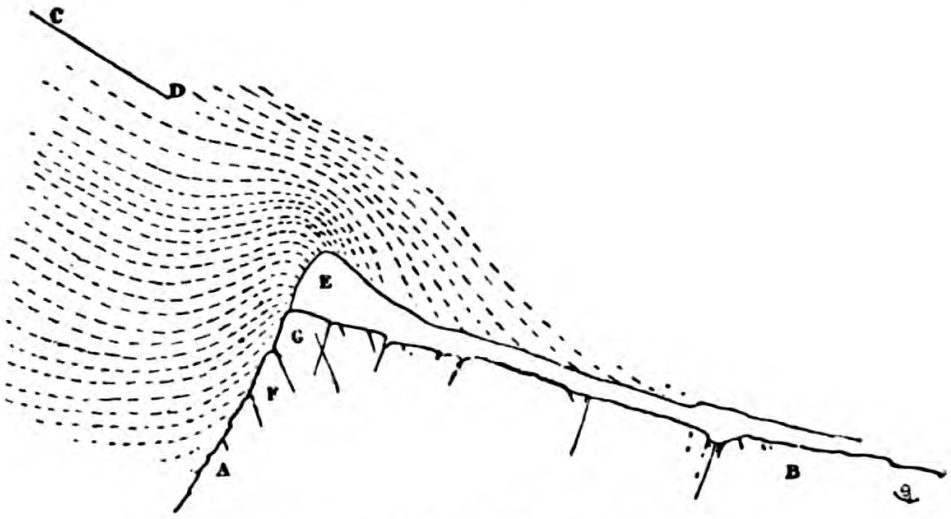


Fig. 14.—Accumulations of Snows on the Ridges.

study the question in its details, for to these we must look for the explanation of the movement peculiar to the fields of snow and the névés.

Suppose the case represented in this last figure. The slope G B is too slight to permit the snow on its surface to slip. How, then, does the deposit comport itself, composed as it is of a series of compressed layers—stratified, in fact? The lower layers, *a b*, Fig. 15, have been subjected to very great

pressure at *a*, and to a less considerable pressure at *b*. The upper layers are less solid than the underlying ones. The effect of the pressures, acting in the direction of A *a*, is to exert a thrust from *a* to *b*. But if there is a rise—an obstacle—at C, which has occasioned a snow-ridge, a bulging-up takes place at D, which results in a rupture or fault at F,[4] and a subsidence from the point I to F. This subsidence, resulting from the thrust which is exerted

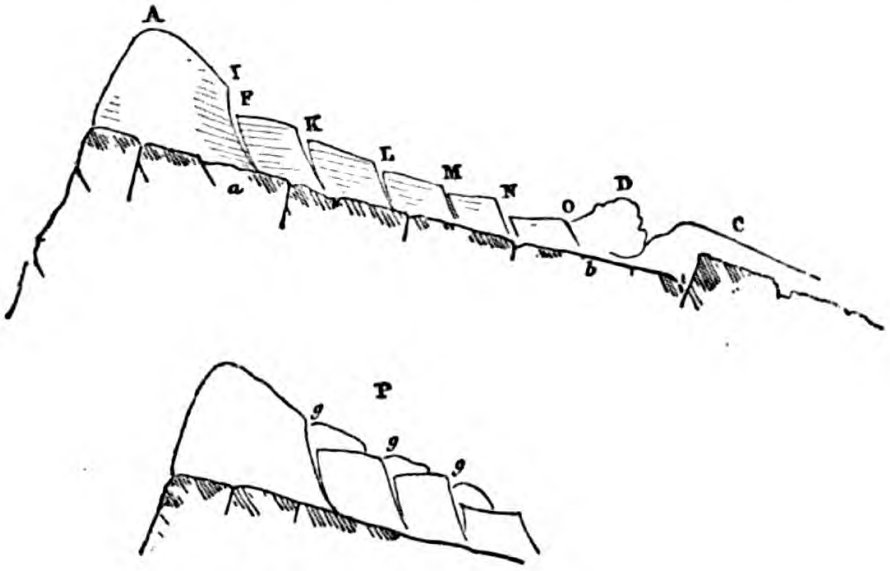


Fig. 15.—Slipping of the Snows.

in the direction of *a b*, cannot take place without causing rifts along the whole surface I D, as shown at K, L, M, N, O, &c., and displacement of the outer faces, which at every rift (*crevasse*) produces a break of level—a fault. Then the asperities, I, K, L, M, &c., become so many fresh occasions for the accumulation of snow through the disturbance which these breaks of level create in the direction of

[4] These faults in the névés, when they occur along the escarpments, are called *rimayes*.

the current of air charged with ice-crystals, so that (see section P) heaps are formed at *g* which, weighting the parallelopipeds on their upper side, tend to tilt them, and to bring their diagonals parallel with the plane of bed, whereby the action of thrust is rendered still more effective, producing folds, breaks of level, and bulgings-up in the lower parts. We have had the opportunity of remarking the phenomenon on the almost level snow-fields of Monte Rosa, but especially of the Weissthor.[5]

Thus, by tilting and occasioning uprisings consequent on a thrust, the snow more effectively arrests the ice-crystals driven by the wind, which, being deposited on a plane in layers of unequal thickness, on account of obstacles, add to the tilting effect produced on the disjointed masses, and therefore increase their action of thrust. Perhaps there is contraction in some parts and expansion elsewhere, both in the snow-fields and in the névés properly so called.

For example, if the névés have accumulated in an amphitheatre, they present a section thicker in the centre than at the edges; consequently, there is a much greater pressure in the middle, and a strain on the edges, producing those *rimayes* which are always apparent at the junction of the névés with the rocks of amphitheatres or basins.

One important point, however, must not be for-

[5] At the point called "Le Passage" the route for nearly half an hour follows a ridge A, bordered by a great *rimaye* F. From this ridge are seen the *steps*, separated by crevasses, formed by the parallelopipeds of névé when tilted up. The same phenomenon may be observed on Mont Maudit du Mont Blanc, and at the Dôme du Goûté.

gotten. The rocks on which the névés rest are frozen at the surface, and the névés seem to adereh closely to them. The action of thrust is therefore opposed by a powerful resistance; accordingly, even on rather steep slopes, we sometimes observe patches of snow that appear immovably fixed,—for instance, when firmly buttressed by a counter-slope. Then there occurs a phenomenon of similar character to the preceding, but which, although limited in extent, gives occasion to the movement of the upper snows by a process of disruption.

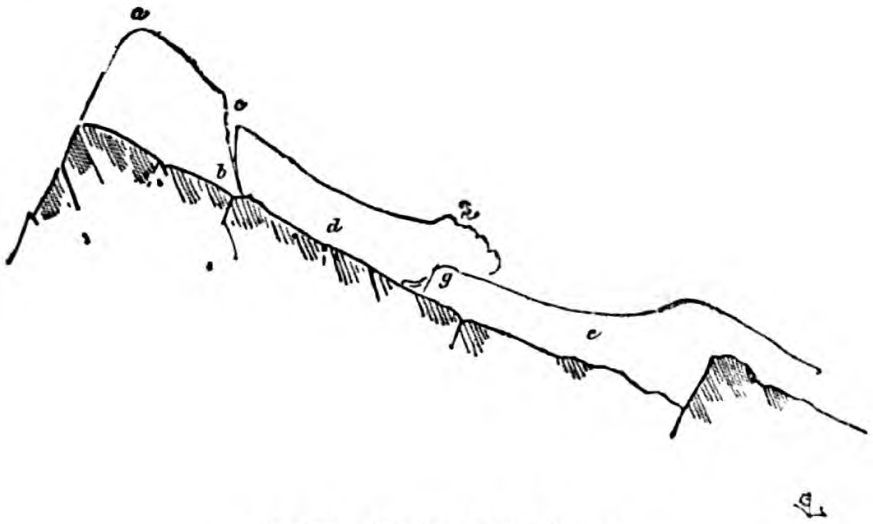


Fig. 16.—Slipping of the Snows.

On the left flank of the col du Weissthor, as seen from the Swiss side, rises a rocky slope exhibiting the following section, Fig. 16. The incumbent weight of the snow-ridge *a* caused a thrust at *b*, an immense *rimaye* at *c*, and a slipping of the entire mass at *d*. But at *e* is a buttressed mass, which offered an insuperable resistance at *g*. The consequence was a protuberance at *h*, occasioning avalanches covering the surface of the plateau *e*,

which in their turn commence a movement in a direction perpendicular to our section.

The action of the currents of air charged with ice-crystals produces other phenomena, which also contribute to facilitate the clearing of the upper snows.

When, for example, there occurs an interruption, an embrasure, or interval *a* between two lofty rocky masses, *b*, Fig. 17, the direction of the wind charged with ice-crystals being B C, the snows accumulate on the ridges *b*, as shown in Fig. 14; but the air, driving violently into the embrasure, deposits the

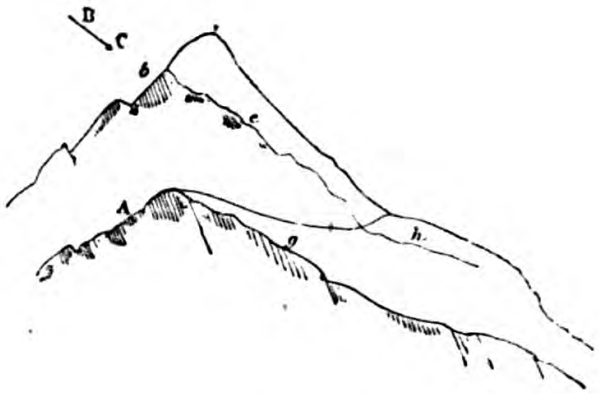


Fig. 17.—Accumulation of Snows through a narrow Col.

snow there conformably with the outline *g h*. Consequently, there remains a more or less considerable hollow, according to the width of the embrasure, which facilitates the discharge of the lateral snows *e*, first into the hollow, thence on to the slope A.[6]

When very abrupt slopes, Fig. 18, are terminated

[6] This phenomenon, on the grand scale, explains the presence of the glaciers, which, even at the close of the glacial epoch, continued to descend from cols existing between summits which were not greatly elevated above their level.

by a ledge R, the direction of the snow-charged wind being A B, the snows fall in dust along this slope, which cannot retain them, accumulate at *a*, and are successively discharged in the form of avalanches down the slopes C. But, in this case, the space at *b* may have been filled with névé ages ago, as the snow discharges occur on the surface.

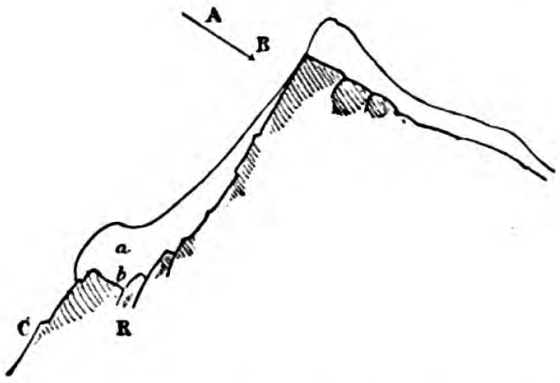


Fig. 18.—Accumulation of Snows on steep Slopes with ledges.

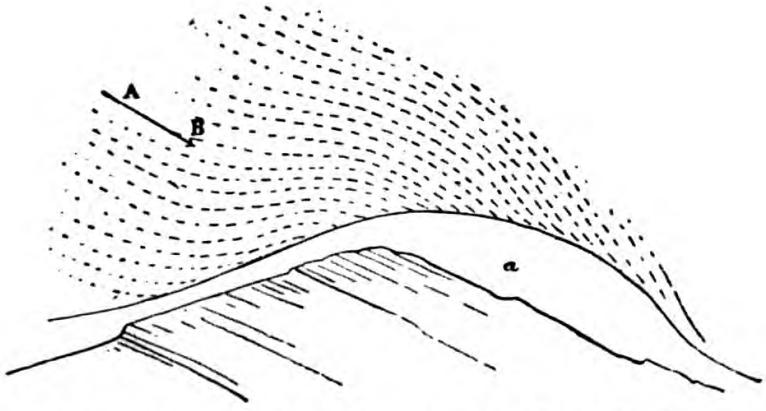


Fig. 19.—Accumulation of Snows on a gently-sloping Ridge.

When two gentle and equal slopes present one of these declivities to the action of the wind, Fig. 19, supposing A B to be the direction of the wind, the snow is deposited as indicated by the outline *a*, and the effects observed in Fig. 16 are the result.

When declivities assume the form of an inverted half-cone (which has been very often the case since the glacial epoch, in consequence of the disintegration of the slopes), the snow slips down the walls of the half-cone, and accumulates in enormous irregular overhanging masses at the apex A of the inverted half-cone (Fig. 20). Thence it is discharged on the lower slopes in the form of avalanches. This

Fig. 20.—Avalanches.

very natural occurrence produces, even at great altitudes, an apparently singular phenomenon.

Suppose A B (Fig. 21) the section of a declivity, with a precipice at C, the upper part of the declivity presenting an inverted half-cone D. In consequence of the narrowing of the walls D C, the snow, as described above, accumulates at E. Thence it falls in avalanches on the surface F of the névé below, on which it presses. And thus it continually impels these lower beds F, in consequence of the pressure

exerted at I, to form an upraised ridge at H, and, notwithstanding the enormous depth of snow accumulated at E and I, the rocky escarpment C always remains visible. This is why, along the northern slopes of the Dôme du Goûté, below the mountain de la Côte, to the left of the Grands Mulets, and on other points of the upper part of the massif of Mont Blanc, are always to be seen nearly vertical sides of rock, which are never covered, though above and below them there are masses of névé which would be sufficient to conceal them if the névés presented the section K.

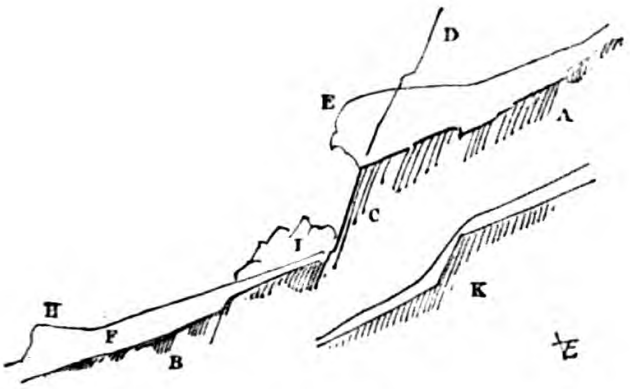


Fig. 21.—Avalanches.

Fig. 22.—Séracs.

But while the snow at its surface is in a powdery state, and is easily blown away in fine dust by the wind in winter, it acquires great consistency and coherence when it has undergone pressure and partial melting, which is naturally occasioned by the addition of successive layers. It is therefore only as the result of great force of thrust that these névés can be dislocated, overcome the resistance offered by friction and the frozen state of the underlying rocks, and quit the upper declivities to nourish the glaciers.

But do they pass immediately from the state of

névé to the state of ice? By no means; they reach the latter state by a series of transitions and in consequence of the absorption of a greater quantity of water.

True névé splits in great lines like stratified materials, but generally curved; vertically its fractures take a conchoidal appearance, Fig. 22. But when it becomes impregnated with water and has begun to pass into the state of ice, it assumes other shapes. It then splits into parallelopipeds, exhibiting its strata in the fracture Fig. 23.[7] But at this stage it

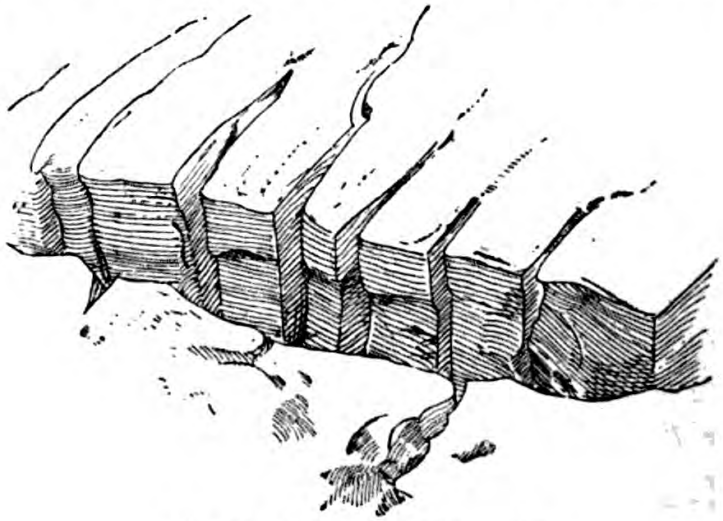


Fig. 23.—Crevasses in the névés.

also acquires a plastic property which it does not appear to possess in the pure state. Thus at the altitude of 10,500 feet crevasses in the névé may be seen presenting the phenomenon of a portion of névé attached to the two faces, and so bending without fracture as it gives to the parting. (Fig. 24.)[7]

Above the Grands Mulets, however, whence these two examples are taken (10,500 feet) we still tread

[7] Crevasse above the Grands Mulets.

an opaque névé which has not the glistening or transparency of ice, especially in the lower parts. A little lower down the transparency begins to appear in the upper layers of the névé, and the melting in the fractures through the sun's heat no longer produces the effects observed 800 or 1000 feet higher up. There, the walls of the fractures of the névé, under the solar action, have the appearance, Fig. 25. The strata form bulgings vertically streaked in a regular manner by the drops of water which fall

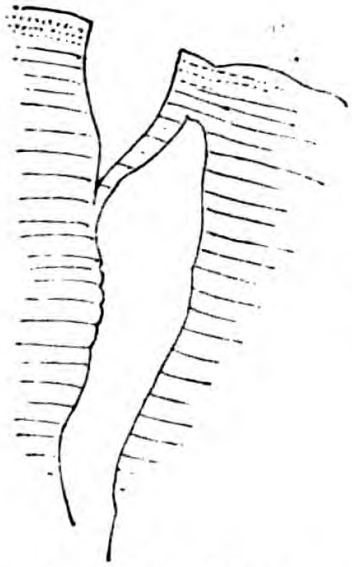


Fig. 24.—Plasticity of the Névés.

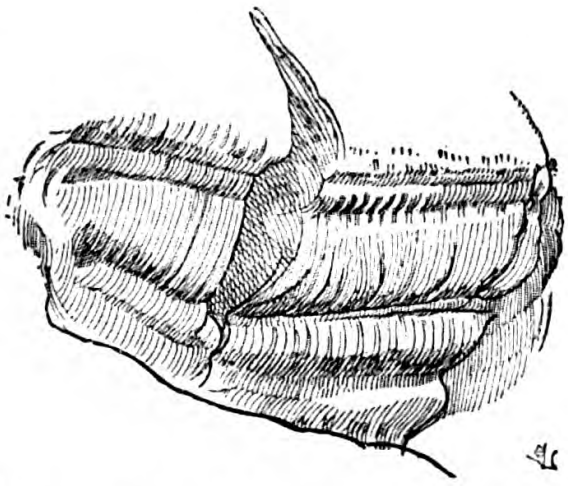


Fig. 25.—Névé changing into ice.

from the upper surface. In the formation of this strata there are, therefore, some layers, softer or more liable to melt under the action of heat than others. These certainly attest periodical summer effects, altering the névés by the heightened temperature, so that even at great altitudes they have been able to preserve those thin crusts of ice that shine in the sun like enamel, but which never attain more than an inch or so in thickness.

There is, however, a cause which, in addition to gravitation, may contribute to the forward movement of the névés, at least at the altitudes in question. On the outer surface of the névés, in warm weather, when the sun shines with all its power, there are formed sheets of water which flow over the surface without being able to penetrate it, but when they reach a crevasse these streams sink in and form ice at the base of the névés, at their contact with the rock. In many cases, therefore, there is a glacier beneath the névé. This glacier becomes a vehicle for the mass of névé that covers it; but this phenomenon would not appear to be general, and we have seen many sections of névés which exhibited no appearance of ice at their base, preserving through the whole extent of their section the opaque white appearance that resembles the cracks in a mass of slaked lime.[8]

The destructive action of veritable névés on the

[8] In reference to this subject we would remind our readers that Agassiz had already made a series of analogous observations. "When," says he, "the temperature is not sufficiently high to favour the formation of névé, it may be induced and hastened by watering the snow. M. Nicolet made several very interesting experiments illustrating this. When he watered the snow very slightly with water at 32° (Fahr.) he always obtained a regular névé, but when he flooded the snow with the same water it did not stay in the interstices of the thin layers, but collected at the base of the deposit, where it wetted the snow and was changed into dull ice by the nocturnal frost." (*Système glacière, ou Recherches sur les Glaciers*, 1st part, p. 141, Agassiz.) Abundant meltings during warm days may thus suddenly soak the under layers of the low névés with water, and form beneath their mass a glacial sheet which lubricates the bed and enables the mass to commence a movement in accordance with the conditions which the glacier obeys.

higher altitudes could not have been exerted formerly in any other manner than it is at present, namely, by pressure and by avalanches.

These névés bore down beneath their weighty mass the looser parts of the rocks and those which were projecting and stood in the way.

But at that time these altitudes were far from presenting the anfractuosities, the rents and ravines they now exhibit, and the névés had only a feeble action on their structure, however great their thickness. The production of the disintegrations whose effects we now behold required a long course of ages, the action of ice, and the gradual subsidence of the glaciers.

IV.

GLACIERS AND THEIR ACTION ON THE ROCKS.

THE observations of men such as Charpentier, Tyndall, Faraday, Thomson, Forbes, Agassiz, Desor, Dollfus, Charles Martins, and so many other distinguished savants, have rendered it impossible to entertain a doubt respecting the movement of the glaciers, or the principal causes that produce it. The glaciers descend the valleys which hold them, not in proportion to the gradient of the slope, but to their volume or rather thickness; so that a thick glacier on a slope of 10° will descend faster than its neighbour of less thickness on a slope of 25°. The glacier does not cease to advance, even when it encounters an obstacle, a dike. It mounts the ridge of the dike, covers it, and descends on the other side, without relaxing or accelerating its speed, which, it must be remarked, quickens as the glacier reaches its middle point, and slackens again on nearing its terminal point. There is, therefore, in the course of a glacier, a maximum of activity about the middle of its length.

It is the névés that chiefly feed the glaciers, and these are more considerable, and consequently descend lower in proportion as they originate in

névés of greater extent and thickness. Thus the glacier des Bossons, which descends into the valley of Chamonix, and whose terminal point reaches an altitude of 3300 feet, is fed by the immense névés which descend from Mont Blanc, the Dôme du Goûté, Mont Blanc du Tacul, Mont Maudit, and the Aiguille du Midi. The glacier des Bois, whose terminal point is now at an altitude of 3630 feet, is fed by the névés from the great amphitheatres of the Allée Blanche, the Géant, the Tacul, Leschaux, and le Talèfre.[1]

We say that the glaciers are fed chiefly by the névés, and not entirely. The glacier has, in fact, other feeders. It receives the avalanches of lateral snows in spring, and it absorbs the vapours and freezes them again, receiving a more abundant augmentation from this source, in proportion to its own volume. If, on the contrary, the glacier is inconsiderable in proportion to the vapours which supervene, by absorbing these too abundantly it takes their caloric and melts, the more rapidly as the air is more heavily charged with moisture. Whence it follows that the greater the section of a glacier, the greater is its power of augmenting its volume; and that the smaller the section, the more subject it is to the chances of diminution. The increase or decrease is, therefore, in direct ratio to their volume.

Messrs. Ch. Dufour, and J. A. Forel, professors at Morges, have lately made experiments of an interesting character on the condensation of the aqueous vapour of the air in contact with ice, and

[1] See the general map.

on evaporation.[2] Agassiz had already as early as 1847, enunciated a hygrometric theory of condensation and evaporation at the surface of a glacier, and concluded, that these two phenomena would probably counterbalance one another, and that the one would restore to the glacier the watery vapour which the evaporation takes from it.

In the present condition of the glaciers, these two phenomena may in fact neutralize each other; but would it be so at the height of the glacial period? It is probable that at that time the glaciers on account of their extent, absorbed and regelated a much larger quantity of aqueous vapour than they gave out by evaporation. These aqueous vapours borne along by the atmospheric currents in perpetual clouds, were converted into snow, or were quickly absorbed by the immense glaciers that covered the Alps.

When a period of fine weather supervened, the sun produced a considerable evaporation, which soon originated terrible storms. These storms deposited hail and snow on the elevated points, and part of the rain was absorbed, and re-frozen, by the immense glacial surface.[3]

[2] *Recherches sur la Condensation de la Vapeur aqueuse de l'air au contact de la Glace et sur l'Evaporation*, by Ch. Dufour and J. A. Forel, professors at Morges; extracted from the *Archives des Sciences de la Biblioth. universelle*, March, 1871.

[3] Even now, the storms on the heights produce a sudden lowering of the temperature; the snow and hail cover the summits and descend even in July, as low as 6900 feet. On the 25th of July, 1874, after a day, during which the thermometer at Plan-Praz, (7100 feet) stood at 77° Fah., a storm came on which lasted all night. The next morning at five o'clock, the neighbourhood of the châlet was covered with snow, and the thermo-

Every mountain climber must have observed how dry the air is on the heights during fine weather; on the glaciers, in fact, wet clothes and provisions quickly become dry. But Messrs. Charles Dufour and J. A. Forel have instituted a series of experiments on the glacier du Rhône, which enable us exactly to appreciate the intensity of the phenomenon.

"On the surface of the glacier the air was much drier than at the Hôtel du Glacier du Rhône, although the latter is very near to the former (about 1000 yards) and consequently subject to the same general influences.

"The result of eighty-five observations made at the Hôtel du Glacier du Rhône, from July the 27th, to August the 4th, 1870, at all hours of the day and night, go to show that the mean relative humidity was .2955 in., or 122.687 grains of watery vapour per cubic mètre (35.31 cubic feet) of air."

The result of ninety observations made during the same series of days on the glacier du Rhône between eight a.m. and five p.m., went to show that the mean positive humidity was .201 in., or 83.489 grains per cubic mètre of air.

"The difference in humidity in favour of the hotel was therefore 39.198 grains per cubic mètre. The air was thirty-two per cent. drier on the glacier du Rhône than at the hotel.

"The average of six observations made the 2nd of August, between eleven and two in the day, in

meter stood at 36.6° Fahr. On that day it preserved a mean temperature of 44.6° Fahr. During the glacial period this phenomenon would evidently produce far more considerable results.

the middle of the glacier, at an altitude of about 7700 feet, gives for the elasticity of the watery vapour in the air .1642 in.

"An observation made the same day at 2.50 p.m., in a meadow a few hundred yards from the glacier at the same altitude, gives for the elasticity of the atmospheric moisture .2334."

What were the hygrometric conditions of the air during the glacial period?

The air must have been highly charged with vapours to have afforded nourishment to the glaciers. But the condensation of the vapour on the frozen surfaces tends to melt the mass, and this condensation of the atmospheric moisture dries the air; to enable the glaciers largely to augment, therefore, it was necessary—first, that the condition of the summits should be favourable to the deposit and preservation of the névés—second, that vapours should be perpetually directed towards those regions to saturate the air, so as to neutralize the desiccation, and to furnish fresh supplies to the névés and ice which were tending to descend into the regions beneath.

Since the movement of the glaciers is in direct proportion to their volume, if, at the present day, the Mer de Glace at Chamonix moves on an average ninety yards annually, we may calculate what was the rapidity of the glacial current that filled the valley of Chamonix to the height of 3300 feet above the present level of that valley (which was much lower, since it had not been filled in) and which then presented an average transverse section of 2,600,000 yards.

The transverse section of the Mer de Glace at

les Moulins, being 190,000 yards, that is, nearly fourteen times less, the speed of the glacier de Chamonix might have been annually about 1200 yards, or perhaps more; for observations have not as yet enabled us to determine the proportion of the speed of glaciers to their volume, or whether their propulsive force increases according to the ratios of their analogous sections, or in the ratio of their cubes.[4] Now a glacier acts on its walls in the ratio of its volume and its speed; that is, it abrades or rasps the rocks with an energy increasing in proportion to the volume and speed of the mass. The thrusting force of the great glaciers of the glacial period, would therefore produce, on a very grand scale, the phenomena of abrasion, tearing, and rasping of the rocks which we still observe on a reduced scale.

But as the glacier moves in consequence of the expansion of its mass, under the influence of the regelation of the water that penetrates it, and other causes which will be considered further on, and as this expansion is in direct ratio to that mass, it is evident, that when, e.g. Fig. 26, the glacier finds itself compressed between two walls of rock A, B, C, the expansion from B to D tends to elevate the surface D and to isolate the under surface I from the thalweg B; and that it exerts a considerable pressure at A, and C. As a result of this the glacial current breaks away, as would a battering ram, all the asperities of the walls, and thus effects a widening

[4] The section of the Mer de Glace, at the point indicated, is analogous to that which the great glacier of the valley of Chamonix presented—that is to say, the relations of height and width are proportionate.

of its bed in the upper part, in increasing extent, according as that section gives greater force to the frozen mass. Thus (section x) the glacier current undermines the slope *a*, the parts *b* fall, and its surface gradually occupies a wider area *c*, *d*, bearing away on its two edges a mass of débris, which, in proportion as the glacier tends to diminish, successively forms lateral moraines.

As the under side of an existing glacier is isolated from the thalweg, and leaves between it and the bed

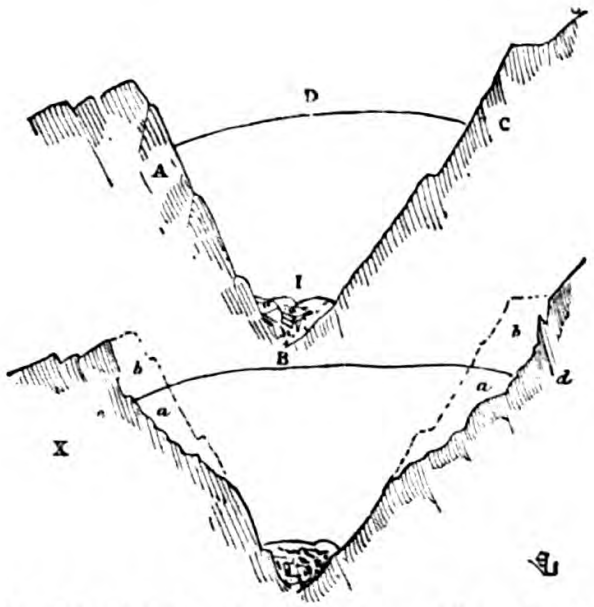


Fig. 26.—Lateral Action of a Glacier Current in a wide Depression.

a free space strewn with stones, some geologists incline to conclude that the action of the glacier on its sides was almost null, and that the widening of certain valleys could not be attributed to it. It is true that the action of the glacier on the thalweg is slight, in proportion to the limitation of the section of the glacier; and it happens in fact, that as some walls of upheaval present the section, Fig. 27, in consequence of a rending of the rocky mass; the

glacier which has found its way through this rent, filled the upper space, scooping out the walls and bringing down the cliffs, but respected the rent in its lower part, which it has affected only by partly filling it with débris,[5] for while ice possesses plastic properties, as the striking observations of Tyndall have proved, its plasticity is not sufficient to enable it to fit exactly into all the lower or lateral sinuosities of a fissure.

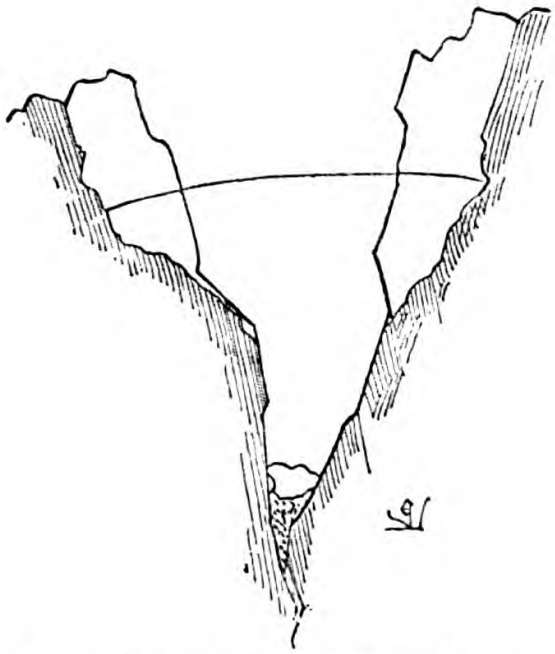


Fig. 27.—Lateral action of a Glacier Current.

The forward action of the glacier current possesses an irresistible force; it acts like a battering ram; but this force is null in the contrary direction. Let us examine the longitudinal section of a glacier. If the ice current encounters a projection, an

[5] This fact may be observed in many gorges, particularly in the Via Mala above Tusis, in the gorge that descends from les Houches to the valley of Sallanches, at the Trient, and the descent of the Simplon, on the Italian side.

obstacle, Fig. 28, the glacier presses closely on the upper face A, but at B, it leaves a hollow—a grotto.[6] On this upper face it exerts such a powerful pressure that the ice strata split, as seen at C. But the result of this action is, that when the obstacle presents a denticulated section (see D) which was very often the case at the time of the upheavals—the pressure of the glacier breaks and carries away

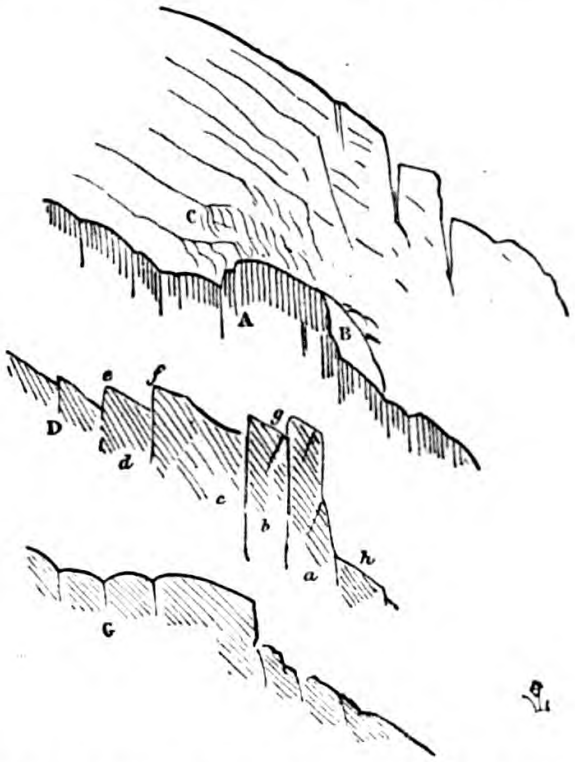


Fig. 28.—Action of the Ice on the Bed of a Glacier.

first, the portion *a*, next that marked *b*. If the portion of rock *c* and *d* resist, it wears and smooths the projection as at *e* and *f*, and from *g* to *h*, forms an arch as shown at B.

[6] See the boundary rock on the right bank of the glacier de l'Argentière, at the extremity of the present moraine; the boundary rock on the right bank of the glacier des Bossons, below the pierre de l'Echelle, &c.

This is why, on the beds of glaciers now melted, we meet disruptions of rock on the down-stream side, and rocks whose surfaces are smoothed and *moutonnés* on the up-stream side, as shown in the sketch G. This fact depends naturally on the contexture or the stratification of the rocks. When the strata are perpendicular to the glacier current, the phenomenon is very manifest; when they are oblique, it is less so, when they are parallel to the current, the glacier ploughs furrows between them, removing the softer parts, and leaving the harder parts projecting, though worn by it.[7]

When, in consequence of the configuration of the upheaved rock, a glacier is compelled to make a turn, it tends to get rid of the projecting angle which forms an obstacle to its direct passage.[8]

[7] We may point in illustration to the bed of the glacier which, during the glacial period, passed over the col des Montets, and descended into the valley of the Rhone by the val de Valorsine and by Salvan. There the schistose furrows, parallel to the glacial current, are very sharply marked, and stand up 150 and even 300 feet above the ancient bed.

[8] M. Desor had observed in 1844, on the glacier de l'Aar, that the ice thus bridged over considerable spaces both in the direction of the vertical and the horizontal plane. "The glacier," says he, "bore right and left on two marginal prominences—a kind of small rounded promontories; and what especially deserves to be remarked, so far from bending to fill the space between the two promontories (as any substance more or less fluid would have done), stretched over, on the contrary, describing a segmental arch from one of the promontories to the other. Between the ice and the rock was interposed a layer of gravel a few inches in thickness, which, after having passed over the first promontory, fell down in the form of scales from the roof of the cavern. These scaly laminæ bore traces of great pressure. The ice of the roof (of the intrados) of the cavern exhibited, besides, wide grooves which the eye followed to a great depth, and which gave to these

During the glacial period, angles, even promontories of tremendous size, were thus removed, broken, and rounded. Examples of this are sufficiently numerous. We will cite only one, which is so striking as to be easily appreciated by all.

The glaciers of the Vallée Blanche descend from the Aiguille du Midi towards the east;[9] it is constricted on the north side by the ridge of rocks known as the Petit Rognon, and is then forced by the position of the Pic du Tacul to turn abruptly northwards; at the glacial epoch, therefore, it encountered a projecting angle formed by a mass of protogine on its right margin. This mass of protogine, formerly compact, divided into aiguilles under the action of atmospheric agencies, and the glacier has cut the most projecting of them down to the level of the existing surface, it has almost disintegrated the second, and has only left standing those which did not present too great an obstruction to its passage. At the present day the glacier, being lowered, exposes the base of the aiguille which formed the angle, and the base of the ruins of the second, Fig. 29.[1]

bright surfaces a very peculiar appearance. It was evident that these grooves were nothing other than the impression of the inequalities of the rock over which the ice had passed, and this confirms what we have shown before, viz. that the glacier ice, though very hard, possesses a certain plasticity." (*Nouvelles Excursions et Séjours dans les Glaciers et les hautes régions des Alpes*, p. 120. Neufchâtel, 1845.)

[9] See the general map.

[1] View taken from the Tacul; A is the summit of Mont Blanc du Tacul; B, the Rognon; E, the Petit Rognon; D, the Aiguille du Plan. At C are seen the ruins of the two aiguilles which formed an obstacle to the turning of the glacier. The line I, K, shows the height of the ancient glacier.

The primitive glacier, therefore, acted on the salient angle like a ram. It removed it—tore it away to make room for itself. Upon the sides of the aiguille M are perfectly distinguishable the surfaces, deeply grooved by the ice; and the ruins of

Fig. 29.—The Envers de Blaitière.

the aiguilles carried away show how the ice proceeded, leaving intact the planes of contraction, and scooping out the softer middle parts in such a way that these bases of aiguilles enable us to recognize the planes marked by projecting ridges jutting out

from the snow. This action, which may be easily verified on the small scale, occurred on the grand scale during the glacial period.

But we must not forget that in the case of Mont Blanc, as the upper plateau presented a bossed surface, supported by the slopes, more or less abrupt, of the crystalline schists and upheaved strata, the presence of snows could only exert a feeble action on the plateau preserved from destruction by this thick mantle. The culminating part of the upheaved mass was thus shielded from the effects of atmospheric agencies. It was, therefore, in the lower parts that the flow of the glaciers began to produce its effect. When, after long-continued efforts, those currents were enabled to clear the dikes which the upheaved mass had opposed to them, and to convert the *glacières*[2] into flowing glaciers, when their movement assumed a determinate direction, and they were able to make themselves beds; it was, as said above, on the marginal walls that their action commenced. By sapping these, they caused the fall of the upper parts, and these falls were effected according to the nature of the wall.

Let us narrow the question, and take a part of the massif of Mont Blanc. If we glance at Fig. 1, we see that the crystalline schists were upheaved and folded to make room for the protogine, and that upon those crystalline schists there remained enormous layers of upheaved systems. The strata dislocated and reduced to débris by the diluvian rains anterior to the glacial period, filled the hollows, and had been partly carried away into the

[2] Ice stores. See Chapter II.

lower valleys. Some layers must, however, have remained along the crystalline slopes, since we still find traces of them.[3]

As soon as the movement of the glaciers began, they first bore down these layers, whose power of resistance was relatively slight, and which did not adhere to the crystalline rocks. When this preliminary work of excavation was accomplished, the higher level of the great glacier which followed the now existing valley of Chamonix, and passing over le Prarion fell into the valley of Sallanches, reached the top of the upheaved crystalline schists. (See A, Fig. 30.) This glacier exerted an action at *a* on the side of the Brévent chain, and at *b* on the side of Mont Blanc, with an energetic force proportioned to its mass, since the distance between these two banks was then nearly two miles. It left at C the débris of the upheaved beds posterior to the crystalline schists; for it could not carry them over the barrier of le Prarion; but it successfully tore away all the asperities of the containing walls and proportionately widened its upper bed.

Widening this bed (see B), and thus finding more room, it lowered its level, and proportionately laid bare the high banks whose sides it had sapped, and which fell, leaving exposed great vertical faces of the rocks, *c*. Thenceforth exposed to the weather, since the snow could not stop on them, these were continually being split by the action of frost and thaw. The weaker and softer parts gave way first. The

[3] Some of these layers still exist, even in the valley of Chamonix, beneath la Flegère (lias) at the foot of the Mountain de la Côte (gypsum).

resisting parts left witnesses of their existence under

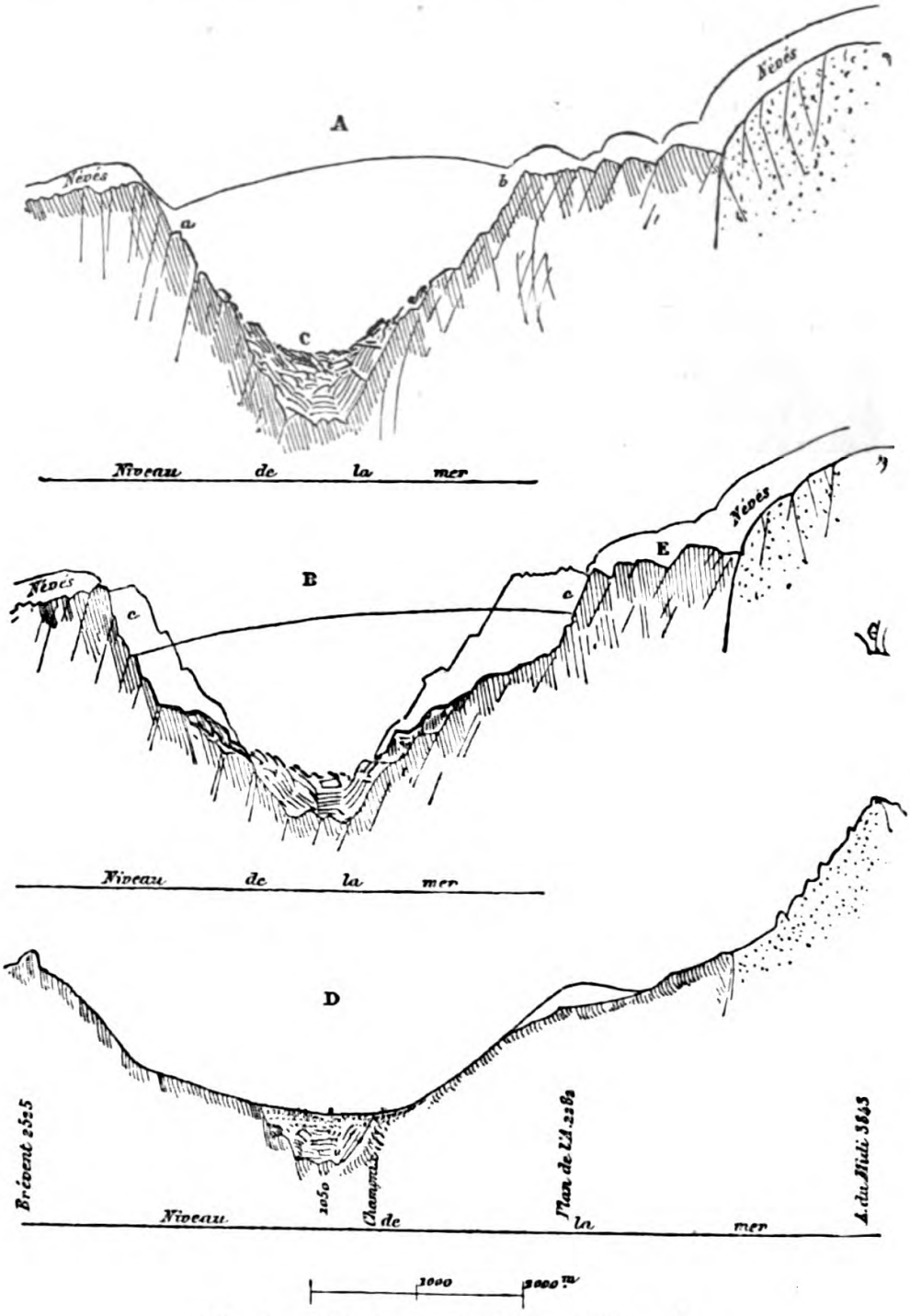


Fig. 30.—Widening of the Valley of Chamonix.

the form of buttresses. Then these fallen weaker parts opened issues for the upper snows, which taking

advantage of these passages, began to form lateral glaciers, which operated in their turn on their walls as the great trunk glacier had done.

The section D shows the present state of the valley, according to a section line drawn from the Brévent to the summit of the Aiguille du Midi. The ancient thalweg may be supposed to preserve beneath the modern alluviums of rolled pebbles and the cones of dejection, the débris of the secondary upheaved strata which could never be carried away. It was under the action of the lateral glaciers that the crests E of the upheaved crystalline schists (see B) were destroyed or reduced, and the slopes of the protogine of the Aiguille du Midi ruined.

The existence of these lateral glaciers, which still continued for a very considerable time after the great trunk glacier had subsided, prevents us from ascertaining now the height to which the trunk glacier originally reached, since the lateral glaciers carried away those limiting banks of the trunk glacier, which preserved the traces of its passage at the time of its greatest force. Between the under part of the lateral glaciers and the upper surface of the trunk glacier there were, during a very considerable period, parts of border rocks which preserved the marks of the passage of the trunk glacier as reduced, as well as of the deposits of lateral moraines. But these are traces of very much later date than the culmination of the glacial period; for an examination of the valleys as they exist, must lead to the conclusion that the glacial epoch had very long periods of decline, and that this decline is due in great measure to the effects of the glaciers themselves.

In fact, the more effectually these cleared their

course, the more easily they flowed, and the more they tended to subside, since the supply did not increase in proportion to the excess of flow. The nearer the surface of a glacier approached the bottom of the valley the more the lateral walls were warmed by the influence of the sun, and tended by radiation to melt the glacier. The disintegration of the slopes and along the spurs, effected by the lateral glaciers, softened the acclivities, widened the valleys, and enabled the sun's rays to penetrate for a longer time into the bottom of the primitive gorges. Thus the glacier, while working for its flow, was, at the same time, working for its ablation. We employ the term *ablation* designedly, because it is in reality by successive reductions that the glacier ultimately disappears or is melted.

All the great valleys of the Alps still exhibit the traces of frontal moraines that mark the successive limits of retreat in the primitive trunk glaciers. It would appear that the glacier withdrew towards the heights by stages, as soon as it had completed its work in the lower districts, and this phenomenon resulted from the obstacles it had to overcome. The obstacle conquered, it abandoned the place to continue its work higher up. We shall endeavour to explain this.

We have seen that the upheavals did not form continuous valleys, having each its outlet as at present. These primitive valleys were most of them subsidences — basins, more or less broad and deep, without issues, or, at least, possessing such only at levels above the height of their bottom.

Speaking only of certain great valleys, it is clear that the valley of Chamonix was barred at its western

end by le Prarion; that the valley of Sallanches was shut in above Cluses; that the valley of Entrèves was also closed in above Cormayeur by the junction of Monts Chétif and la Saxe; that the Swiss Val Ferret was closed by the junction of the Catogne with the Mont de la Rive Haute; that the val de Sembrancher was limited by a formidable schistose barrier between that town and Bovernier; that the existing Rhone valley consisted of only a series of depressions and narrows, one of which was opposite Viesch and Ernen; another lower down below Brieg; a third at Sierre; a fourth at Sion; a fifth below Martigny, and a sixth at St. Maurice; so that the longitudinal section of this valley was as represented in Fig. 31. The glacier which

Fig. 31.—Action of a Glacier on the Bottom of a Valley.

ultimately filled lake Leman, and which found another barrier below Geneva, passed over all these dikes with an energy that was increased by the confinement resulting at each of these points from the contraction of the banks. But when it had forced its way below Geneva, and could flow unhindered, its force became weakened in consequence of that very facility of movement, and it ultimately melted on reaching the dike of St. Maurice, being no longer fed from above in proportion to its advance below. It therefore filled the enormous depression which constitutes lake Leman, and the ice fell in seracs into that reservoir over the dike of St. Maurice. Gradually these discharges, and the action of the weather

on the dike, wore it down, so that the glacier lowered its outer surface; then, lastly, the ablation of this section between St. Maurice and Martigny took place. For a long time the glacier left a second lake in this part—a narrow, long lake, as the lakes of Thun and Brienz still present; then also occurred the ablation of the upper sections one after the other.

The ablation of the sections is produced as follows (Fig. 32):—Let A, B be the longitudinal section of a valley before its levelling produced by the glaciers and alluvial deposits. Let C, D be the higher level of the glacier. As there is always constriction, produced by the lateral walls C, E, D, opposite each

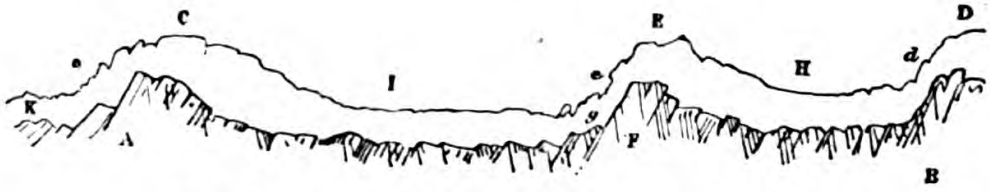


Fig. 32.—Action of a Glacier on the bottom of a Valley.

ridge A, F, B, there are accumulations of ice at D, E, C, and séracs *d*, *e*, *c*.

The solar action is more active on the séracs than on the smooth mass of the glacier, the air and heat penetrating between the masses of fallen ice. When the activity of the glacier is lessened by a diminution of the primary sources of supply, the melting at *g* is more considerable than the supply E. Continuity ceases between the section H and the section I. Thereupon, the latter left to itself melts with great rapidity, and produces a torrential flood that carries down with it the moraine sands and stones, which fill up the subsidence—the lower hollow, K. This

torrential flood contributes to the opening of ways in the dam, A. Here we have a section of the valley prepared for receiving the levelling by alluvial deposit, and which will soon be covered with vegetation. If the dam is not entirely broken down, there remains a lake in the place of the glacier section; but in process of time this lake is filled up by the materials the torrent brings down. Frequently, also, without the existence of a transverse dam of any importance in a valley, the glacier itself makes a

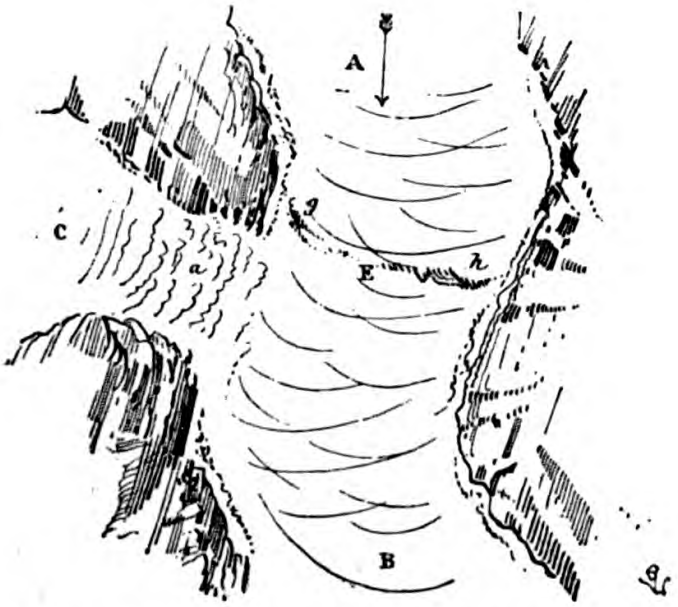


Fig. 33.—Trunk Glacier and lateral Glacier—Ablation.

halt, deposits a frontal moraine, and thus forms a dam for future lakes that will result from the meltings. But these stations without rock barriers are generally occasioned by the moraine deposits of a lateral glacier; for the lateral glaciers greatly influence the stages of retreat occurring in the trunk glacier.

Suppose, in fact, a trunk glacier A B, Fig. 33,

met by a lateral glacier C. The glacier contributes to supply the trunk glacier. But if, in consequence of its inconsiderable volume and of a fall of séracs at *a*, the lateral glacier happens to retire—that is, to cease to be in communication with the trunk glacier—the latter on its part suffers a diminution of supply, which causes it to melt rapidly between B and E. But if it receives a supply from above considerable enough to enable it to maintain its limit at E for a long time, it deposits at *g h* a frontal moraine, which may form the dam of a future lake at A. Natural rocky dikes, therefore, or lateral glaciers, determine the stages of retreat in the great trunk glaciers. The torrents undertake the clearing and levelling of the ground, while always leaving visible traces of these natural or deposited dikes.

Nature never destroys all the evidences of her work. It is for the observer to discover and point them out. Sometimes, as above Sierre, for instance, the two phenomena we have been describing occur together. Rocky dike, formation of moraine by lateral glaciers, deposit of a frontal moraine from a stage of retreat in a great trunk glacier, and effects of tremendous torrents which made their way through these obstacles, and which carried down the greater part of these débris to level the valley below.

Independently of the periodic causes, which were, perhaps, the primary occasion of the successive ablation of the great primitive glaciers, it cannot be doubted when we observe the district and the phenomena which are still manifestly occurring:—

1st. That the glaciers, in consequence of their

operation on the upheaved masses, contributed in great measure to their own melting by clearing a way for themselves, and widening out the walls that confined them.

2nd. That the glaciers first operated at their terminal parts, leaving the névés on the upper plateaux that supplied them relatively intact.

3rd. That strictly in proportion to their ablation below, which was partly induced, as we have just shown, by their own work, they retreated towards the heights, became lowered in level, left bare the rock walls originally concealed by their mass, and thus surrendered those walls to all the destructive effects of atmospheric agencies.

4th. That then, and subsequently to the principal part which was played by the great trunk glaciers which had been reduced, began that of the lateral glaciers.[4]

As long as the thickness of the great glaciers reached the height of the lateral névés, the latter largely supplied the trunk glaciers in the form of avalanches and flowings; then, when the great principal currents had lowered their level, the lateral névés were in their turn the origin of glaciers, which, proceeding like the principal current, gradually made a way and bed for themselves, tending more and more to render themselves independent of one another—to subdivide—and thus augment the causes of their melting.

If the upheaved mountain masses had consisted

[4] At the present day there no longer exist any but lateral glaciers, or the very reduced upper recipients of trunk glaciers—the Rhone glacier, and the Rhine glacier, which are not even so considerable as certain lateral glaciers or affluents.

of a homogeneous, amorphous material, resisting equally in all its parts, there would have been no reason why the glacial period should not have been indefinitely prolonged; for the action of the ice on a homogeneous hard substance smooths its surface very slowly, but cannot disintegrate it.

The plasticity of the ice enables it to pass over obstacles with comparative facility. It conforms to all the prominences, horizontal or vertical, with marvellous pliancy, without a check on the part of these dikes or spurs to a movement which is independent of conditions of slope or parallelism of the walls; and it is in this that the flow of a glacier differs essentially from that of a river, whose current acquires greater speed in proportion to the fall, and the evenness, straightness, and parallelism of the banks.

The mountains in question consist of substances greatly differing in point of hardness. Moreover, even when they are formed of the same substance, they present, not an amorphous mass, but a juxta-position of bodies separated by stratification, or by numerous fissures; planes of contraction caused by crystallization, refrigeration, or desiccation, according to their origin. So that certain substances, each of whose parts is of such hardness that steel cannot scratch it, present in the mass a kind of structure entirely composed of fragments, not joined by any cement. Such is protogine, such are gneiss, crystalline schists, granites, and all crystalline rocks. As regards the stratified rocks—those, namely, which were originally deposited in layers under the pressure of water, such as the liassic beds, the jurassic groups, the older sandstones, the chalk, &c.—to say nothing of their stratification, which

makes them present so many feebly-united beds —their materials are subdivided in consequence of desiccation and refrigeration, by fissures, planes of contraction—generally oblique—which thus form a number of rhombohedrons in juxta-position.

It also happens that in crystalline rocks which have a stratified appearance, such as the crystalline schists and gneiss, certain strata are softer than others, or more fissured, or intermingled with foreign substances that render their mass more easily assailable.

Constantly frozen beneath the thick layers of névés, these materials remain inert, and can suffer only trifling disintegration; but as soon as their surface is exposed to the air, the destructive conditions begin to tell seriously. Then the water resulting from the melting of the névés in a temperature above freezing point percolates into these fissures, widened by the expansive action of the sun's rays on the outer surfaces,[5] and penetrates more or less deeply into them. Night supervening, with a very low temperature, this water freezes and separates the walls. This process, repeated thousands of times, widely opens the fissures eventually, and then the snow which lodges in them, melting and freezing again, acts exactly like a wedge. Thus we see enormous rocks, composed of a substance proof

[5] Being on the Grand-Plateau at sunrise, I heard the exposed rocks of the Dôme du Gouté, struck by the sun's rays after a night in which the thermometer had sunk to 20° Fahr., give out sharp prolonged notes, as a slab of resin does when it is suddenly exposed to heat. At Maladetta, in the Pyrenees, I have heard the same sounds produced by the rocks under the influence of the sun's rays after a cold night.

against a tool, detach themselves from a cliff, and roll suddenly down the mountain slopes or on the surface of a glacier, which transports them to its frontal moraine, or gently deposits them on one of its lateral moraines. It is thus that the peaks, the aiguilles of protogine, which, viewed from a distance, seem imperishable—so keen are their angles and so sharp their points—exhibit, when closely observed, only a pile of blocks, separated by gaping joints, and which appear ready to tumble down.[6]

The snows which had so long protected these lofty upheaved plateaux, became, directly they were converted into glaciers, one of the most active causes of their ruin. But it is deeply interesting to examine how the process of ruin was effected—how it must have gradually produced the now existing appearance of the mountains, and formed the numerous valleys secondary and tertiary, the amphitheatres, the hollows and certain glacier ravines.

What has just been said is sufficient to explain how the rocks are disintegrated according to the nature of their formation. When an upheaved mass consists of protogine or granite, it presents in its primitive aspect a mammillated surface. (See Figures 2 and 4.)

When that mass consists of crystalline schists, or gneiss, the outer surface presents great faults—assemblages of rhombohedrons—rents, because the mass has been upheaved and broken, but is not

[6] And so it happens:—the slightest terrestrial movement—an earthquake scarcely perceptible—sometimes causes the fall of prodigious masses of these slopes. And this phenomenon must have occurred very often formerly, when the slopes were more exposed and terrestrial commotions were frequent.

eruptive, as are the granites, syenites, protogines, and porphyries.

First let us see how at certain places the crystalline schists and gneiss which surround the dominant plateau of Mont Blanc are disintegrated.

Figure 34 presents the section of an upheaved mass of gneiss; the lines approaching the vertical giving the stratification, and the lines cutting these obliquely, the planes of contraction forming rhombohedrons.

The rhombohedrons *a*, are successively disintegrated, then those marked *b*; and the slope A D is

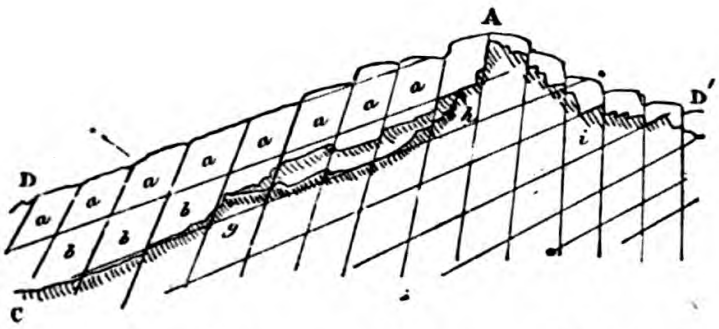


Fig. 34.—Disintegration of the Crystalline Schists.

reduced to the section A C. At intervals, according to the altitude of the summit A, and the greater or less hardness of the rock, basins *g h* are formed,—beds of lateral glaciers. The disintegration of the mass on the slope A D′ cannot proceed in the same manner; it is necessarily more broken—the unequally hard strata are more or less eaten away. And at *i* are hollowed out a kind of basins in the direction of the strata—long and narrow—which when the glaciers have disappeared, will form the beds of mountain tarns.

This diagram gives the section of the Brévent

chain, whose aspect taken from the top of the Grands Mulets,[7] is given in Figure 34 *bis*. This view exhibits the faces of the great disintegrated rhombohedrons, and the beds D of the ancient lateral glaciers, marked in section in Figure 34. At E is seen the base of the great cone of dejection, produced by the ruins of the upper slopes of the Brévent, and by the recurring spring avalanches. It is in fact only by taking up a position on elevated points at a great

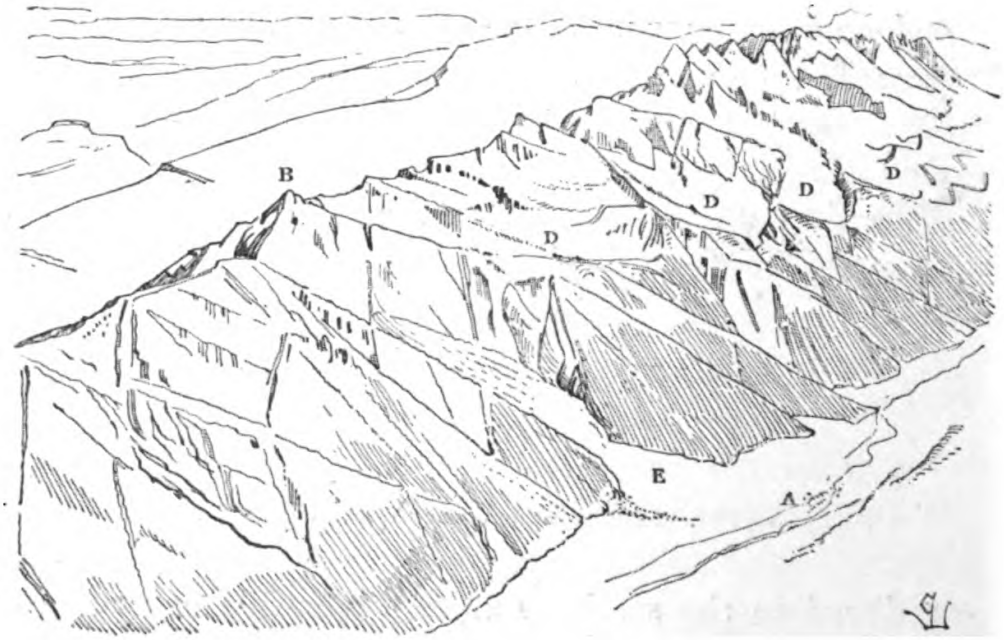


Fig. 34 *bis*.—The Range of the Brévent.

distance that we can appreciate the general configuration of these crystalline formations. In a near view the details assume such importance as to prevent us from appreciating the masses. For instance: What is this summit of the Brévent B, seen from a point more than 3000 feet above its level, and

[7] A is the village of Chamonix, B the summit of the Brévent, C the Aiguilles Rouges.

at that distance? A barely perceptible prominence; and yet when we approach that point, it presents a formidable escarpment.

Let us now examine how the upheaved eruptive mass of the protogine of Mont Blanc has suffered dilapidation.

Long protected by the casing of crystalline schists the protogine of Mont Blanc could not be materially acted upon until these schists themselves had undergone the disintegrations of which we have just seen an example.

In consequence of the height at which it emerged from its casing, the upheaved protogine could only be affected by the névés, and they could have no action on this mammillated plateau. It was at its base therefore that the plateau would be acted upon, and when the crystalline schists had by their disintegration exposed the lower part of the protogine.

But the protogine, being much more homogeneous than are the crystalline schists, in spite of the numerous fissures of contraction which traverse it, did not present the soft or incompact strata or the argillaceous and micaceous constituents of the gneiss. All its parts possess an equal or nearly equal hardness—an identical crystallization; but as was said above, the great surfaces of contraction form a crust of greater hardness than the interior, and the quartz crystals which coat them increase this hardness.

When the encasing crystalline schists were, as shown above, sufficiently disintegrated to lay bare the lateral surfaces of the mammillated plateau of the protogine, the margins of this plateau presented the appearance shown at A, Fig. 35. The névés then left uncovered the surfaces approaching the vertical;

and the projecting parts of the lobes were more exposed to the effects of weather than the more retiring

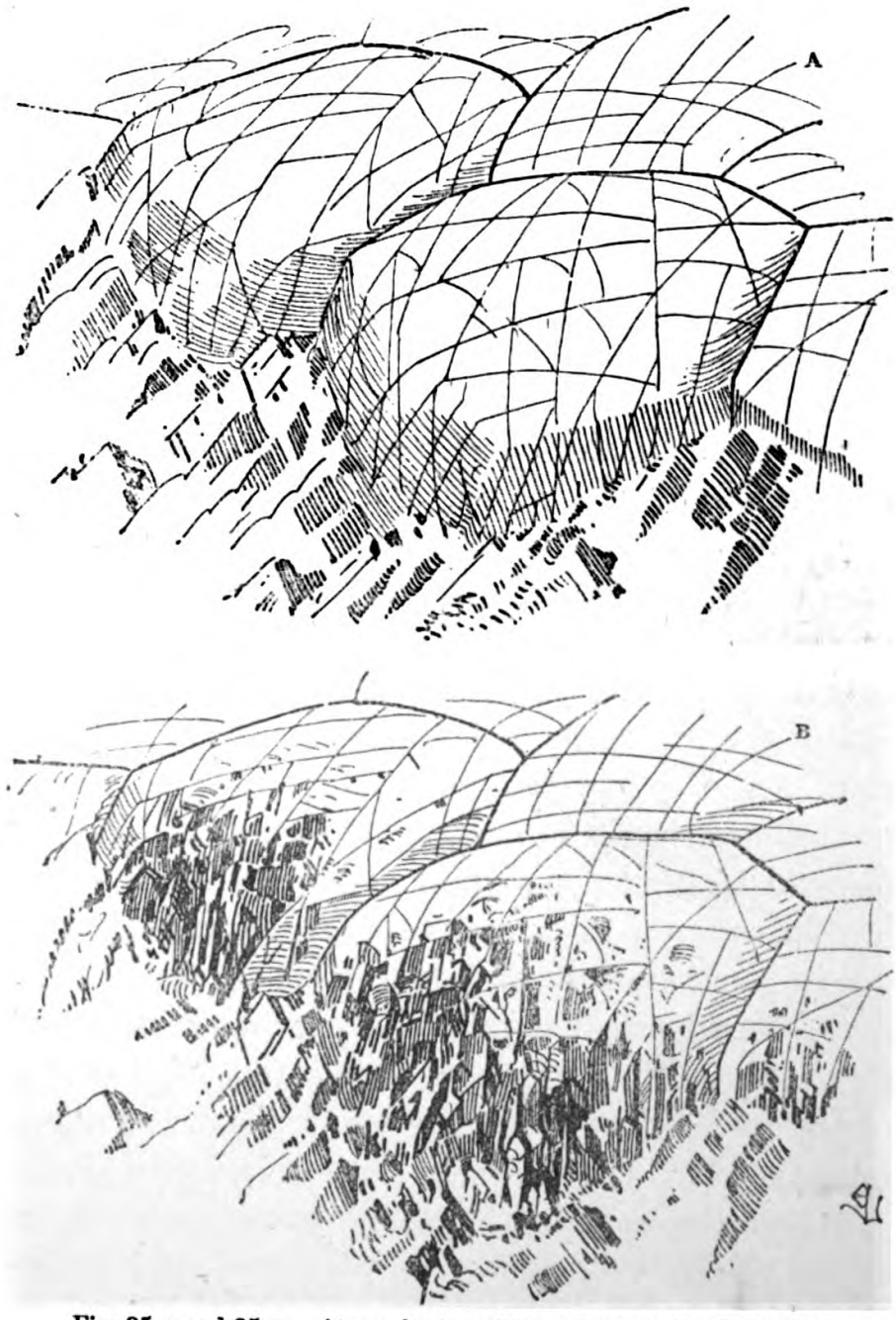


Fig. 35 A and 35 B.—Atmospheric and Ice Action on the Protogine.

planes of contraction and the surfaces approaching the horizontal could have been. Then, making its

way into the fissures which intersected these great agglomerations of crystals,—fissures more numerous at the centre of the masses separated by the great planes of contraction than along those planes,—the frozen water began its work of destruction, and these surfaces were ruined in the manner shown at B.[8] Eventually these mammiform protuberances were thus eaten away more deeply towards their centre than on the walls of contraction, and left the great

Fig. 36.—Result of Atmospheric and Ice Action on the Protogine.

crystals contiguous to those walls projecting, so that they formed ridges, and their junction, summits,[9]

[8] This phenomenon still occurs along the rocks of la Côte, called also Murs de la Côte, beneath the summit of Mont Blanc. The upper surface, covered by the névé presents a mammillated convexity, and the ruin of the vertical face is continually going on under the action of the frost. (See Fig. 42).

[9] The dotted lines show the ancient meeting lines of the great polygons marked on the previous figure.

Fig. 36 and the intermediate parts, combes, or hollows wherein were accumulated the névés, which, descending more rapidly in their under parts, composed partial glaciers; these continued to ruin the lower slopes, widened their beds, overturned the abrupt obstacles that opposed their flow, and during a long period supplied affluents to the trunk glacier.

When, through insufficient supply, or from atmospheric causes, the ablation of the trunk glacier was complete, these secondary glaciers still continued their work for many ages, successively hollowing out all those broad polygons; until the entire plateau presented a surface consisting only of ridges separated by concavities, in lieu of convexities united by furrows (planes of contraction).

In order to render still more evident the mode in which these crystalline rocks were disintegrated, we give, Fig. 36 *bis*, four successive stages of ruin of an upheaved crystalline mass A, showing at a glance how the upheaved masses have changed in aspect much more than in height, how and by what cause the extreme summits are, if I may use the expression, sharpened by the destruction and clearing out of the plane or convex areas which connected them; how the frosts disintegrated these crystals, how the masses of ice bore away the débris to a distance, how they scooped out and rasped down beds to make themselves room, and how after this long continued labour, above these ice masses and névés, stood out pointed summits, jagged ridges, and projecting spurs.

At the present day we observe many summits which present an aspect similar to the sketch B. The glaciers and even the continuous névés have disappeared; but they have done their work, and these

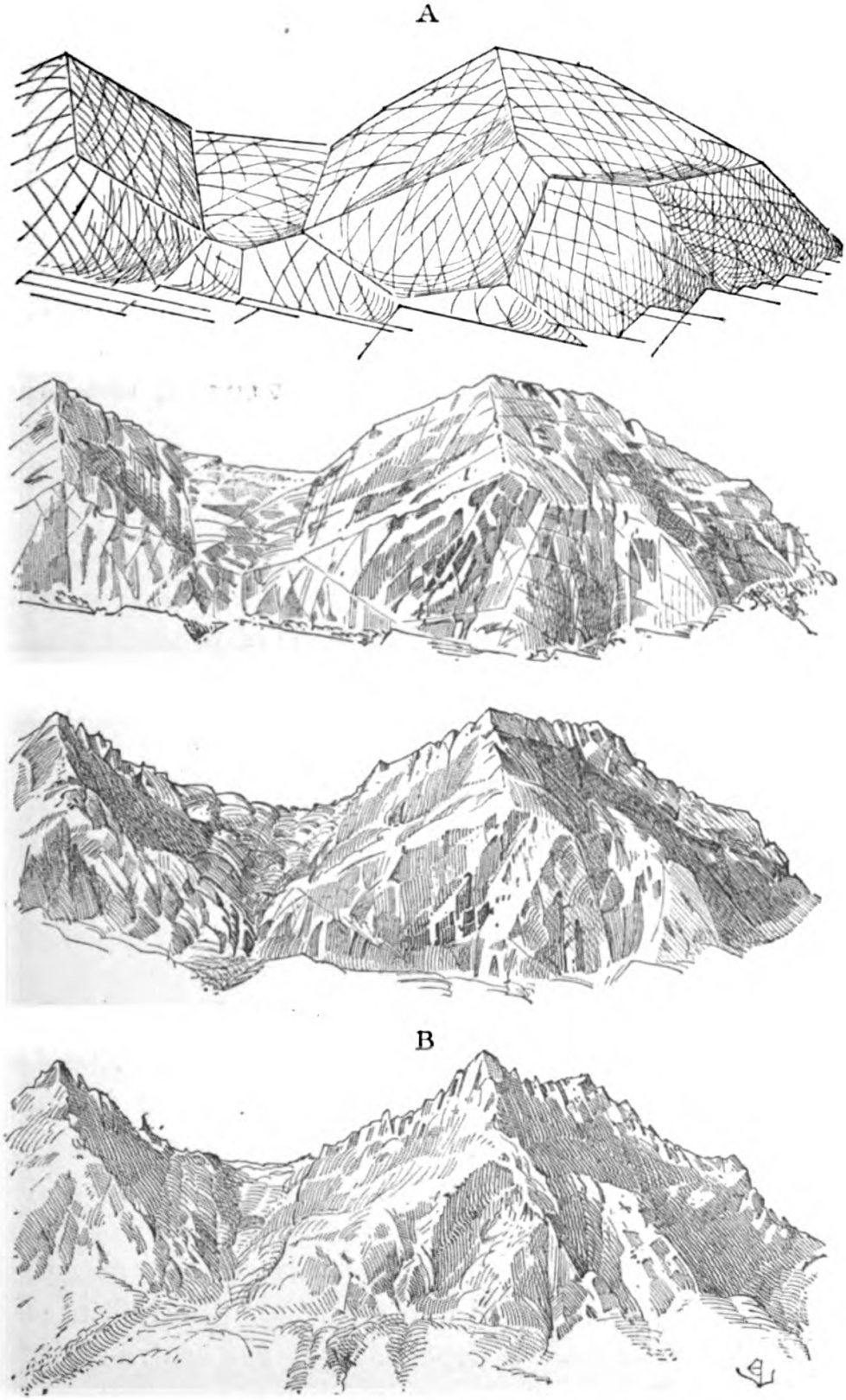


Fig. 36 *bis*.—Disintegration of the Crystalline Rocks.

skeletons enable us to restore in idea the primitive mass.

Thus the wide protogine plateau of Mont Blanc now presents to the view only prisms, pyramids, and aiguilles connected by ridges more or less ruined rising out of valleys and concavities filled with névés and ice.

It is not without a kind of awe that we endeavour to compute the ages that must have elapsed to effect these results. But Nature does not count; she has eternity to work in.

It is not enough to give a theoretical view of the way in which rocks are thus ruined; we must bring proofs; and as Nature always employs the same means, as she constantly follows the same course, we may even now observe her methods of procedure on a reduced scale.

Ice has been the chief agent in the great operation of shaping the slopes on the mountain masses. Ice has brought this chaos into regular form, broken down the obstructing barriers, eroded the too abrupt declivities, and widened the depressions. In their turn the torrential currents continued and completed the work.

Figs. 36 and 36 *bis* are of a general character, and do not represent any particular part of Mont Blanc. We shall see that the phenomena observed *in situ* will render evident this mode of disintegration.

Let us take as an example the glacier de Talèfre, which offers one of the most characteristic of the upper and interior amphitheatres of the massif. It has been shown, Fig. 4, that the upheaved mass of protogine had a depression in the centre of its widest part.

The great crystalline masses therefore presented a surface declining from the north and from the south towards this depressed centre. Here, Fig. 37, we see the position of the summits and ridges that surround the glacier de Talèfre, whose issue sunk out between K and I is turned towards the middle of the plateau.

A is the Aiguille Verte . .	height	13,540	feet.
B the summit of les Droites .	„	13,220	„
C the summit of les Courtes .	„	12,510	„
D other summit of les Courtes .	„	12,650	„
a the Tour des Courtes . .	„	12,110	„
E the Aiguille du Triolet . .	„	12,730	„
F the little Aiguille de Talèfre .	„	11,960	„
G the great Aiguille de Talèfre .	„	12,290	„
H	„	10,990	„
I the Aiguille de Beranger . .	„	9,650	„
K the Aiguille du Moine . .	„	11,212	„
L	„	11,245	„
M the Aiguille du Drû . .	„	12,515	„
O le Jardin (higher part) . .	„	9,830	„

We perceive that these summits become lower towards the south and rise towards the north. They are placed on the same line or connected by ridges rising nearly to their altitude. There is reason to suppose that this great polygon was divided by a plane of contraction connecting the parts D and H, for we perceive a very prominent ridge emerging from the névé, descending from the summit D in the direction of the summit H; moreover the angle *p r s* forms a shelf, and the point *o* juts out from amid the ice.

The line of the plane of junction K I being that which was at the lowest level, and the surface of the protogine E being very depressed, it was in that

direction that the ice took its course to join the Mer de Glace by a long détour.[1]

It is clear therefore that the interior glacier de Talèfre was not able to begin its work and to make its way out until after the bed of the Mer de Glace had been traced out through the ruins of the depressed part of the massif, the surface of the polygon R has been disintegrated by the glacier de

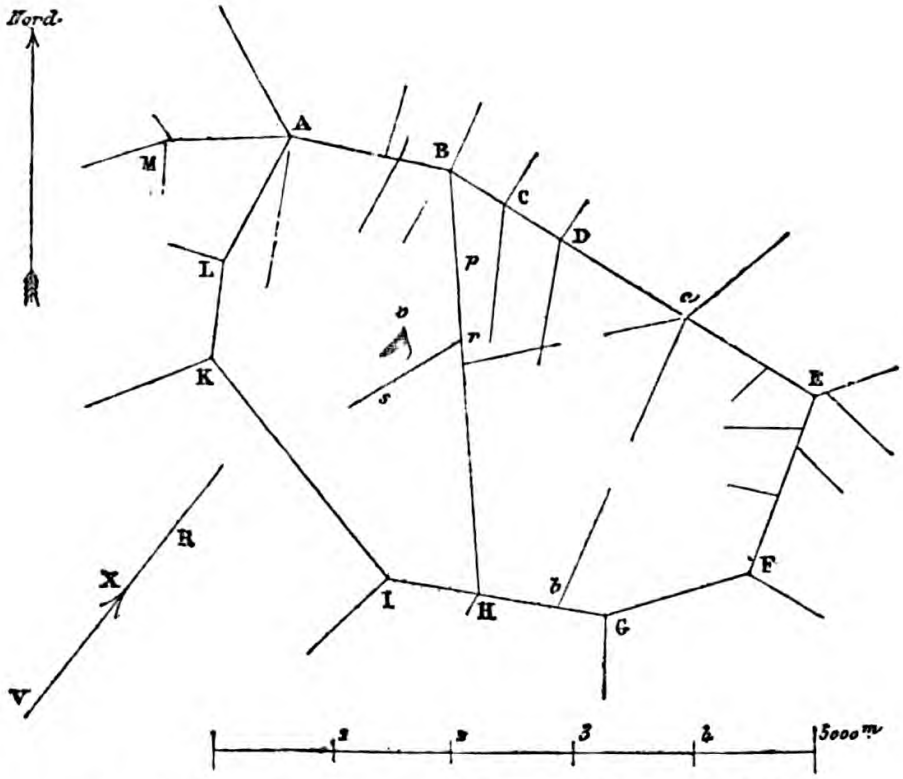


Fig. 37.—Planes of contraction of the amphitheatre de Talèfre.

Leschaux, and the plane of contraction K I was in its turn exposed to the action of the weather.

Here, we see the aspect now presented by this glacier de Talèfre from the summit of Mont Blanc, Fig. 38; the view being in the direction of the line

[1] See the general map.

V X of the preceding figure—that is, almost perpendicular to the line K I. It must be observed that the protogine is absent on a part of this line K I, and that beneath the summit I of the Aiguille de Béranger appear laminated rocks of a mixed nature.[2] Besides a depression between these two peaks K E, the material was therefore characterized by a tendency to yield, and there was a cause of rupture.

These modifications in the configuration of the mass of protogine which composes the culminating parts of Mont Blanc are to be found over the whole extent of the "massif," and are manifested as clearly

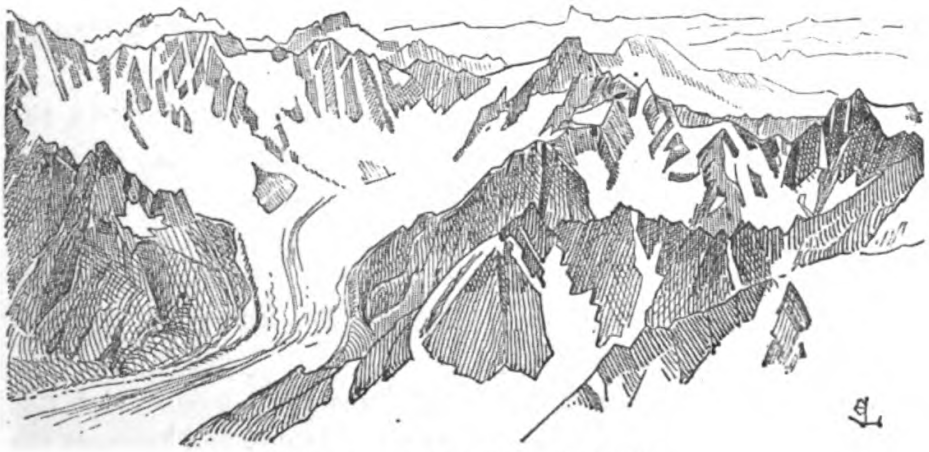


Fig. 38.—The Glacier de Talèfre.

in the details as in the whole; or rather each part of the rock decomposes, and is destroyed in accordance with the laws in action on the grand scale.

In fact, when we examine one of these rocks, we perceive that it is split by planes of contraction, that these planes are harder than the middle parts, and

[2] Schistose protogine with molybdo-sulphuret. (*Payot, Catalogue des Roches du Mont Blanc.*)

that the small polyhedrons disintegrate in the same manner as the large ones, which in fact are nothing more than an assemblage of small ones.

We observe besides, that these polyhedrons are not all equally hard, although in juxtaposition. Some resist atmospheric agencies better than others, present a more felspathic or a more quartzose crystallization, contain hyaline corundum, titanium, iron, talc, laminæ of serpentine, and of black mica, and resist or disintegrate in proportion to the toughness or feebleness resulting from the presence of various substances.[3]

[3] The various kinds of protogine observed on the elevated parts of the "massif" of Mont Blanc are, according to M. V. Payot, as follows :—

White protogine with gold-like spangles of titanium in the cavities of the rock ; also containing anatase, greenish white epidote, and grey orthoclase felspar of a coarse cellular texture (very durable, Aiguille de Charmoz).

Greenish protogine: quartz and felspar of a pale green, talc of a dark green (moderately durable); neighbourhood of the culminating parts of Mont Blanc.

Red protogine, whose orthoclase felspar has a pale scarlet tint (very durable; found at the Envers de Blaitière, and towards the bottom of the Mer de Glace).

Corundum protogine: of a beautiful appearance, interspersed with numerous crystals of hyaline corundum, cloudy sapphire, as also with greenish or thallitic epidote (very durable, found over nearly the whole extent of the "massif").

Ferruginous protogine, corroded, granular; the crystals of nacreous oligoclase, are pale yellow (not very durable, easily disintegrated; found on the declivities of the Aiguille Verte, eastern slope).

Grey protogine, yellowish white talc, brown felspar, dirty coloured quartz (easily crumbles, found in many places.)

Greenish yellow protogine; yellowish orthoclase felspar, smoky quartz, greenish chloritic talc (of moderate durability; found at

There existed therefore, when crystallization took place, affinity by groups, so that beside a polyhedron of red protogine we find one or several of grey or greenish protogine. Generally the harder protogines constitute the summits and ridges, and the less resisting the intermediate portions; whence, in accordance with what was said above, we might conclude that the crystallization of the more homogeneous parts along the planes of contraction took place with greater energy, allowing the intermediate matter to crystallize in its turn, but under con-

the base of the Aiguille du Drû, the Aiguille de l'Argentière, and the slopes of the Petites Jorasses).

Gneissic protogine; with numerous spots of chlorite and mingled with stratified serpentine (decomposes by layers: frequently found on the Italian slopes).

Talcose protogine; with large hemitrope crystals of orthoclase felspar, yellowish white (of moderate durability; forms a zone along the crystalline schists from the Aiguille du Midi to that of l'Argentière).

Protogine of rosy yellow quartz and felspar with here and there scales of black mica (durable; aiguille du Midi, du Plan, de Blaitière, de l'Argentière, and du Tour).

Olive-grey protogine, or of a livid greenish yellow (easily disintegrated, contains iron; found in the aiguilles above the right margin of the glacier de l'Argentière).

Talcose protogine; talc in abundance, dark and compact (of indifferent durability; base of Mont Maudit).

Yellow talcose protogine of la Griaz (of indifferent durability; from the Aiguille du Drû and de l'Argentière).

Granular protogine, of very fine grain, passing into leptinite, with green talc and white felspar (very durable, from the Grandes Jorasses).

Protogine du Geant, with greenish talc, yellow quartz and felspar, in very small grains (very durable).

We are glad to testify here to the exactness of the observations of the conscientious geologist of Chamonix.

ditions of heterogeneity which rendered it less solid.

If, for instance, we examine the summit of the Aiguille du Chardonnet, Fig. 39,[4] we see how the ruin was effected; how hollows were formed, on the small scale, resulting from crumbling between the former parts, just as the effect was produced on the grand scale in the previous figure; how the ridges

Fig. 39.—Summit of the Aiguille du Chardonnet.

remained, exhibiting intact the faces of the polyhedrons, as also sometimes the section, the mutilated stock emerging from the névé of those that have been broken, overturned, and borne away.[5]

[4] Taken by means of the teleiconograph (enlarging six times) beneath the last of the Aiguilles Rouges, above the Col des Montets.

[5] See also Fig. 29, which shows sections of broken polyhedrons.

If we observe the Aiguille Verte, Fig. 40,[6] we see the two great planes of contraction, A, B, C, D, and the Aiguille du Drû at E, whose face F presents curvatures concentric with the section F B. Taking the same aiguille from the south-west, opposite,[7] Fig. 40 *bis*, the Aiguille du Drû presenting itself at A, and the Aiguille Verte at B, the line C D giving the separating plane of contraction of the two great mammiform masses,—we see another example

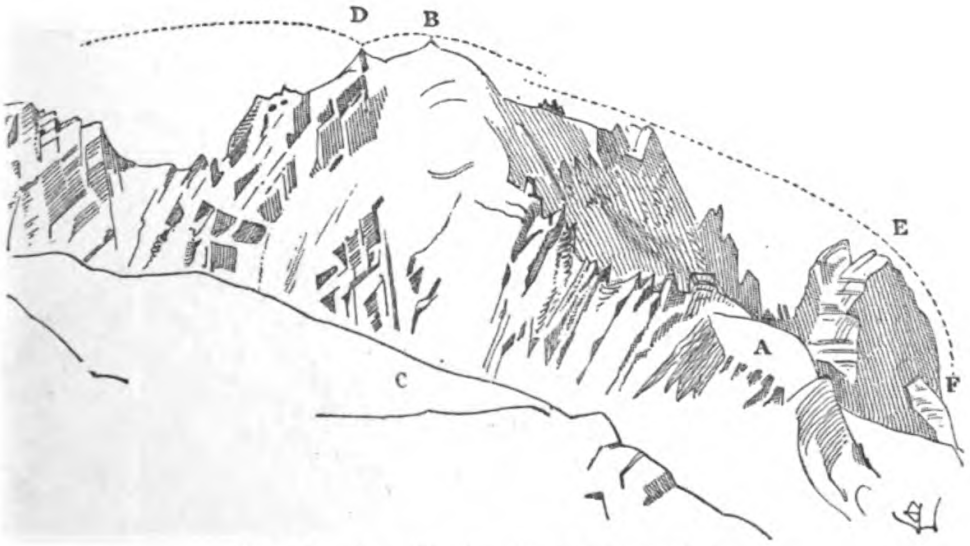


Fig. 40.—The Aiguilles Verte and du Drû.

of how the ruin was effected, only the most durable of the aiguilles being left standing in the neighbourhood of the secondary planes of contraction.[8]

If we again observe the same Aiguille Verte from the Lacs Blancs, below the Aiguilles Rouges, that is, from a point of sight at right angles to the first

[6] Taken from the Croix de Fer, above the Col de Balme.

[7] From the bottom of the glaciers des Pelerins.

[8] See the general map.

two,[9] Fig. 40 *ter;* the Aiguille du Drû being at A, the Aiguille Verte at B, and the plane of junction being at G B, we have a similar view of the method in which the ruin was effected, the hardest of the polyhedrons being left standing, on the principal and secondary planes of contraction.

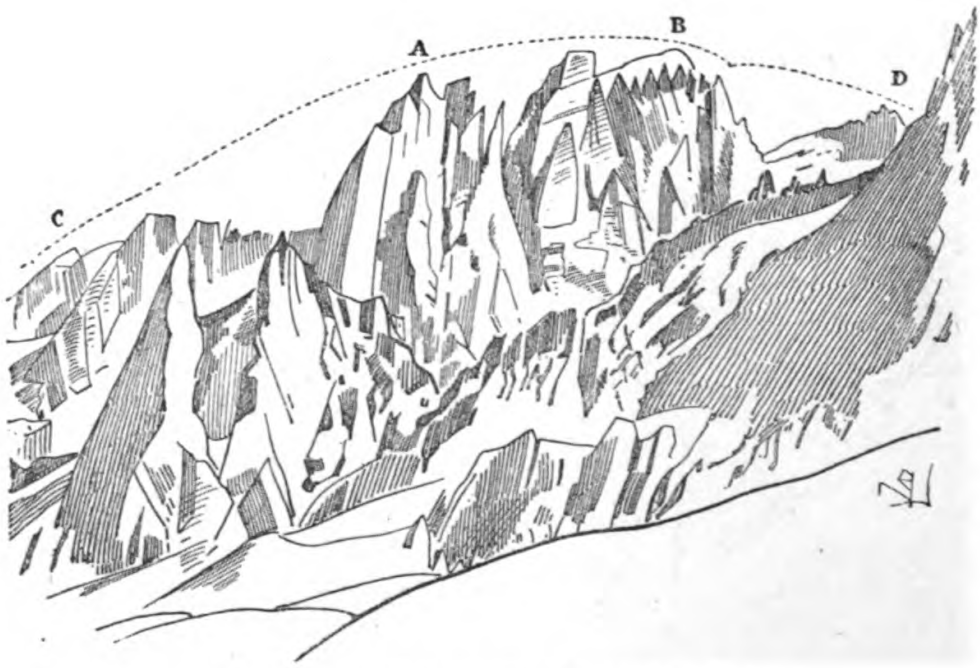


Fig. 40 *bis.*—The Aiguilles Verte and du Drû.

But, as we approach the top of Mont Blanc, the disintegration is less advanced—less thorough—which clearly proves that the mountain masses were attacked first at the base, and that the ruin reached the summits in proportion as the glaciers were lowered; when the névés, more readily cleared, gradually laid bare the slopes.

[9] At the north-west of the Aiguille Verte.

We have, in Fig. 41, the top of Mont Maudit, taken from Plan-Praz by means of the teleiconograph.[1]

The dotted line shows the part disintegrated. Following the line of descent from A and from B, we see the two planes of contraction with their fine

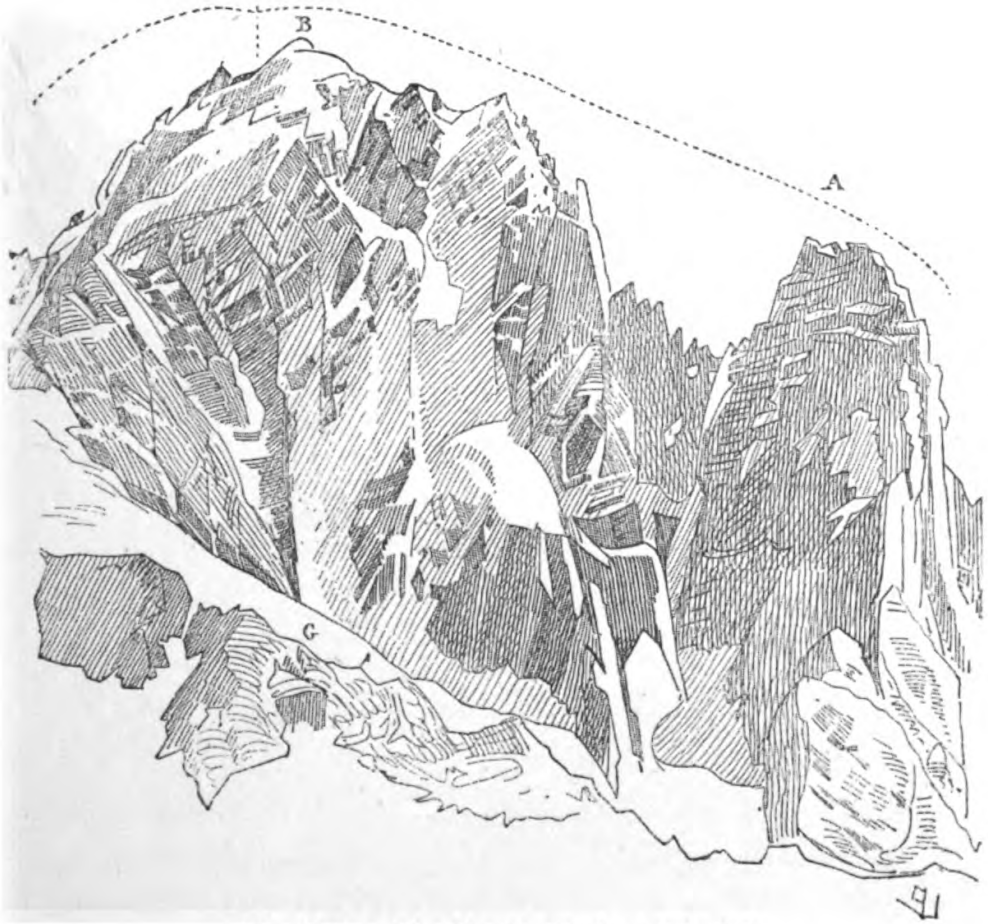


Fig. 40 *ter*.—The Aiguilles Verte and du Drû.

crystalline groups emerging from the névés and forming arêtes. At C are seen the remains of the curvature of the mammiform mass B C, which was connected with the Mur de la Côte. If we mount

[1] Enlarging four times.

still higher, and approach this Mur de la Côte and the Rochers Rouges, the mammillated upper surface

Fig. 41.—Top of Mont Maudit.

is still visible, and the rock is disintegrated exactly as shown in Fig. 35.

The drawing, Fig. 42, made with the aid of the teleiconograph, from Plan-Praz,[2] and giving the Rochers Rouges, R, and the Mur de la Côte, C, clearly explains the way in which the mammiform masses were thus disintegrated on the flanks. A considerable depression of the mass at A, at the bottom of which névés are formed, laid bare the face of the mammiform mass B. Exposed to the action of sun and frost, the latter is constantly disintegrating, and will thus be reduced to the plane of junction of

Fig. 42.—The rocks of la Côte.

this mammillated mass, with that which forms the very summit of Mont Blanc, a junction which is now concealed beneath the snows.

In the structure of the protogine therefore, the snows and ice found the conditions of destruction which allowed of the storage of those accumulations of water in the frozen state, in amphitheatres, hollows, ravines, and fissures as the disintegration proceeded.

[2] Enlarging four times.

But in proportion as the 'massif' was suffering dilapidation by atmospheric agencies, avalanches of snow or névés, and by the ice itself, the more separated were the reservoirs and beds formed by the glaciers, and the more were the causes of their ablation augmented. While the altitude of the summits was then nearly equal to that of the different culminating points of the 'massif,' the latter, instead of presenting an undulating surface, was being hollowed out in its least resisting parts, and gradually forming cavities where plane or convex surfaces had existed; and sharp ridges and peaks where there had been lines of planes of contraction scarcely apparent on the primitive surface of the upheaved mass.

The névés were descending with constantly increasing rapidity from the elevated amphitheatres, bearing down with them the dislocated masses. The glaciers having broken through the dikes which hindered their passage, forced a way down to the lower valleys, and flowing away, left the precipices bare, thus subjecting them to the action of frost, and hastening the general ruin. The sun warmed these denuded rocks, and the radiation tended proportionately to thaw the ice existing between them.

We must, however, also examine how the crystalline schists were disintegrated. Their structure, being much more determinately stratified than that of the protogine, their laminated character, their absence of homogeneity, and their crystallization often incomplete and heterogeneous, would cause them to be disintegrated in a manner different from that of the latter rock.

Besides planes of stratification, the gneiss and crystalline schists present, as shown in Fig. 34, oblique planes of contraction which convert the mass into an agglomeration of rhombohedrons, Fig. 43. We have here a normal structure, which is often disturbed by flexures and curvings of the stratified rock, and which was still pliant at the date

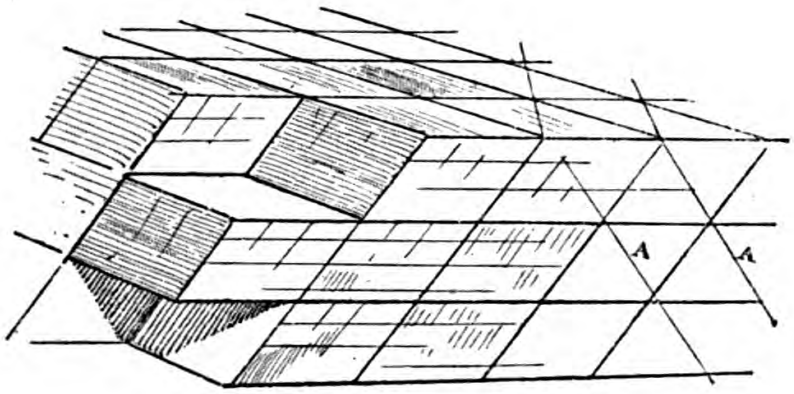


Fig. 43.—Stratification of the Crystalline Schists.

of the great upheavals. Sometimes the planes of contraction intersect again, as seen at A. These rhombohedrons are of considerable dimensions, or very small, according to the state of the materials when cooling and crystallizing. Moreover, as just remarked, the strata exhibit great differences in point of hardness. Occasionally also, the mass presents abnormal crystals, and the most confused interpenetrations of polyhedrons; and veins of protogine, porphyry, serpentine and granite, injected through the fissures of the mass. Gneiss and the crystalline schists therefore, are liable to disintegration from the very irregularity of their constitution.

The forces of upheaval and contraction which raised the crystalline schists from the depths they occupied, to the level at which we see them now, on the acclivities of Mont Blanc, on the Brévent range, and the Aiguilles Rouges, produced marked irregularities in the strata—faults and ruptures that have not a little contributed to hasten the ruin of the slope. When the great trunk glacier, which at the height of the glacial epoch filled the valley of Chamonix, and rose to a height of more than 3000 feet above the level of the village of Chamonix, was lowered, the lateral glaciers began their work of destruction on the slope of the Brévent, and the Aiguilles Rouges (see Figs. 34 and 34 *bis*). But there, the form of the upheaved mass which only presented a ridge, in lieu of a plateau, did not favour the hollowing out of interior valleys, as did the massif of Mont Blanc itself.

Some few evidences of the former state of things remained amid the immense clearing away of materials which these lateral glaciers effected, and whose well-marked beds we still see from Plan-Praz to the Col des Montets.

At the two extremities of the massif itself, viz.:—in the neighbourhood of St. Gervais, on the south-west, and of Catogne, on the north-east, the crystalline schists raised nearly to the level of the upheaved protogine, form as it were two outer buttresses that maintain the great axes (see Fig. 12). These crystalline schists are remarkably firm in structure on the south-west side, which is the highest; less firm on the north-east side—the lowest—where they no longer appear in such great mass,

and were unable to force their way with such energy through the liassic deposits.

The crystalline schists which form the Aiguille du Gouté and Bionnassay, and which extend as far as the Col du Bonhomme, offered a more powerful resistance to atmospheric agencies than the protogine itself, and were disintegrated more slowly. However, the structure of these schists being such as we have described, the disintegration takes place in accordance with the character of that structure; i.e. the upheaved rhombohedrons suffer dilapidation in their least resisting parts, and are sometimes entirely carried away.

There will then remain in place of the rhombohedron that has disappeared, a hollow occupied by the névé.

The upheaved mass of crystalline schists in this quarter would not present the characteristics of the protogine, but on the contrary, acute ridges or pretty sharp peaks, which must have been rapidly acted on by atmospheric agencies, since the snows could not cover them to the same extent with a dense coating.

We observed, Figs. 1 and 11, that the junction of the crystalline schists with the protogine, in the neighbourhood of the vale of Chamonix, presents a vertical plane, nearly parallel to the great axis of upheaval. Descending to the valley from the line of junction, we remark the schistose strata tending to present a fan-like inclination, as indicated in Fig. 44. What aspect would the fracture of the crystalline schists and gneiss A B, and the micaceous schists A C, present, at the epoch of upheaval?

We can only form conjectures on this point. The material thrust back and folded was insufficient to form a continuous arch above the protogine. It must necessarily have been rent, to allow the latter to pass. But since these schists must have still preserved at that epoch, a condition of softness and pliancy which allowed them to bend—as, in fact, happened at many points—the fracture C, A, B, could present only an irregular aspect. Whatever may have been the case, the cracks occasioned by contraction intersecting the stratification of the crystalline schists, arranged themselves as if the matter

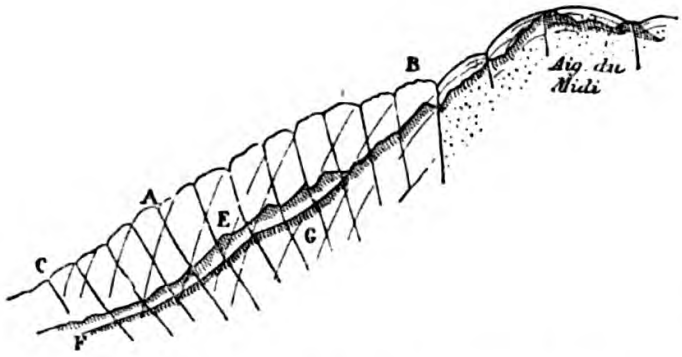


Fig. 44.—Junction of the Crystalline Schists with the Protogine.

had been in its normal state, and formed immense rhombohedrons composed of a multitude of others;[3] and the dilapidation took place in accordance with this structure; i. e., the rhombohedrons resisted or

[3] We use the term *stratified* here in reference to gneiss and crystalline schists, though the examination of these rocks leaves doubt in many respects as to its propriety, and the supposed stratifications may often be regarded as planes of contraction. This limitation which we have observed in relation to the protogine would be less absolute as respecting the gneiss and crystalline schists.

yielded in proportion to the degree of hardness, or the favourable or unfavourable position they occupied in respect to the protogine.

In parts where the protogine withstood and resisted destruction, in the way remarked above, the crystalline schists, being protected, were also preserved.

In those parts where the protogine, disintegrated by the névés and atmospheric agencies, allowed a glacial current to pass, the schists were borne down and disappeared. At many points, however, they long resisted, either because their texture was particularly tenacious, or because the material was harder. Between the beds of the glaciers there remained ridges which were themselves greatly dilapidated, but which, nevertheless, rose above the surface of the great lateral currents, like hills, as seen at E, F, G, which gives the section of the bed of these lateral glaciers. All the part C, A, B, E, of the crystalline schists, whose surface section we cannot exactly estimate at the epoch of upheaval, was successively swept away, first at C A, by the great trunk glacier, then from A to B, by the work of the lateral glaciers. In accordance with what was said above, the degradation of the slopes had begun from below, i. e. from C to A, and had then been gradually extended to the summits.

The ruins of these crystalline schists, and of the gneiss, however, have not taken the pyramidal or prismatic appearance—sometimes presenting sharp and very peculiarly jagged outlines—of the protogine; they present on the contrary a geometric regularity which results from the structure. It is especially at a great distance, and from elevated points, that we

are struck with the regular aspect of these dilapidated masses.

The aspect of the massif of Mont Blanc, for instance, taken from the signal above the Col de Balme, is faithfully represented in Fig. 45. The crystalline schists, encasing the protogine, follow a line which passes through the letters *a*, *b*, *c*, *e*; s being the summit of Mont Blanc, *e* the Dome du Goûté, and *f* the Aiguille du Goûté. On all the acclivities formed by the gneiss rocks we observe

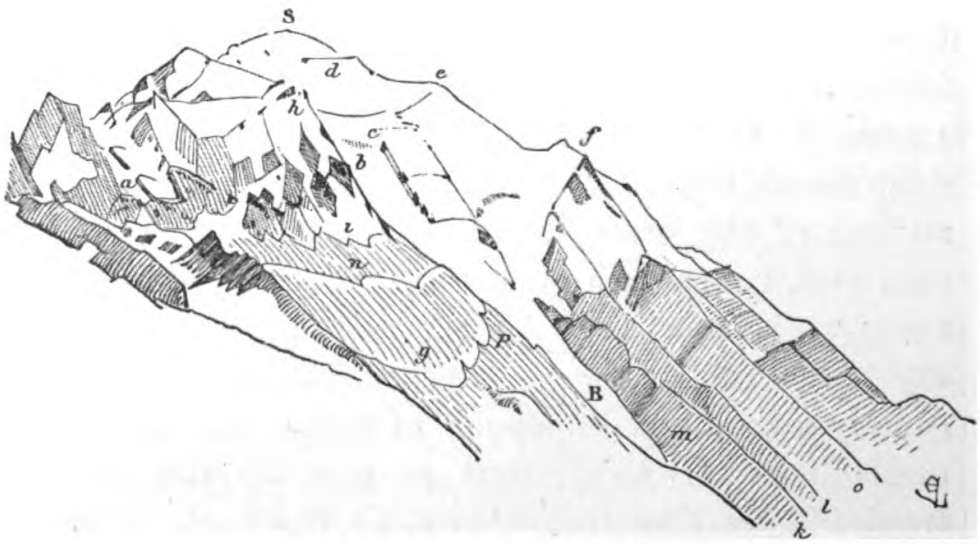


Fig. 45.—The summit of Mont Blanc.

rhombuses regularly arranged, and the elevations *k*, *l*, *o*, standing up between the lateral glaciers, of which Fig. 44 gives the section.

As compared with the gneiss, we observe that the protogine presents an irregular, disjointed aspect ;[4]

[4] The space *g* marks the bed of the great lateral glacier which existed at the base of the Aiguilles du Midi, du Plan, and de Blaitière, at the close of the glacial epoch; *n*, a stage of retreat in this glacier; *i*, the modern glacier des Pélerins.

defects of parallelism not seen in the crystalline schists; which, when pure, offer a powerful resistance to dislocation, and do not exhibit those accumulations of piled up blocks, disjointed and tottering, which characterize the summits of the protogine.

When, however, these encasing rocks composed of crystalline schists were subjected to the action of ice, but especially to atmospheric action, and when their levelled down slopes laid bare the mass of protogine, time attacked the latter energetically, and produced the disintegrated condition it now presents. Fig. 45 shows how the immense deposits of névés accumulated on the slopes north of the summit of Mont Blanc, and which extend from the Aiguille du Midi, *h*, to the Aiguille du Goûté, *f*, made their way at B [5] into the valley.

On this line deep fractures had been produced in the mass of the gneiss, caused by the general upheaval.[6] The ice therefore found weak points in this part of the declivity of the massif, broke down the obstacles and descended in a straight line into the trunk glacier, leaving as banks the Aiguille du Midi, and the Aiguille du Goûté, the Montagne de la Côte, *m* and the slopes of the Pierre Pointue, *p*. The Aiguille du Midi, of which the entire upper part consists of protogine, is constantly disintegrating; the Aiguille du Goûté, composed of crystalline schists, does not appear to be undergoing any alteration, and preserves its arêtes intact.

[5] Glacier des Bossons.

[6] One of these fractures is still very manifest, extending from the Pierre à l'Echelle to the moraine on the right hand at the bottom of the glacier des Bossons.

'But the encasing crystalline schists on the north-western slopes of the massif, did not allow the ice at all points to find a direct passage. While the steepness of the declivity opposite Mont Blanc favoured a direct discharge, the breadth of the massif opposite le Tacul and le Géant and the slight relative incline enabled the gneiss to present dikes which the glacier currents had difficulty in passing, which they could not entirely sweep away, but in a fault in which they ultimately made themselves a narrow bed. Such is the Mer de Glace at the part where it takes the name of glacier des Bois, and such also is the glacier de l'Argentière at its lower part.

It will be observed that the Mer de Glace[7] must have been long obstructed by the upheaved mass of gneiss which joined the Aiguille de Bochard to Montenvers and la Filiaz, that it reached an altitude of 6600 feet,[8] and that only with difficulty, taking advantage of a fracture, of which traces are found below the Chapeau,[9] the current bore down the rocks and made itself a bed; while it descended into the valley only by making a decided bend towards the west. The same phenomenon occurred at the glacier de l'Argentière; after having taken a direct course from south-east to north-west the current was compelled by

7 See the general map.

8 Altitude of Montenvers 6340 feet, the glacial currents exceeded this level by more than 300 yards.

9 In fact at the base of the Aiguille de Bochard we observe lias and nodules, whose presence indicates an inversion of the crystalline schists at this point, and consequently stratum of slightly resisting nature, which have been in great part carried away by the glacier.

the arrangement and resisting force of the base of the gneiss, to make a sudden turn towards the west.

The tenacity of the gneiss, therefore, on the north-west part of the massif long offered a resistance to the trunk glacier; and when this had at last cleared out its bed, the gneiss formed banks which had to be laboriously cut through to make way for the glaciers descending at right angles to the trunk glacier from the summits of the massif. At that time these latter currents were only lateral currents —affluents. For many centuries their embouchures kept at an altitude of more than 6000 feet, i. e. at the level of the surface of the trunk glacier; and it was only after the ablation of the latter that those affluent glaciers suffered a lowering of their embouchures at the expense of the ancient banks, and with the disintegration of their rocky walls.

On the Italian side the narrowness of the valley, the abrupt escarpment of the protogine, the unresisting character of the encasing lias, and the almost entire absence of gneiss, produced very different results. The affluent glaciers, short and rapid, descended direct into the trunk glacier, hollowing out the slopes of the protogine to a great depth, and leaving extremely sharp aiguilles between the ravines thus formed.

Thus the summit of Mont Blanc, which on the Chamonix side is buttressed by those great spurs of crystalline schists, whose wide footing is shown in Fig. 45, rises on the Val Veni side, and on that of the Italian Val Ferret, from the very edge of the escarpment, Fig. 46.[1] The crystalline schists are

[1] View taken from above d'Entrèves, ascending towards the Col Ferret.

not found at the base of this escarpment, but only a belt of liassic deposits of no great depth and turned over. The protogine has therefore been very deeply disintegrated, not possessing here that solid base which encases it on the other slope. The aiguilles left as witnesses of its former extent are very greatly dilapidated on their exterior, whence blocks of all dimensions and a fine dust are being continually precipitated.[2]

Fig. 46.—The Glacier of la Brenva.

It is on this south-east flank that the destruction of the massif will be effected. The glaciers have begun by bearing down the parts offering least resistance. The more these are cleared away, the more exposed are its walls, the more powerful is the

[2] A is the posterior part visible of the summit of Mont Blanc; B, Peuteret and les Dames-Anglaises; C, the Monts de la Brenva; D, the glacier de la Brenva.

action of sun and frost upon them, and the more rapidly they are ruined. We observe at R the truncated remains which now emerge from the ice, of great crystal masses which formerly joined the Monts de la Brenva, C, with the Aiguilles des Dames-Anglaises and de Peuteret. Between these two ridges (de la Brenva and de la Peuteret) there was certainly a depression of the mass, but not such a deep hollowing out, since we see the base of the disintegrated crystal masses that intervened. The most homogeneous and firmest crystals in the neighbourhood of the great planes of contraction resisted destruction there, as they did everywhere else, while the mass that exhibited more fractures—that was less resisting—occupying the intermediate part, was swept away by the névés and ice, and then carried along in the form of sand and pebbles as far as the lower valleys.

We will return to the crystalline schists and gneiss whose ruin presents an altogether different aspect, and which, unless when there were fractures before the epoch of upheaval, are not scooped out so profoundly, and do not exhibit those striking relics —those vast and pointed aiguilles which were left by the protogine.

The more tenacious mass formed by the gneiss, after the superficial asperities had been disintegrated, formed a resisting block which cannot be easily attacked; the acclivities relatively gentle and accessible, are not hollowed out and are decomposed only at the surface.

The rhombohedric formation being evident, the sharp points, the upheaved ridges, would be disintegrated in the way shown in Fig. 47. A repre-

sents the mass of crystalline schists, as also of gneiss, in their intact condition.

The rhombohedrons *a*, which are the most exposed to atmospheric action, are altered so as ultimately to leave recesses bounded by the rhombohedrons *b*, and those behind *c*.

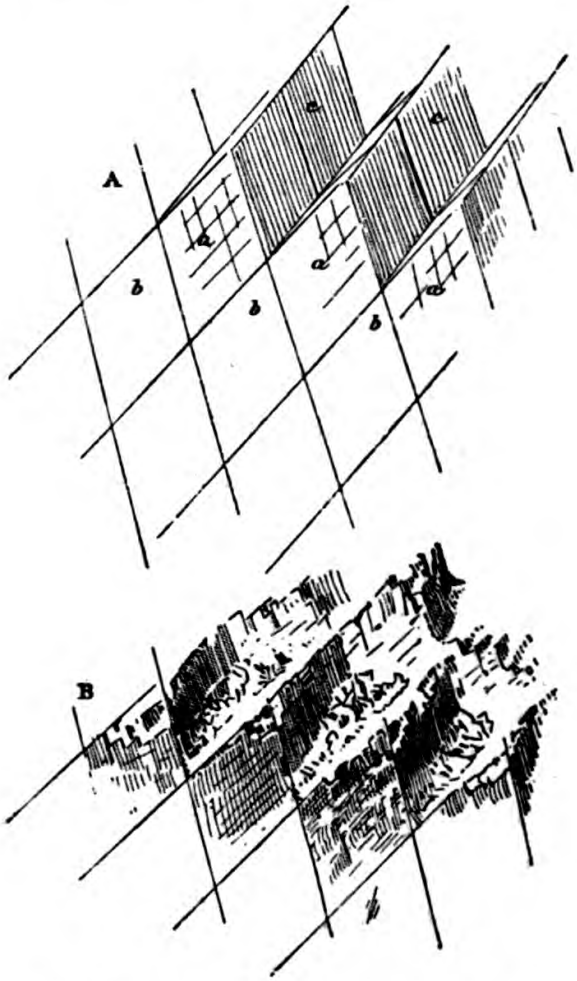


Fig. 47.—Disintegration of Rhombohedrons.

These recesses retain the débris of the rhombohedrons until the névés and ice sweep them away (see B). Then the rhombohedrons *c*, being exposed, are ruined in their turn, as also the rhombohedrons *b*. Gradually these crystalline masses are attacked,

though they always leave apparent a kind of *chair*, with arms and back, singularly adapted as a receptacle for the snows.

The decomposition of the schistose crystalline rocks which form the Montagne de la Côte, A, the Montagne des Jours, B, and the Montagne des Faus, C, Fig. 48,[3] buttresses which separate the glacier des Bossons from the glacier de Taconnaz, and the latter from the glacier de Bourgeat, shows

Fig. 48.—Crystalline Schists. The Mountain of la Côte, and those of les Jours and les Faus.

how the ridge rhombohedrons, as they gradually perish, leave those *chairs* which are favourable to the preservation of the snows.

But the crystalline schists and gneiss do not always present that beautiful regular formation which

[3] View taken from la Pierre-Pointue.

enables them long to resist atmospheric agencies, and causes their destruction to be methodical, so to speak. The crystalline systems often present very strange interpenetrations of crystals between their planes of stratification.

They form macles,—present certain groups which offer much more resistance than others—imperfect formations, amid which appear masses of foreign matter—porphyritic, granitic, veins of mica, sections of laminated schists, petrosilex, &c.

In these instances the disintegration, though conforming to the same conditions, is irregular. Such is the case with the rocks, which are above la Flégère, and form the summits as far as la Floria to the north, and the Aiguilles Rouges on the east (Fig. 49).[4]

We see here that although the crystalline groups interpenetrate and intersect each other, nevertheless the disintegration has taken place as described above, attacking the weaker or more exposed parts, hollowing out the faces of the rhombohedrons (see A), and ultimately, in conformity with the character of the rock itself, forming those *chairs* on which the snow rests and is preserved. At the present day, the great lateral glacier which descended as far as la Flégère, and covered all the moutonné surface, B, B, B, is reduced to the small patch G, and shows, in a denuded condition, the ancient bed furrowed by the lines of planes of junction of the disintegrated crystalline groups, whose débris have been transported into the valley by the ice.

It is possible, therefore, with the help of the

[4] Taken from the acclivities of the Aiguilles du Bochard.

considerations suggested respecting the manner in which the rocks have been destroyed, to estimate the volume of the parts that have been swept away, and to complete those portions of the crystalline groups of which only ruins or truncated bases, rasped by

Fig. 49.—Chain of la Floria.

the passage of the ice, are now left. And from these observations it would result—1st, that the actual height of the summits reaches that of the highest parts of the primitive upheaved rocks;

2nd, that these rocks, though they may have lost little in height, have suffered a vast diminution in volume, through the changes on their acclivities, the ruin of the lateral salient parts, the widening of the valleys, and the destruction of the dikes, which, in various quarters, dammed up the depressions in the upheaved material; 3rd, that the upheaved massifs exhibited elevated plateaux, more or less bulging, which have been formed into ravines—gradually hollowed out—by the combined influence of the névés, the glacier ice, and the considerable and sudden changes of the temperature; 4th, that the destruction of the slopes and alteration in the plateaux has had as its result the filling up of the lowest parts of the depressions produced by the upheaval, and of sending, even down into the plains, immense cones of dejection, which have shaped the great valleys, and have levelled the course of the larger and smaller streams; 5th, that in aiding in this great work—in rough-hewing it—the glaciers themselves have contributed to their own ablation.

By filling up the depressions, replacing the "glacières" by glacial currents, breaking down the declivities, and rendering them less steep from the lower parts as far as the higher level of the plateaux, by breaking through the dikes, and transporting to a distance the débris of the undermined escarpments, the glaciers enabled the sun's heat to penetrate more easily into the midst of these upheaved masses. They were then reduced by this solar action, and proportionately laid bare the rocky walls which banked them in. The latter, being more exposed to frost and heat, were more

rapidly disintegrated, and sent back the heat on these glaciers by radiation.

When the great trunk glaciers had ceased to exist, the effective action of the lateral glaciers commenced, but they found themselves in different conditions. With less power, they were approaching altitudes where the thermometer seldom rises above freezing point. Limited and divided, they acted on the rocks, no longer as the trunk glaciers had done, by great levellings,—by overwhelming incursions,—but by keeping within the depressed parts of the massif, eating them away gradually, and penetrating to the very heart of the plateaux. At all events, if they exerted incontestably an action, by shock and thrust, on the flanks on their embanking walls, and consequently on the escarpments, they never had more than a very feeble one on their beds, limiting themselves to polishing and rasping them, but not being able to hollow them out to any extent, unless they encountered a barrier—an obstacle to their passage; for then they acted by shock or thrust, and tore down the obstacle. Hence we might conclude that the extreme limits, superior and inferior, of the great 'massifs' have varied but little, and that the difference between their present and the primitive condition consists in the profile of parts.

However considerable the dilapidations suffered may seem, what are the débris that have been broken down and swept away in proportion to the masses still existing? A trifle; and yet these clearings have levelled innumerable gorges, and valleys, and basins which extend from the Alps to the Mediterranean, the North Sea and the Adriatic. It is when we observe mountain ranges from elevated points

that we see the inconsiderable volume of the waste as compared with the masses still intact.

If, for instance, we contemplate the mountain group of the Oberland, from the summit of the Croix-de-fer, above the Col de Balme, the mass exhibits the aspect of an immense plateau, presenting only planes, forming with each other very wide angles, Fig. 50. It is evident that the relative importance of the parts carried away is trifling compared with the mass; that the outline as a whole has undergone only inconsiderable alterations, and that this outline has been modified only in the details. For us these details have an immense value, and appear to us to prove gigantic ruin; gigantic

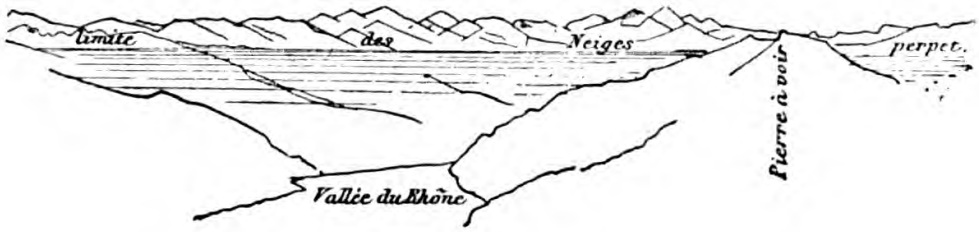


Fig. 50.—The Bernese Alps.

certainly, in our estimate, but of little account as compared with the mass.[5] It is therefore, a

[5] On this question, we think it desirable to quote the opinion of M. Alphonse Favre, although we do not entirely agree with it: "We are led," says he, "to conclude from these collected data (exhibiting the enormous transport of débris), that the massif of Mont Blanc was formerly much higher than it is at present; I will even venture to say *that it is impossible that this massif should not have been in its entirety*, greater than in our days. This conclusion is supported by various considerations, drawn, 1st, from the observations made by De Saussure at the Col du Géant on the continual degradation of the mountain ranges, and the observations of a similar kind which I have made myself: 2nd, from

great exaggeration, we think, to assert that the glaciers hollowed out valleys, and reduced and destroyed part of the summits. If the glaciers exerted any action on the natural depressions of the upheaved district, it was in the way of breaking through or reducing certain barriers, and opening a communication between depressions, which rather formed long basins than valleys properly so called; eroding the margins of these basins, when, after the dams had been broken through, they constituted valleys, and the glaciers could advance towards the lower parts of the massif; transporting to a distance the débris, which the embanking walls of

the corroded aspect of the higher portions of the massif, where the existing aiguilles are evidently *witnesses* to the elevation of the entire mass in former times, just as the calcareous fragment on the summit of the Aiguille Rouge is a witness to the mantle that once covered it." But the learned Genevan professor supposes that the triassic and jurassic deposits, which occupy a part of the flanks of the massif, had been upheaved, and formed a vaulted covering over its upper surface. But for this to have been the case, we must imagine that these strata had the power of stretching, like india-rubber, whereas we are led to suppose that they were, on the contrary, broken through as a result of the more extended development of that surface when folded and thrust back, and that they suffered fracture to allow the crystalline schists and the protogine to pass as through a *button-hole.*

That remnants of these strata remained on the secondary slopes and flexures—e. g. those of the Brévent, the Aiguilles Rouges, and the parallel Italian chain, is by no means doubtful, since we find traces of them ; but we can scarcely suppose any to exist on the culminating part of the massif of Mont Blanc itself. These strata have necessarily been thrown right and left; and the ruins observed by De Saussure, several geologists, M. A. Favre, and myself, in the vicinity of the summits, are certainly lateral dilapidations rather than débris from the culminating points.

these glaciers, disintegrated by atmospheric agents, allowed to roll down on their surface, and rasping and smoothing the slopes of these walls, already reduced by the fall of abrupt escarpments, or of projecting parts exposed to atmospheric influences. This continuous action, during thousands of years, with means whose power during the glacial period is scarcely conceivable, and which was first exerted on the lower parts, has been prolonged with less energy towards the middle, in proportion as the ablation of the great glacial currents advanced; and is still taking place now, on the heights, according to the same methods, and producing on a small scale the same results as were formerly obtained on a much larger one. Nature always proceeds according to the same methods. The means she makes use of may be endowed with more or less efficiency, but they never vary.

V.

MORAINES AND OTHER GLACIER DEPOSITS: OBSERVATIONS RESPECTING THE MOVEMENT OF GLACIERS.

As we have just seen, the glaciers continued their advance without either hastening or slackening their course, whatever the gradients; they passed the dikes by rising over them, merely rasping them when unable to break and bear them down. Melting as they neared the lower districts, and then again withdrawing by successive stages of retreat, towards the more elevated regions, they left bare the still unshaped ground.

In cases where they had proceeded only to a certain extent in scooping out the deep depressions, and had even left at the bottom of their beds débris of the upheaved strata, and of the dilapidations effected in their course, and, during one of their long stages of retreat, had left on their lower limit more or less considerable frontal remains,—the whole formed a veritable chaos, of which the recent ablation of certain glaciers gives us an idea on a small scale.

No scene presents a more striking aspect of desolation than the bed of a glacier that has melted.

Fine sand, enormous masses of rock, débris of every size and shape, with their sharp corners intact, set down not in stable equilibrium, but by haphazard, ready on the slightest shock to fall on their neighbours; the bed scored, moutonné, hollowed in the softer parts, presenting protuberances in the harder; boggy pools in the depressions, rocks uniformly grey and bare, absence of vegetation, which, independently of the altitude, could not adhere to the devastated and shifting ground; such is the picture presented by the area that has been occupied by the glacier. And yet, if we examine this apparent chaos attentively, we shall soon perceive a certain order. In fact the glacier has deposited on its margins two lateral moraines, whose mass is in proportion to the more or less perishable character of the surrounding summits.

If the glacier has pursued its course between banks and peaks of a firm and durable nature, adapted to resist atmospheric action, its lateral moraines are scarcely perceptible. If, on the contrary, its course has lain amid banks and peaks, whose disintegration is easy, the lateral moraines become very considerable. The same rule applies to the frontal moraines which are merely the accretions of sand and rocky débris, which are carried along the surface or on the flanks of the glacier, and which it deposits on the ground in melting.

While the lateral moraines affect a high degree of regularity, this is not the case with the frontal moraines, whose bulk depends on circumstances. The lateral moraines are produced by the fragments and dust which falling on the surface are deposited by the glacier on its margins. The greater the

volume of the glacier, the greater the regularity of the lateral moraines.

The glacier, properly so called, which of course must not be confounded with the névés—as explained in the preceding chapters—presents in transverse section a surface whose convexity is greater in proportion to the abundance of the névés above, by which it is fed, v, Fig. 51. As the current of a glacier is more rapid in the middle than at the sides, it follows (see horizontal projection of the current at A) that a row of stones placed at equal distances on its surface between *a* and *b* naturally ends by being ranged in two parts, as the Figure clearly shows. The volume of ice being more considerable, and the current stronger from A to B in the direction of the longitudinal axis than at the sides, the line *a b* is always tending to increase its curvature, and the stones, instead of leaving equi-distant spaces between them, are more and more widely separated in the neighbourhood of the main axis, and ultimately range themselves on the margins *a c b d*. As the mountaineers say in their figurative language, the glacier throws off what soils its surface. The lateral moraines, therefore, are thus regularly formed of all the sand and stones that fall on the surface of the glacier.

If the glacier should increase in volume and raise its surface, its borders sweep and bear away all or part of the pre-existing lateral moraines *e f*, and deposit two fresh ones *i* K. If on the contrary it decreases and lowers its surface to G H, the moraines *e f* partly shift down on the new ones.

Thus we may observe as many as five, six or seven parallel lateral moraines, sometimes more—marking

the successive lowerings of a glacial current at comparatively recent epochs.[1]

But many rocks and heaps of sand fall into the crevasses which furrow the glacier. These rocks and accumulations of sand, if they do not sink down

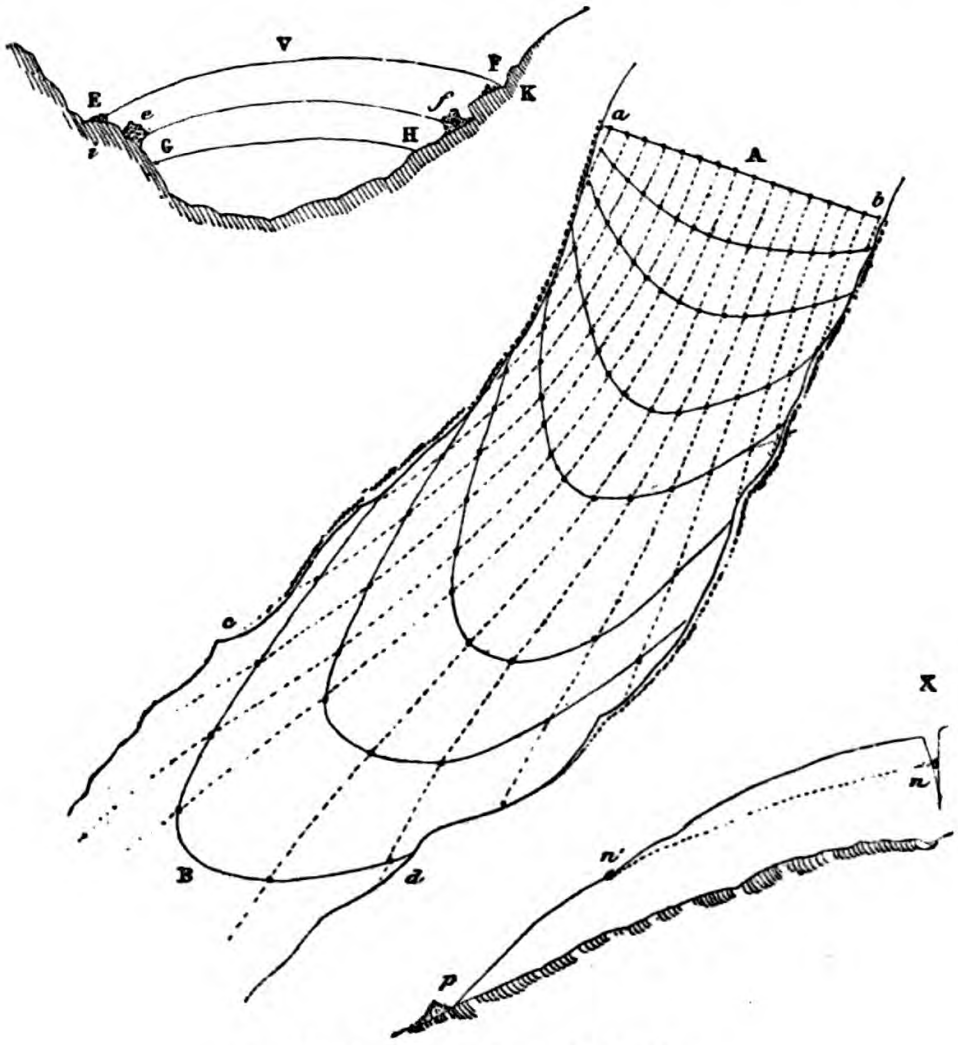


Fig. 51.—Formation of lateral Moraines.

to the bottom, if they remain imbedded in the mass and are not thrown off laterally, present themselves

[1] As for example in the glacier de Bionnassay, which exhibits at its lower end six very regular parallel moraines, deposited as the result of successive periods of ablation.

on the surface of the glacier again near its lower extremity, and are deposited by it on its front.

Let x, Fig. 51, exhibit a section of the terminal part of a glacier; and let *n* be a stone that has fallen and been retained in a crevasse. As the glacier continues to advance and ablation takes place at its surface, the stone will necessarily reappear on the surface at *ń*, and will be deposited by the glacier at *p*.

We can now understand why the frontal moraines

Fig. 52.—Medial Moraine.

cannot present the same regular appearance as the lateral moraines. Medial moraines are the most efficient cause of their accumulation. Every one knows that the medial moraines are formed by the junction of two glaciers, which bringing each its lateral moraine, unite them in a single moraine at the line of junction.

Thus, Fig. 52, a glacier A and a glacier B unite to

descend to D, their terminal point. The moraine *a b* on the right of the glacier A, will unite with the moraine *c d* on the left of the glacier B, and these two moraines will form a single medial one from *e* to *f*, where it will present an accumulation more or less considerable in proportion to the deposits of the two glaciers. It is on this account that the frontal moraines of glaciers cut by medial moraines, exhibit those vast hills of stones and sand more or less distant from the actual terminal point, and which give these frontal moraines an aspect quite different from that of the lateral moraines, which can be recognized by their perfect regularity.

If, e. g., one of the two glaciers is smaller than the other—if the glacier B is fed by névés of less considerable volume than those supplying the glacier A, the latter occupies the greater part of the width of the bed in consequence of the more rapid ablation of the glacier less abundantly supplied, and the medial glacier *e f* will take its place against the lateral moraine on the right of the glacier B. The result will be an apparent irregularity, but which a practised eye will soon account for.

The glacier is not always able to deposit its lateral moraines. When, for instance, it moves between steep banks;—thus shut in, it does not find in these vertical or steeply inclined walls any ground on which to deposit the stones which encumber its margins. Then it is obliged to carry them further and to set them down as soon as the steep banks make way for ground capable of receiving a deposit. This explains why we observe at the point in the glacier just below these abrupt escarpments,—i.e. as soon as the ground allows it—a very considerable lateral moraine deposit.

The glacier has been eager to get rid of its burden as soon as possible.

But the moraine deposits exhibit other very striking peculiarities.

When the glaciers experience a period of decrease, they leave lofty moraines on their margins, testifying to their ancient level.

But it is worth while to examine how these relics of their former extent acquire the regularity displayed by their section. Figure 53 represents a

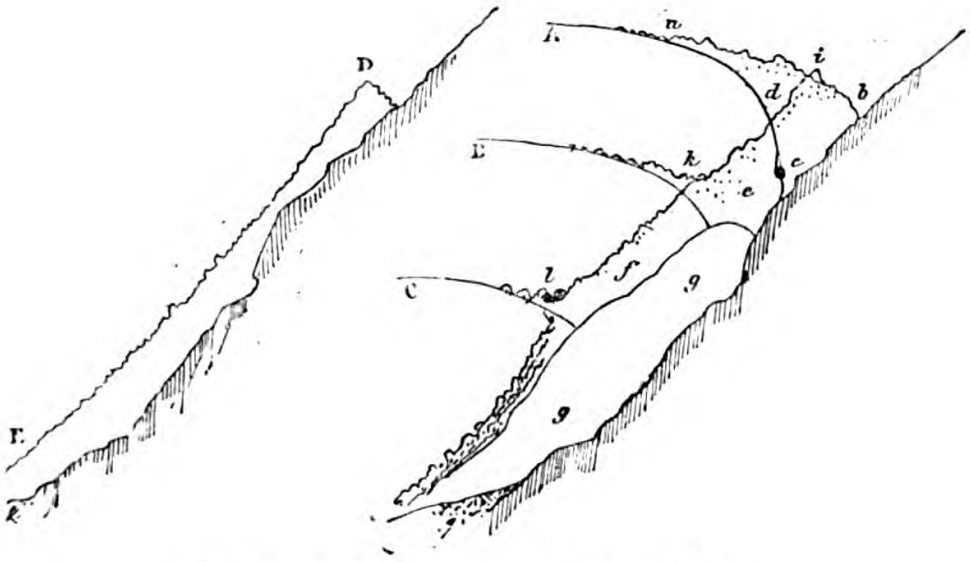


Fig. 53.—Successive deposits of a lateral Moraine.

glacier whose outer surface is at A; it deposits in advancing, as already described, the lateral moraine *a b*, along the escarpment which embanks it. If this glacier diminishes, and the external surface is lowered to the level B, the part *d* of the moraine will be successively lowered and deposited at *e*. While the lowering is taking place the glacier will have been continually occupied in strewing its margin with new materials; then the section of the moraine will

be *b i k*. Suppose the glacier to continue to sink to the level c, it will frequently happen that the higher moraine débris and those which are added from time to time will cover, as at *f*, a part of the ice *g*, which remains unmelted, protected as it is by these débris; then the moraine presents the section *b i k l*; and an inert mass of ice will long remain at *g*. We call it inert, because being no longer connected with the moving mass, it ceases to advance with it.

Suppose that ultimately the glacier entirely disappears. By degrees, in spite of the layer of débris that protects it, the remaining ice *g* melts, the débris which cover it are continually giving way, and a slope D E of sand and rocks is formed, in accordance with the laws of statics,—or i.e. of 45°, sometimes rather more, on account of the cohesion of the compressed sand and the size of the blocks, which are wedged together. Vegetation ultimately invades these acclivities, and thus, after the lapse of ages we observe lateral moraines, presenting slopes of perfect regularity, with here and there huge pieces of rock jutting out.

The moraine on the left of the glacier des Bossons still covers masses of ice now considerably above the surface of the glacier—greatly reduced since 1835—and which, melting very slowly in summer, are incessantly producing slips of débris which *tend* to render the internal slope of the moraine regular, and which unite with that which the glacier is incessantly forming.

Sometimes these masses of ice, arrested beneath the moraines, may remain there for more than a century; if, e.g. to a period of glacial decrease has

succeeded one of increase, and subsequently one of ablation.

Fig. 53 *bis* represents a glacial current A, which has deposited the lateral moraine B. Subsiding gradually to C, it deposits fresh débris from D to E. A period of increase ensues. The glacier, instead

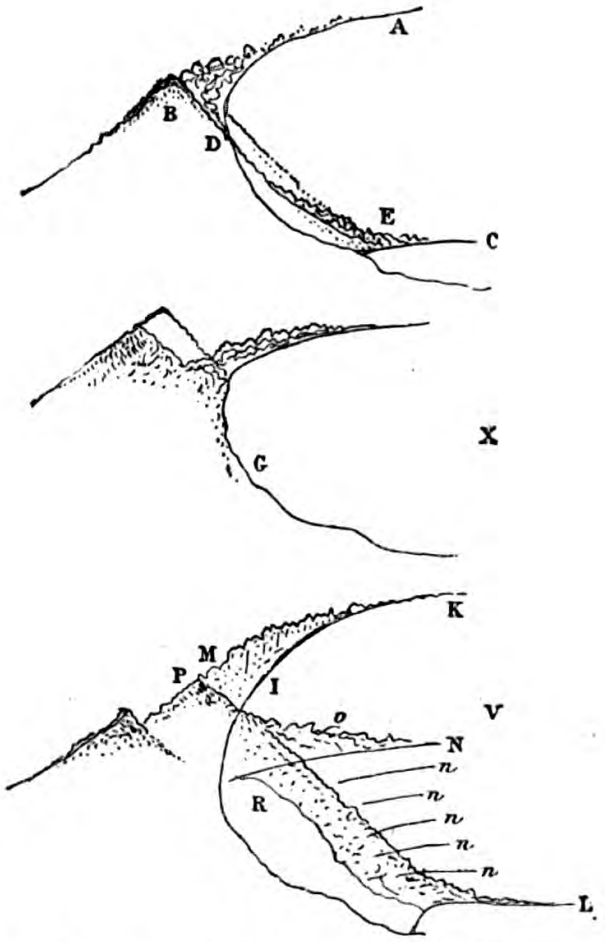


Fig. 53 *bis*.—Ice left beneath the lateral Moraine.

of having only a power of dilatation which is continually diminishing, is on the contrary endowed with a constantly increasing energy. While, therefore, the glacier, through successive ablation, had been wont formerly to *leave* its débris on its margins,

now, being endowed with increasing force, it *sweeps away* these same débris in proportion as it increases in volume and power. Then along the slopes of the moraine it proceeds by erosion, as we see at G (sketch x), and while it imports new materials it brings down the crest of the moraine upon its margins. But the more powerful the glacier becomes,—as we shall have occasion to explain further on,—and the more it tends to swell at its external surface, and to concentrate its power and activity in the direction of its longitudinal axis,[2]—the more declivitous are its sides. It thence results that if the glacier continues to increase and attains a considerable elevation above the level of the ridge of the moraine B (see V), it exhibits the section I K, bearing along at M an enormous mass of débris, collected on its route.[3] It then deposits a second moraine on the first. Sometimes this new moraine covers up the first; sometimes it takes up its position higher up, as this figure shows.

But if the glacier should once more suffer diminution and reach the level N, its new lateral moraine will have descended with it and assumed a position, when lowered to level N, in accordance with section P *o*. The part R of the ice is well protected and does not melt; and in proportion as the surface of the glacier is lowered to the levels *n* successively, the débris *o* covers up the portion of ice R, which, being separated from the glacier ceases to move, and may

[2] When the glaciers suffer a great decrease, they become flat towards the middle; we observe this at the present day in almos all the Alpine glaciers.

[3] In fact, when a glacier increases, it bears down its ancient lateral moraines with it and sweeps its banks.

remain buried for a very long time;[4] for, at these altitudes, the sun's heat cannot penetrate effectually more than six or seven feet.

Other phenomena also are exhibited. When a glacier is increasing, it behaves (at least beyond a certain altitude which we have not been able to determine exactly, but which we think but little below the névés), not like a stream of water, which in becoming greater, carries away the whole section of its bed,[5] but like a new river of ice, moving over the surface of that which existed before the increase, and appearing to have properties dependent on its volume. We refer once more to a diagram to make our view more intelligible. Let the névés A be supposed to feed a glacier C B, Fig. 54.

It so happens that the great amount of melting which it experiences causes the terminal point of this glacier (C B) to move back (as the mountaineers say) to D. A period of fifty or sixty years has been required to cause the retreat from B to D to reach a distance of 500 yards. But when point D is reached, the glacier is much shallower—thirty or forty yards, perhaps; its energy is therefore diminished. It

[4] This effect has been produced on the right bank of the glacier de Miage (val Veni) and we clearly see the new moraine rising above the ancient one across the vale. The ancient one rises 100 or 120 feet above Lake Combal, which it has dammed up, while the more recent moraine rises 60 feet at least above this level. Vegetation covers the ancient moraine, but has not yet invaded the new one.

[5] As regards this, however, it may be observed—as we have witnessed ourselves—that, when violent floods occur in rivers, the fresh material carried down is rolled along the original stream in front of the flood waters, and forms a *bar* which advances, covering the normal current.

advances less rapidly and reaches its lower extremity in an almost inert condition. If a great quantity of snow falls and the summers are rainy for several years in succession, the reservoir A will be copiously supplied; but however full it may be it can scarcely produce any effect on the long tongue of ice, C D. If it exerts an action of thrust it can be only in the higher parts, where it then forms bulges and *séracs*, and subsequently a new glacier (G H) is produced above the old one by this chaos of ancient ice and

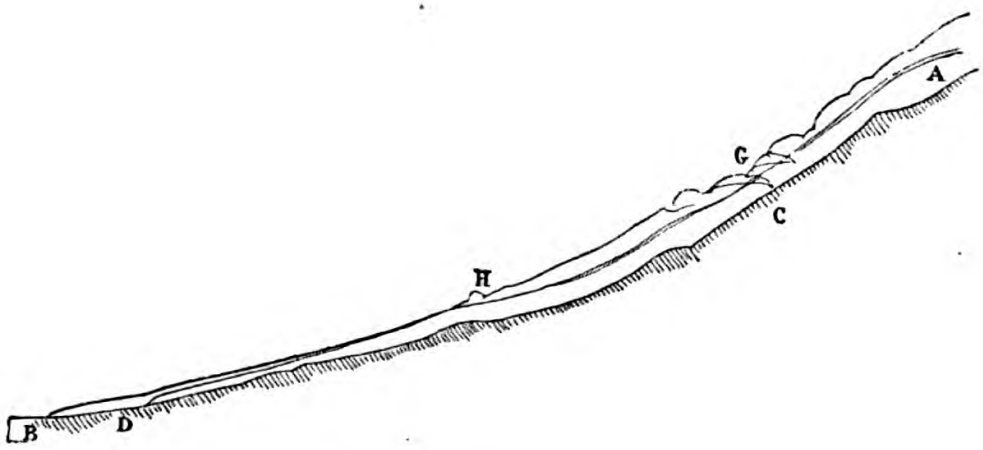


Fig. 54.—Increase of a glacier.

new contributions. Many years, however, pass away before this new layer has regained the ground lost,[6] and has returned to point B. But it is not point D (if we deduct for loss of bulk in the summer) that will reach this point B; it is point H.

We have a clear proof of this fact at the bottom of

[6] Towards the year 1770, the glaciers of Mont Blanc were very low. In 1835 they reached their culmination; now the winters at the close of the last century were long and cold. From 1812 to 1818 the winters were similarly cold, or the summers very wet. The winter of 1829-30 was particularly severe.

the glacier des Bossons. The fresh glacial layer which in 1835 was near reaching the Chamonix road and damming up the valley, having retreated since that epoch in consequence of the diminution of the glacier, laid bare a part of the upper surface of the glacier, which about the year 1770 had its terminal point above its present limit. There is good reason for supposing that when the fresh layer completely covers the old one and goes beyond it, in consequence of its greater energy, the two currents will unite; but the welding of the two masses cannot do away with the dirt and stones which covered the ancient one—stones and dirt which are thus intercepted between two glaciers and distinctly mark a separation, which evidently testifies to the covering of an older current by a more recent one (Fig. 55) A;[7] old ice partly covered by débris of the moraine B; débris which are found again overlaid by the more modern current C. The cohesion between the two currents is so perfect at the present day that a small stream flows along the junctions and sinks at *t* into a *moulin*.[8]

The section of the glacier des Bossons, taken at E, C, B (Fig. 56) clearly exhibits the situation of the two currents, a little above the terminal point. The part *g*, of earlier date, is covered with moraine débris, *m*. The fresh accumulation *k* has covered the older glacier, being welded to its surface; the dotted

[7] Lower part of the glacier Bossons, taken from the opposite slope at the altitude of the Châlet des Bossons, B (July, 1873).

[8] This name moulin (mill) is given to holes made in the glaciers by the melted waters, and into which they are observed rushing with considerable noise.

line *l n* indicates the section of the glacier in 1835.

Fig. 55.—Terminal point of the glacier des Bossons.

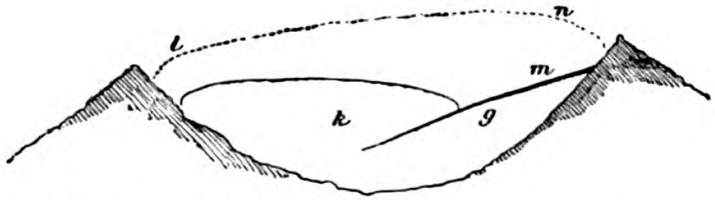


Fig. 56.—Section of the terminal point of the glacier des Bossons.

We see that the ancient glacier *g* has melted much more towards the right bank, looking south-west, than towards the left bank, looking north-east, whereas the new glacier has comported itself otherwise. We proceed to deduce an inference of considerable importance from this fact.

In 1835 the surface of the glacier des Bossons was approaching the ridge of the moraine of the châlet now at B, and the bend D (Fig. 55), and from that point rapidly decreased in volume to end in a narrow termination, stretching as far as the Chamonix road.[9] Why this indentation D? It is due evidently to the ancient underlying glacier A, which—as a rock would have done—forced the new glacier to form a bulging, —to mould itself on this icy surface. The terminal point of this ancient glacier A was, therefore, at this time very nearly at the point at which we see it now; it would, consequently, not have advanced,—would no longer have continued its progress with the new one; it formed a bed immovable as the rock itself. In the case of the new glacier the ablation would, since 1835, have exceeded the movement in advance, and the old glacier would have remained fixed. The importance of the questions thus suggested, and to which we by no means pretend to give an answer, is evident. What is certain is that a little above the terminal point *t* (Fig. 55), the new current blended with the old one, and that the sand and stones which covered the surface of the glacier A are closely moulded and held between the beds of ice; that the water resulting from the melting does not infiltrate into the junction, but flows all along it as far as the

[9] See the general map.

point *t*. Is the blending of the two glaciers a proof that these two currents must move together? To this question it may be replied, that at an altitude of 8000 feet the glaciers adhere, or appear to adhere, to their frozen and rocky bed, while it cannot be denied that they advance, whereas their basis is immovable.

Has this underlying glacier A descended from a higher level, and did it descend at the same time as the upper current?

Probably so. We observe, in fact, that the older current was directed towards the left shore, but on this side, the glacier des Bossons, above the moraine, must always have been deeper than on its right bank, on account of the escarpment and the shelter presented by the Montagne de la Côte, M, while the right bank is exposed. This portion of the older glacier, A, might therefore have taken the same course as the more recent one, C, after the latter had covered it and was thoroughly welded to it. But there must, in any case, have been a time when the advance of the glacier C was more rapid than that of A, since it not only surmounted it but passed beyond it, as the indentation D evidently proves.

The question of glacier movement is, in fact, far from having been thoroughly investigated. The adhesion of the ice to its rocky bed appears incontestable; but the regular and periodical advance of the glaciers in summer is no less so. The wearing of the beds in which the glaciers advance is a manifest fact. How can these two contradictory propositions be reconciled? Professor Tyndall's observations have demonstrated the plastic nature of ice; its flexibility may be verified in the glaciers them-

selves;[10] but the fields of observation are so extensive, and the details, relatively insignificant, assume so great an importance in our eyes, that it is difficult to ascertain the general laws. It is incontestable that a glacier current advances more rapidly at its outer surface than on its bed; observation confirms this law, which is natural to all currents; but is it possible that a glacier should advance at a perceptible rate at the surface, but not at all where it adheres to the rock? No: since all the glacier beds exhibit the most evident traces of a frictional power sufficient to round and hollow out the hardest rocks. Would the ice along its bed act like an india-rubber band heavily loaded, which, presenting every appearance of close adhesion to a body, would nevertheless stretch through tension, while gliding over this body and following all its inequalities?

Let us then imagine an india-rubber band, A B (Fig. 57), laid on a rough bed, and this band so loaded with a flexible material C, as to force it to follow all the inequalities of that bed. Suppose a stretching action at A. There will be resistance at *a* resulting from friction on a rough and unyielding surface, and an absence of resistance at *b*, since the entire mass C is the occasion of the tractive movement. How will the india-rubber comport itself? The molecules in the upper part will tend to yield, while those below will resist the disturbing force; the result of which will be such a change in the arrangement of the particles of the mass, that, from presenting the appearance T, it will assume that exhibited in V (Fig. 57 *bis*); but if the mass is

[10] See Figure 24.

homogeneous, if it is rigorously elastic and proof against resistance, the molecules *a e* must follow such a decided displacement, as appears at *f g*. Observation here comes to the aid of theory; or, rather, theory is verified only by observation.

Ice has various properties. It is dilated as the result of the regelation of the water it contains, or

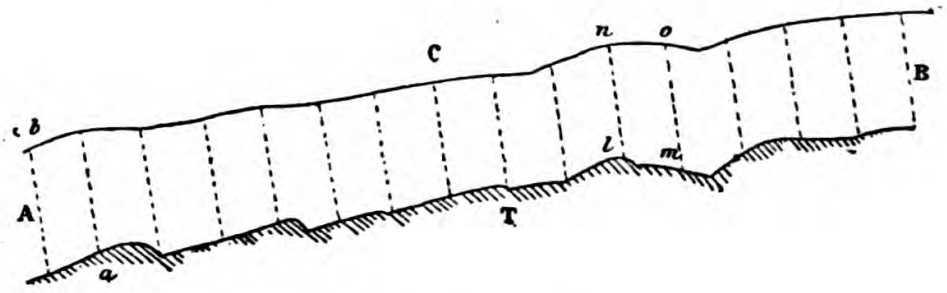


Fig. 57.—Strata of a Glacier—Crevasses.

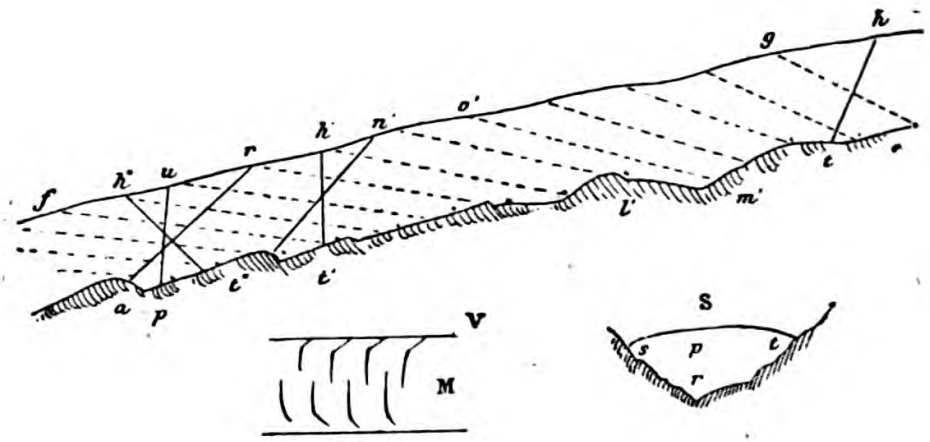


Fig. 57 *bis.*—Strata of a Glacier—Crevasses.

which it absorbs, and of other causes which are not yet clearly understood; it is plastic, i.e., it will lend itself to all the forms we choose to give it, and if reduced to fragments and subjected to pressure in a low temperature it can be made to assume the shape

of the mould in which it is enclosed. Thus a cylinder, a sphere, a pyramid, a rod, or a slab may be made of a piece of ice. The parallelopiped *l m n o* (Fig. 57) may therefore become the polyhedron *l′ m′ n′ o′* (Fig. 57 *bis*). The thickness *f a*, after the stretching, will necessarily be less than *b a* before the stretching, and the elastic mass will have gained in length what it has lost in thickness; in fact, it will have advanced irregularly.

It is certain that the glacier is not stretched at its lower part like the india-rubber band; but it is expanded, and this expansion of all its parts being in direct proportion to the mass, it is at that point of its section at which the glacier is widest and thickest that this expansion is most effective. s represents the transverse section of a glacier (see Fig. 57 *bis*).

The most considerable expansion takes place from *s* to *t*, transversely, and longitudinally at *p*,—i.e. near the outer surface. While at *s* and *t* there is less energy in producing longitudinal movement, the banks also retard the advance caused by expansion; at *p* this action is not impeded, it is freely exerted, while it is less powerful below, and is impeded by friction on the bed. Thus the higher part of the centre advances more rapidly than the margins *s* and *t*, and than the part *r* which rests on the bed; in fact, the action, in a longitudinal direction, is equivalent to a stretching action, such as is indicated in Fig. 57 *bis*.

But, if we stretch an india-rubber band, we cause it to lose, not only in thickness, but in breadth, what we make it gain in length; it is otherwise with the glacier, which is not itself subjected to a tractive

force, but produces one of expansion. While the longitudinal expansion of the glacier has for its result a more rapid advance of its centre than of its margins, and of its surface than its base, the expansion in a transverse direction compensates for the lateral diminution produced by the more rapid movement of the centre. We have, then, a longitudinal and a transverse tension; and these two impulses, which are contrary to each other, have for their result ruptures—transverse or oblique cracks, which are widened by the tension on the lower side and the melting in summer. These cracks or *crevasses*, as the transverse ruptures of the mass are called, are generally at right angles to the zones of tension l' n' (see Fig. 57 *bis*) i.e. in the direction of h t, inclined upstream; but as the upper part of the glacier advances more rapidly than its lower part, these crevasses tend towards the perpendicular as at h' t', or even beyond it as h'' t''; in the case of the position h' t' the tension of the ice will have formed a new crevasse n' t'', and both—following the same movement—will produce the section h'', t'', u, p; then again tension will result in a third crevasse a r. These crevasses will then have formed a complicated network which tends to dislocate the glacier, and to hasten its ablation.[1]

It cannot be doubted that tension produces the crevasses; for these are not observed until the glacier has assumed its definite form,—established a current. The upper glaciers of inconsiderable size, which are sometimes formed, even above the altitude of the névés, and where the snows are saturated with the

[1] See Tyndall's *Glaciers of the Alps.*

water that results from thawing under the action of the sun's rays, or of the Föhn (south-east wind), have no crevasses, or begin to exhibit them only at their lower part. But on a great glacier, especially towards the middle of its course, i. e. at an altitude of eight or ten thousand feet, we may see, or rather hear, these crevasses formed; for in rending, in consequence of the tension of the mass, the glacier produces actual detonations, followed by a whistling sound. These fissures, which are at first only half or three quarters of an inch in width, are soon enlarged, and the surface water rushes into the cavities, carrying with it a quantity of bubbles of air.

Of all the striking natural phenomena of Alpine regions, none is more vividly impressive; even the boldest guides lose their *sang-froid* when the glacier thus splits beneath their feet with alarming detonations and hissing, though a crevasse never presents an opening wider than an inch at first.

M. Desor, describing the glaciers in his *Excursions et Séjours*, gives an account of one of these ice *débâcles* on the Aar glacier, and adds, "As the general result of these observations we find that the formation of crevasses takes place more frequently when cold nights follow very wet days; and this fact seems to tell very strongly in favour of the theory of infiltration. In any case, the sudden formation of the crevasses, which are propagated with extreme rapidity over a very large extent, seems to me a capital objection against the theory of semi-fluidity. How, in fact, can we conceive of a tension and rigidity, such as all the circumstances connected with crevasses necessarily indicate, if we

suppose the glacier to be a semi-fluid body moving like lava." [2]

We may add to these observations that, as these crevasses are formed during a lowering of temperature, and after the glacier has been abundantly saturated with water, we must suppose that regelation produces a powerful action on the mass, though the variation of the thermometer plunged into the mass is scarcely perceptible, when the external air passes from 44° Fah., or 46° Fah. to 25° or 24°. Crevasses are the result of tension only, and tension cannot manifest itself unless the ice expands.

If the bed presents prominences which oblige the glacial current to rise in order to pass them, the transverse crevasses are frequent, and open in their upper part; if, on the contrary, the glacier descends on a smooth and but slightly inclined bed, the crevasses are few, and are at regular distances. Near the terminal point they cease to occur, because there the effect of tension is nil, even in summer, which is the season when the glaciers advance most rapidly. These transverse crevasses are also called *lateral*, because, in fact, they present a more open appearance laterally than at the axis on account of the more rapid movement of the central current; but they often extend across the glacier, or usually overlap, as seen at M, Fig. 57 *bis*; a phenomenon which is sufficiently explained by the greater tension and more rapid movement of the centre of the mass. As regards the *marginal* crevasses, which are observed only on the extreme edges of the glaciers, and are parallel to the sides,

[2] Desor, *Excursions et Séjours dans les Glaciers*, p. 489.

they are produced only by the separation of the ice from the banks. Embanked glaciers end at their terminal point in a narrow tongue isolated from the banks. This narrow tongue is the longitudinal axis of the glacier, which is most active, and advances farthest.

The proof of the retardation produced in the current by friction on the bed and the pressure exerted by the upper part, is the appearance x, Fig. 57 *ter*, presented by the layers or strata at the extremity of the glaciers. The movement being more

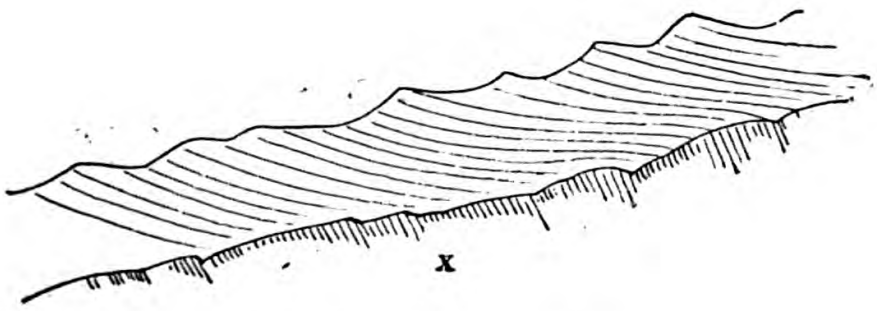


Fig. 57 *ter*.—Strata of a Glacier.

decided at the surface than at the bottom, the strata are bent, as our longitudinal section shows. This arrangement of the strata is clearly manifest in the glacier de l'Argentière, below the last séracs. The ice is therefore at once plastic and flexible, since it stretches, bends, lengthens, or is compressed without breaking.[3]

[3] We think it unnecessary to dwell at length here on the various theories proposed by observers who have investigated glacier phenomena with reference to the crevasses and their formation. See the observations of MM. Forbes, Tyndall, Ch. Martins. Major (William) Hüber very clearly sums up the result.

But why these strata *l' n' o' m'*, Fig. 57 *bis*, whose lines are more or less close to each other, but which are observed in most glaciers? The strata shown at C, Fig. 57, in the normal state, i. e. perpendicular to the bed, are produced by the regelation and plasticity which are incidental to ice. They are scarcely ever observed except in glaciers that are embanked, and which originate in abundant accumulations of névé.

Suppose Fig. 58 a mass of névé, A, falling in

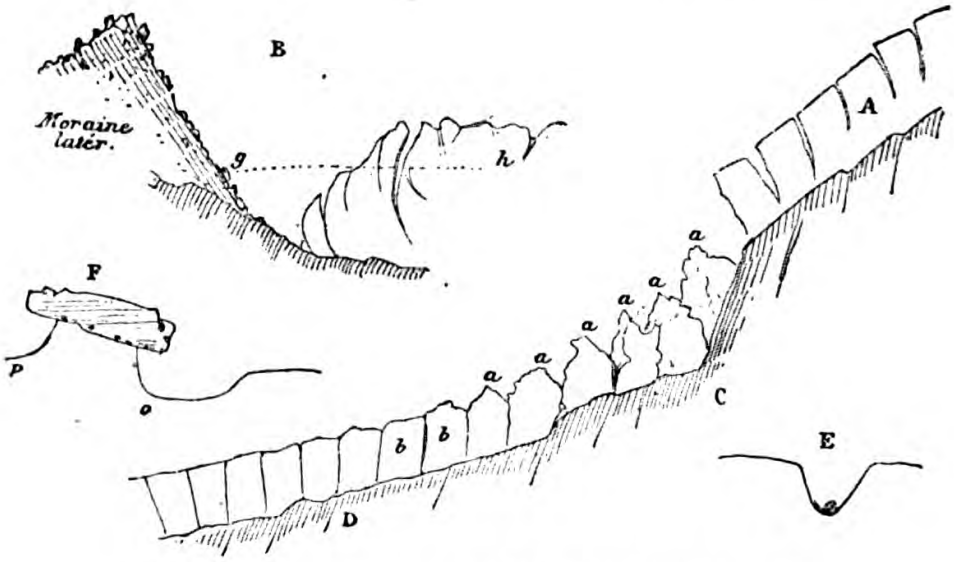


Fig. 58.—Phenomena relating to the movement of Glaciers.

avalanches on the slope C D. In the winter avalanches are only running falls. The névés slide along like ashes over the slopes; they do not cohere, but fall as dust. The glaciers are then stationary, and the alternations of frost and thaw do not occur at these altitudes; there is no regelation, consequently no expansion, and therefore no movement. It is not so in the summer. The lower compressed névés, which are already penetrated by re-frozen water, are

compact, and break up into large parallelopipeds (see Figs. 22 and 23). They fall in masses only at certain times in the day, according to the energy of the sun's action. In the night tranquillity is restored and the mass freezes again.[4]

The glaciers are therefore fed by quasi-regular supplies, so that the fallen masses form slices separated at regular distances by a narrow interval of water that is frozen during the night. Thus slices of ice not yet duly formed, but yet separated, begin to arrange themselves in a certain order,—presenting a series of ridges, *a*, continually diminishing in prominence, in proportion as the ice descends and is welded together. Accordingly we see these prominent bands prolonged to a considerable distance from the place where the mass originally fell.[5] But while these layers (see Fig. 57) tend to be more decidedly inclined towards the lower parts of the glacier, they tend also to bend in horizontal projection, as shown in Fig. 51, since the longitudinal axis advances more rapidly than the margins; so that in fact the separating planes of the zones or slices, *b*, form portions of cones—the slices tending to preserve a greater thickness in the middle of the glacier current than at the margins, and to give the glacier a bulging external surface; to concentrate its power in the section of its main axis, and thus enable it to resist the action of the solar rays more effectively; to exhibit a greater amount of expansion in the direction of the

[4] In summer avalanches are rarely heard during the night.

[5] This phenomenon is very manifest to the right of the Grands Mulets, between these rocks and the bases of Mont Maudit.

main axis, and to discharge on its margins the dust and stones that are scattered over its surface.

When a glacier diminishes and no longer occupies the space between its lateral moraines, we observe with some surprise, that its margins are often escarped, as shown at B, Fig. 58, and ask ourselves why the glacier current does not proceed like a liquid touching its banks, and following the surface line *g h*. The reason is—as just demonstrated—that the glacier is always tending to accumulate its mass in the direction of its longitudinal axis. The reflection of the sun's rays from the moraines or the rocky banks, also tends to melt the lateral surfaces of the glacier current, especially if the margins are not much covered by transported débris. For if these margins are well-sheltered by such a layer of sand and stones, the ice is better able to resist the sun's action than when it is clear. In regard to this point, however, certain distinctions must be observed; for we shall find in the study of the glaciers, opposing effects at every step which greatly complicate the problems to be solved.

Grains of sand or small stones isolated on the glacier, absorbing in consequence of their darker tint a greater quantity of heat than the white surface of the ice, radiate and form around them a small cavity, so that these fragmentary bodies are found at the bottom of an inverted cone (see Fig. 58). If, on the contrary, a large flat stone is resting on the glacier, it protects the ice beneath its bed, and causes it to melt by radiation around its margins, especially on the side exposed to the sun (see F, Fig. 58), and ultimately slips down on

the side *o*, which has been more rapidly melted, while it continues to protect the side *p* with its shade.[6]

Similarly, when a heap of sand falls on the glacier, this local deposit protects the subjacent ice, and retards its melting; so that a projecting cone of ice is soon formed beneath this layer of sand, regular in shape in proportion to equality in the thickness of the deposit.

Thus we see on the surface of a glacier current *tumuli*, sometimes separated by regular intervals, produced by slight periodical avalanches of gravel fallen from the summits.

While, therefore, isolated rocks or grains of sand tend to hasten the melting, a thick layer of these materials will retard it, and, as Figs. 53 and 53 *bis* show, may preserve intact masses of ice for a very long time.

We said that frontal moraines do not, and in fact cannot, exhibit the regularity of lateral moraines. They are composite formations consisting of the débris and detached materials that fall into the crevasses and are borne along the sides of the glacier, but especially of the supply furnished by the medial moraines (Fig. 52), which always form *tumuli* at the terminal point of the glacier.

Frontal moraines have given rise to a great deal of controversy among men of science. Our intention here is only to contribute some additional observations which may perhaps throw light on the discussion. All observers of glaciers recognize the fact that the beds of the glaciers exhibit rocks

[6] These stones are what are called *Tables*.

that are rasped and moutonné, removing all doubt as to the powerful effects of friction produced by the ice on these beds; and yet, at the lower parts of the glaciers, on these very beds there are resting stones of comparatively small size, which are not by any means swept along by the ice, but are allowed to stay exactly where they were. A distinction is necessary here.

There is a variety in the beds. Sometimes a glacier bed exhibits a very concave section or even one of a V form; sometimes on the contrary it bulges up. In the first case the glacier current is closely embanked, and acts powerfully on its margins, producing but an insignificant effect on the thalweg (see Fig. 27 and 30). In the second case, on the contrary, being free on its margins it acts powerfully on its bed.

But while we find stones and fine débris at the bottom of embanked glaciers, we do not find any on the beds of glaciers which are spread out, and have not steeply escarped banks. Moreover, while we observe accumulations of débris beneath glaciers, near their terminal point, we do not find any beyond a certain altitude, except at the points where the glacier has left a void, in consequence of the arrangement of the rock (see Fig. 28).

It must not be forgotten that, near the terminal point, if a glacier advances, this motion is due only to an effect of expansion occurring much higher up, —i.e. at such an altitude as allows of a certain degree of intensity in the action of nocturnal regelation. At its terminal point the glacier is in an inert state, and even when it increases and advances over a bed that had been abandoned, but which it covers once

more, it exerts only a moderate action on the materials previously deposited, that is, on the frontal moraines. If these are of considerable size it does not sweep them away or bear them down before it, but moulds itself against their sides, shaves their tops and overrides them; if they are of slight bulk it planes them, but does not disturb the larger blocks. This fact is very manifest at the lower part of the glacier des Bois.

This glacier, which, in 1835, almost overflowed the great frontal moraine behind the village des Bois, and was threatening, not indeed to bear down this moraine, but to fall in séracs on the village and level the small secondary frontal moraines; as respects the great blocks of protogine, it restricted itself to rasping their upper surface without displacing or even overturning them. It left—as it still does at the source of the Arveiron—the small stones on its bed, without sweeping them away.

Near its terminal point, therefore, the glacier produces but an insignificant effect on its bed, and it is only on its lateral moraines that it has, when greatly augmented, an erosive action, tending to give it more room. But at an altitude of 8000 feet or more the glacier is by no means inert; there in fact is the scene of its greatest expansive action, and consequently of its most powerful operations.

It is evident that this point has varied, and that at the glacial epoch this zone of activity was at a much lower level than it is at present. It is also evident that the form of the bed has always been an important element in the results we observe. And what are the scenes presented, not at the terminal point of the glaciers, but at an altitude of something

less than 7000 feet when these glaciers have disappeared or have greatly diminished? Cleanly swept beds of a "moutonné" appearance, sometimes even with deep hollowings out of the more yielding strata,—débris thrown down behind faults, as seen at A, Fig. 59, because the glacier, in sliding onwards, has left hollow arches *a b*. But this happens only when the bed does not present an acute-angled section.

In cases where it does (as at D) the "mou-

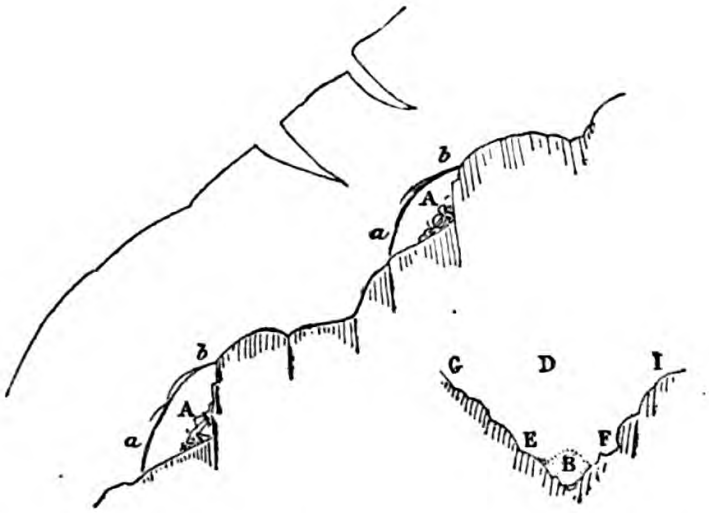


Fig. 59.—Phenomena relating to the movement of Glaciers.

tonnage" is strongly marked at G E I F, and at B débris are deposited, whose larger and more prominent fragments are worn on their upper surface. The glacier has therefore taken the form of a thick arch, in consequence of its expansion transversely, which tended to make it rise along its two inclined walls.

It may be said that the débris B are the result of disintegration occurring after the passage of the ice in these gorges; but this is not the case, for these

débris have been covered by fragments brought down by torrents, which in their turn are filled in with modern débris, and this section is visible now only in consequence of the erosion occasioned by a waterfall. A similar phenomenon may be observed along the glacier des Bossons—in ascending from the Pierre Pointue to the Pierre à l'Echelle—in the fracture of the schists a little beyond the Chalet des Motets; in the Val de Bérard; at the lower part of the glacier de Tré-la-Tête; at the bottom of the Val de Bionnassay, opposite Champel; in the gorge between Mont Rouge and the Aiguille de Peuteret, (Val Veni), &c. It is evident, therefore, that whenever the glacier in its active condition found a surface wide enough to afford it a passage, it wore down and widened this area proportionally, reducing the obstacles and rough prominences that obstructed its progress, but that where the space was narrow, and bounded by closely approaching walls, it passed over, i. e. did not force its way through the narrower passages. And this might be reasonably expected; since the glacier being plastic and expansible, is effective only by its mass; it cannot, like drops of water, make a hole for itself with the aid of time. It passes where its properties can produce an effect—where its efforts will have a practical result.

We must perhaps apologize for thus ascribing a kind of intention to a merely material substance. But this substance possesses properties peculiar to itself; and the more we study these natural phenomena, the more we are struck with admiration at the series of operations which, though slow, always produce their effect in the direction of the forces

proper to them, without spending useless effort, or losing time.

We will now consider glaciers whose surface is widely extended, and which are not laterally bounded by rocky banks.

Such glaciers in fact can only exist at great altitudes. Exposed to the sun's rays, they have quitted the lower grounds and taken refuge at a height of 8000 feet, with a northern aspect, and protected by elevated peaks.

When these conditions are wanting they have almost entirely disappeared, and we must ascend more than 11,000 feet to find them at all. Even then they can scarcely be called glaciers, but consist of snows or accumulations of névé.

At the present day therefore, the only glaciers of this order on the massif of Mont Blanc, are, the glacier du Tour—the largest of all; the glacier de Lognan, and the small glaciers des Nantillons, de Blaitière, des Pèlerins, and de la Frasse.[7] Most of these glaciers are fed by névés situated at great heights, insignificant in point of extent, but very thick, on account of the depth of the ravines that form their beds.[8]

In commencing they descend along comparatively gentle slopes. Instead of forming lateral and frontal moraines, they arrange their rocky débris in an elliptic curve, so that there is an insensible transition from lateral to frontal moraines. Natural embankments being absent, they produce them mechanically,

[7] See general map.

[8] The glacier de Tour whose névés occupy a large plateau, at a mean height of 9500 feet, must be excepted.

making a bed with its margins for themselves,—a bed that is sometimes convex.

At an era not very distant from our own, there existed a much greater number of glaciers of this kind.[9]

In the present day, therefore, we can easily study their beds, which are barely abandoned. Such are the glaciers above the Lacs Blancs; those of Lac-Cornu, below the Aiguille de la Floria, which are much reduced; such is that of les Fours, which has been completely melted, but of which a remnant existed three years ago.

The beds of these glaciers exhibit the moutonné aspect in the rocks, immediately below the summits against which they rest. These moutonné surfaces are perfectly clear, and the débris have been thrown into the hollows of the rock which the glacier did not mould, or under the shelter of breaks, as shown in Fig. 59. The moutonné prominences are more or less salient in proportion to the resistance offered by the rock; and between the hardest strata erosions have been produced, which hold pools of water. At the glacier des Fours, the strata exhibit themselves transversely to the incline; the whole of the surface of the bed presents a succession of furrows more or less convex, with hollow fractures above or below, as shown in Fig. 60, before or behind which moveable débris have been left by the current (see A).

These glaciers, extensive in surface, flat, and with their beds convex, have been often formed with destructive effect to the more elevated plateaux,

[9] In 1873.

which they have successively razed. This requires some explanation.

Fig. 61 represents an upheaved mass, A B, presenting an elevated plateau, whose strata are almost vertical, with an abrupt escarpment, A C. The snows were accumulated from A to B during the glacial epoch and are lying in fallen masses, between C and D, where they have begun to form a glacier.

Fig. 60.—Bed of the glacier des Fours.

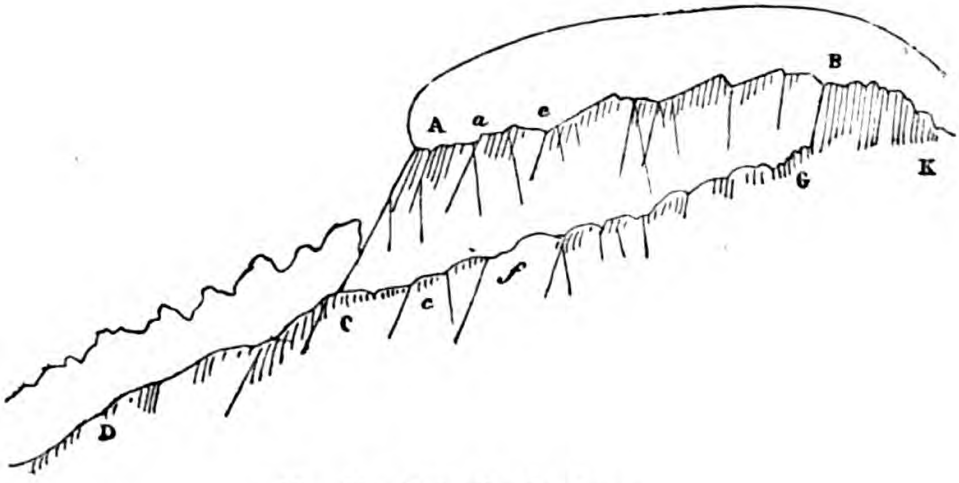


Fig. 61.—Ruin of rocky slopes.

But the slope A C, which is precipitous, was generally bare;[1] and this cliff, exposed to atmospheric agencies, was being constantly disintegrated. The débris borne down by the avalanches fell on the glacier, which carried them away. The cliff A C would

[1] See Figs. 30 and 42.

have retreated chiefly during the summer, to *a c*, then to *e f*, and so on as far as B. The dilapidation, however, could not extend below C, because, in proportion as the wall fell away, the glacier increased and covered the ground rising towards the summit, since it was being constantly fed by the higher névés.

But as the plateau A B became smaller, the névés began to diminish, and the glacier was less copiously fed. It thus tended to decrease; and if the last portion of the plateau B was in its turn disintegrated, the glacier had no longer a reservoir to supply it. Unless, therefore, we suppose the altitude of the bed C G K to be considerable, the glacier would disappear and be replaced by patches of snow, which, melting during the summer, could no longer form a glacier properly so called.

This phenomenon very often occurs, and all the nnconfined glaciers occupy the place of plateaux higher than their present bed—plateaux of which a few ridges or peaks are the only remains.

These unconfined glaciers follow in other respects the laws which govern the glaciers of the valleys. They advance as do these, and survive only as long as they have an upper reservoir considerable enough to supply them and to provide a longitudinal axis, that is an active nucleus. They have their zones which present a curvature more and more decided towards the limit of ablation.

They throw off their débris in a similar way on their sides, thus forming moraines. Only as they are not closely shut in by rocky walls, and have no other banks but those they have made for themselves, they produce a more powerful effect on their

beds than the glaciers of the valleys have on theirs, because their expansion does not force them to thrust against the banks and form an arch.

The sites of the unconfined glaciers, especially if these sites are slightly convex (which sometimes happens), are therefore more deeply eroded than are the lower parts of the beds of the valley glaciers, and exhibit less of débris on their surface when they have disappeared through ablation.

But it will also happen that glaciers have filled wide valleys, and are afterwards, when the reservoirs become less considerable, sensibly reduced in width, while continuing to descend down the thalweg of the valleys, forming in them a long train of ice, gliding between elevated moraines.

And this is a satisfactory proof of the energy of the glacier in the direction of its great axis, as compared with that of its margins; since we see the central current continuing so long after the ablation of the sides. This phenomenon is exhibited with singular clearness in the upper part of the Val de Macugnaga (Italy).

The glacier which descends from Monte Rosa into this valley, and is crowned by the Zumsteins-Spitze, formerly filled the slopes of the Jager-Horn, of the Cima di Jazzi, and of the Weissthor on the north-west, and that of the Pedriolo-Alp on the south-east, with a thickness of from nearly 1700 to 2000 feet. But the reservoirs lying between the ridge which unites the peaks Zumstein-Spitze, Dufourspitze, Signal-Kuppe, and Jager-Horn—a ridge which forms an immense amphitheatre—have long ceased to be capable of supplying so extensive a basin. The glacier has diminished in width though it still con-

tinues its course as far as the cascade of Rogo-Staffel, and looks like a long serpent of ice winding through the middle of the vale, rising much above the level of the thalweg, and bordered by two lateral moraines

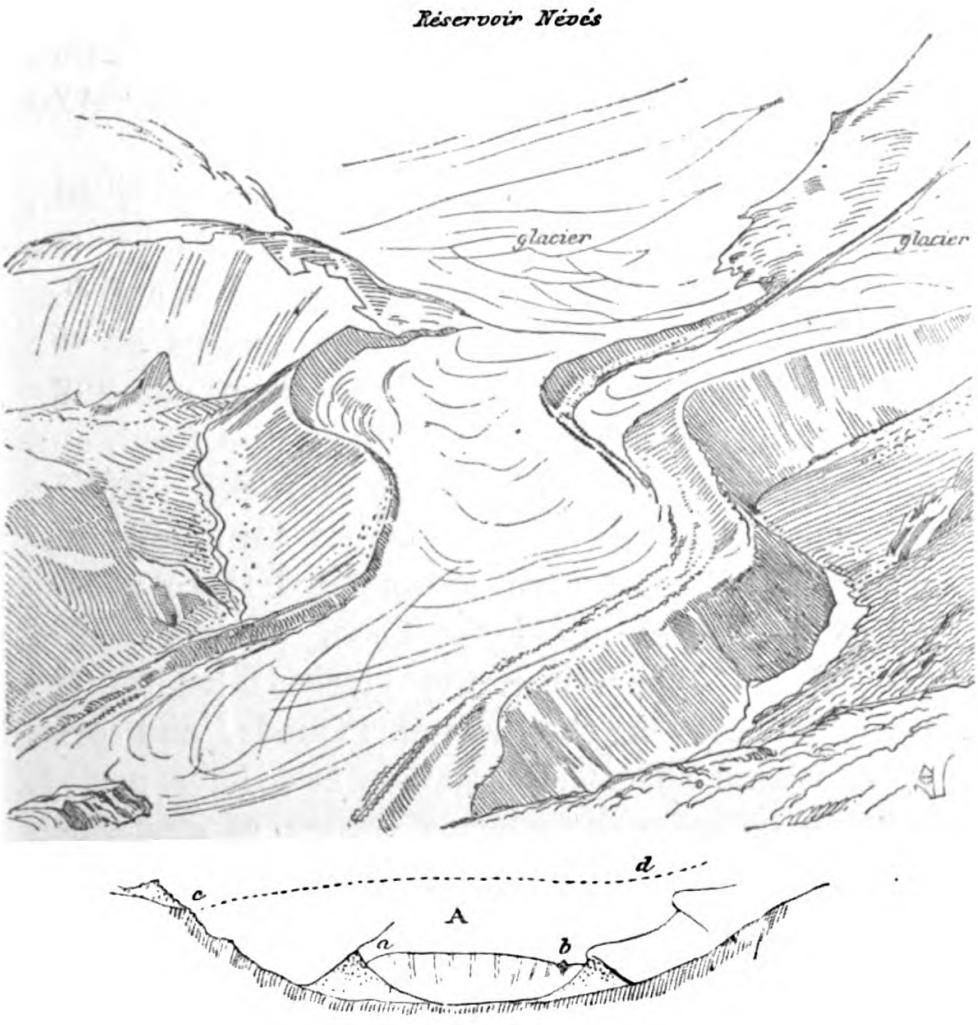


Fig. 62.—The glacier de Macugnaga.

which are perfectly regular—Fig. 62.[2] Section A shows the present position of the glacier de Macugnaga in the valley, with its two lateral moraines *a b*,

[2] Taken on the ascent to the Weissthor.

and its ancient surface at *c d;* that is, during the last period of the glacial epoch.

Some glaciers have had time to deposit very extensive frontal moraines, which are remarkable for an irregularity contrasting with the regularly and equally sloped arrangement of the lateral moraines. The reason is, as already indicated, that the deposit of these frontal moraines is subject to various accidents.

Independent of the medial moraines (Fig. 52), which necessarily accumulate in mounds at the terminal point of the glacier, if materials are dislodged in such quantity that the surface of the glacier cannot entirely distribute them along its shores, the débris are deposited in the front, and form there a heap of sand and rocks. But it happened that the glaciers whose terminal point remained the same have accumulated there a considerable frontal moraine. Then, when a period of increase supervened, the glacier filled up the intervals between the frontal mounds, and even went beyond them. Decreasing at a later period, it leaves between these heaps masses of ice, which it has covered with débris, and has thus long retained unmelted.[3] These ice-masses ultimately melt, and disclose the fosses and intervals which they had filled.

It may also happen that medial moraines pass into the condition of lateral and frontal moraines.

If, for instance, one of the two glaciers between which a medial moraine descends happens to decrease

[3] In 1872, in the frontal moraine of the glacier de la Brenva, masses of ice could still be seen beneath the sands and stones which the glacier had left there in retreating.

more rapidly than its neighbour, the medial moraine becomes a lateral moraine to the other. But if a lateral glacier descends into a trunk glacier, Fig. 63 —A B being the trunk glacier, and C D the lateral glacier—there is a medial moraine at *a b*. Supposing the lateral glacier C D to be more active than the glacier A B, because the reservoirs of the latter are

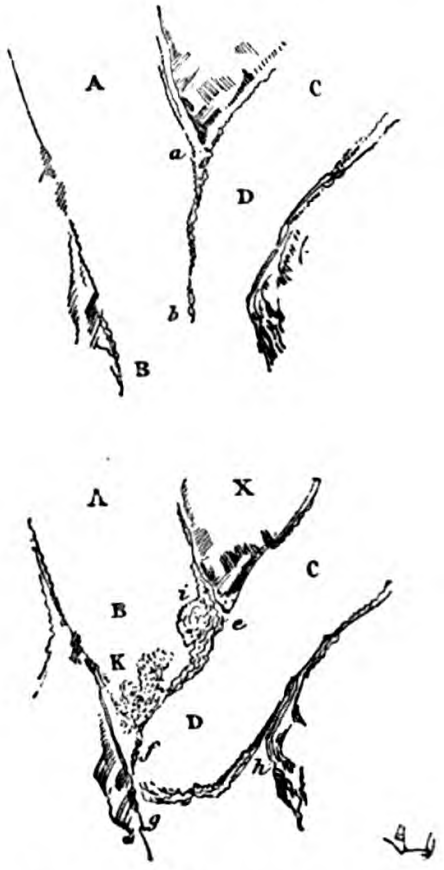


Fig. 63.—Dikes produced by moraines and glaciers.

more distant, or its slope is less decided from A to B than from C to D, and there is a successive ablation of this glacier A B, so that its surface is depressed, the glacier C D passes over this surface (see X), deposits a lateral moraine, *e f*, on this surface, and another lateral moraine at *h g*. If the glacier A B

completely disappears below *g h*, the glacier C D bars the main valley, and the moraine, which was formerly a medial one, *e f*, having become a lateral moraine, joins with the frontal moraine of the glacier A B. If subsequently the two glaciers melt at their terminal point, so that this retreats to a higher position, we can understand the disorder in which the moraine *e f* will be left, and what accumulations it will have deposited at *i* K. This phenomenon frequently occurs, and may be observed on the right bank of the glacier des Bois, whose immense moraine almost entirely blocks up the valley of Chamonix, below Lavancher, changing from medial to lateral, and subsequently becoming frontal to the glacier that came down from l'Argentière. It may also be seen below Mattmark (the upper part of the Val de Saas). There the glacier d'Attalin blocks up the valley, and the glacier de Schwarzenberg (a trunk glacier) has for a long time brought its terminal point to impinge upon this barrier, and has deposited an enormous mass of débris upon it.

Having retreated higher up, the right lateral moraine of the glacier d'Attalin, which is also frontal to the glacier de Schwarzenberg, forms a dam which shuts in a lake. The torrent is compelled to find an exit through a tunnel which it has hollowed out for itself beneath the extremity of the glacier d'Attalin. Originally these two glaciers descended along the Val de Saas, and the right lateral moraine of the glacier d'Attalin was the medial moraine whose débris are found lower down.

We see also in the Val Veni a similar arrangement in regard to the great glacier de Miage, which bars the valley and retains a lake. But in the Val Veni

the trunk glacier which descended from the col de la Seigne has completely disappeared, like most of the glaciers of the great cols in the Alps.

In discussing the general aspect of the glaciers, we have still to mention the glaciers of these cols. All the wide cols that are now passable are only the beds of ancient glaciers, which, instead of following one declivity, pursued their course along two opposite slopes. The cols de la Seigne, de Balme, Ferret, du Bonhomme, around Mont Blanc—of the Splügen, Saint Théodule, Saint Gothard, the Furca, the Ober-Alp, &c.—are beds of immense glaciers which divided into two branches in opposite directions.

Among all those just mentioned, the col du Saint Théodule is distinguished as occupied by two glaciers still active—one which descends to the Breuil in the Val Tornanche, the other into the valley of Zermatt. We are not speaking here of very elevated cols, such as those of the Géant on Mont Blanc, and the Weissthor on Monte Rosa, which are only depressions in a ridge at an altitude of from 10,000 to 13,000 feet. These are mere accidents, not general features, resulting from the conformation of the mountains. The great cols are the remains of a line of junction between two mountain massifs. Referring to Fig. 12, we see, e. g., that the massif of Mont Blanc was originally bordered by two long depressions, which were interrupted on the south and on the north by elevations uniting the massif to its neighbours. On the south-west the elevation was not considerable enough to prevent the great primitive glaciers from passing over it, and partly disintegrating it. But towards the south-east,[4] the

[4] Col de la Seigne.

north-west,[5] and north-east,[6] the connecting heights almost reached the altitude of the massif,[7] constituting real dikes which the glacier-currents could not pass, but on whose ridge they took up their position to descend on the two opposite banks. These dikes, however, formed a depression uniting more elevated points. The névés were accumulated on their ridge according to certain special conditions, determined by the neighbouring summits, the slopes and the aspect. Let us examine one of these cols—the col de Balme, situated at the northern extremity of the valley of Chamonix, and dividing the waters which flow on the one side into Switzerland, on the other side into France.

The col de Balme, Fig. 64, during the glacial period, reached within a few hundred yards the two summits B of the Croix de Fer, 7675 feet, and C of Les Grands, 8800 feet.

At the present day the col, properly so called, is at A, 7230 feet, but it was at that time at a higher level, and on the junction line of the two summits B C—a ridge which has been much broken down on the eastern side, and consequently presents the curve B A C. It must be remarked that I K is the line separating the mica schists from the lower jurassic series; the jurassic beds being situated at the north-west, and the schists at the south-east, and a belt of *cargneule*[8] at M. There was therefore a weak, vulnerable part in the middle of the depressed junction ridge B C.

We observed that everything led us to suppose that during the glacial period the prevailing winds,

[5] Col de Balme. [6] Col Ferret. [7] See the general map.

[8] *Cargneule*—name in Alps for the concretionary, rubbly, and some what marly limestones of the Keuper. (F. S.)

charged with snow, blew from west-south-west; if, then, we make a section on the depressed ridge which formed the original col de Balme, from west to east, Fig. 65, the slope A B, opposite to the west, is less

Fig. 64.—The Col de Balme, glacial epoch.

declivitous than B C, opposite to the east; and the difference was still more marked originally, as numerous proofs attest. As the direction of the wind

followed o v, the snows must have been deposited on the ridge, as seen at *a b c*, so that in consequence of the inclination of the escarpment B C, and the sectional form of the névé itself, the avalanches must have been chiefly produced on this slope B C, opposite the wind. Consequently this escarpment B C was first exposed to disintegration, and the lower point of the ridge, the col, retreated to D. Thus we see at the present day, in the slope D E, deep erosions in the rocks, small lakes, and considerable excavations, as we approach the neighbouring summits left behind the curve B A C, Fig. 64.

The col de Balme, therefore, which reaches an

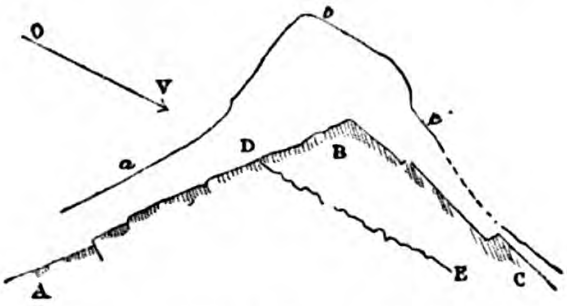


Fig. 65.—Disintegration of the Col de Balme.

altitude of 7230 feet, has been lowered by the difference between the points B and D, and presents, as do all the great cols, in vertical projection, a manifest curvature.

But the cols did not always present a ridge in transverse section like the cols de Balme, Ferret, and de la Seigne; sometimes this section exhibited a kind of depressed plateau between two more elevated plateaux—a depression more or less wide and irregular. Such was originally the col du Saint Gothard. In this case two glaciers, formed on the ridges, descend from opposite directions, meet, pro-

duce a vast accumulation, and take their course on the two outer slopes; but their opposing efforts have occasioned considerable disintegration on resting-places of this kind—erosions which show how powerfully the ice acted. Here there are no steep escarpments enclosing the glacier, and hindering it from acting on its bed. The depression was inconsiderable; but the altitude and the winds caused enormous masses of névés to accumulate on these points during the glacial period, and the beds are profoundly furrowed, all the less-resisting parts having been ploughed and rasped without leaving much débris. In the hollows, moreover, small lakes show their surface of sombre blue,[9] and the salient points of the rock are smoothed, grooved, and *moutonnés*. These cols present a most striking aspect of desolation, and we ask ourselves how, at altitudes which seem to be so little overtopped by the neighbouring summits, the ice could have produced such deep erosions and so powerful a smoothing effect.

The reason is that the arrangement of the rocky masses themselves made the depressed part adapted to receive an immense thickness of snow, occasioning tremendous pressure.

At the present day, when the same phenomenon

[9] These small lakes are characteristic of the cols, and are always hollowed out in the rock; proving the powerful action of the ice on these passes—which generally have no great masses impending over them—and consequently the depth of the primitive glacier. It must also be remarked that several of these cols were, during the glacial epoch, dikes over which enormous glacier currents passed. Such, e. g. was the col de Voza, and perhaps the col de Balme. But we shall have occasion to give the direction of the glacial currents, at the culmination of the glacial epoch, in the "Description of the Massif."

is produced on a small scale, we see that in depressions of this kind the snow is heaped up in compact masses, in consequence of the currents of air eddying about between the two neighbouring summits. On these cols, therefore, very considerable accumulations of snows were produced, further augmented by the avalanches precipitated from the two neighbouring summits, which were then nearer to each other than they are now.

The level character of the neighbourhood of these depressions was also a cause of accumulation. We must therefore not be surprised that, during the glacial period, these cols were the starting-point for great trunk glaciers, and that the ice before quitting these plateaux, and beginning its advance, produced a mass of disorderly ruin such as is witnessed nowhere else.

If from the col du Saint Gothard we look at the granite peaks which bound it towards the east, we perceive in fact nothing but a skeleton, as it were, of the ancient glacier—a skeleton which sufficiently demonstrates the power of ice to ruin and denude; (Fig. 66).

Thus, therefore, even at its starting-point, the glacier acts as energetically, if not with so decided a rapidity as during its course. From its very formation it breaks off and rasps down the asperities, and removes their débris. It hollows out the less resisting parts by friction, under a very considerable pressure; it gathers the fragments that have fallen from the neighbouring peaks, and reduces them to sand; using them like emery to polish its bed; and then deposits this detritus on its margins or front, where, during a later period, the melted snows will

come and carry down these heaped-up materials to fill up the bottom of the valleys.

These moraines, whose aspect is so dreary, where vegetation is absent, and which present to the explorer such formidable dikes to be crossed—these moraines, I say, are the great stores of sand, which, carried to remote distances, and mixed with vegetable detritus, and perpetually watered, furnish those deep and fertile soils in the lower valleys, which are covered with a rich vegetation.

The glaciers are, then, the first and the most powerful of the agents employed in forming the alluvial lands. They have prepared the materials destined subsequently to level the bottoms of the great valleys. They have placed barriers which dam up lower lakes, forming great reservoirs adapted to regulate and feed the supply of the water-courses.

They have opened out the valleys which were at first only depressions—hollows without issues. They have rendered the mountain masses accessible. Water then was to accomplish the ultimate completion of this immense labour.

VI.

GLACIER MUDS.

THE glacial epoch had a very long period of decrease. The trunk glaciers which, fed by the lateral glaciers, descended to an altitude of six hundred feet above the level of the sea, around the massifs of the Alps, and perhaps still lower, retreated by successive stages, always leaving in front of them, and on their margins, those frontal and lateral moraines whose vast remains we behold.

We have indicated, Figs. 31, 32, and 33, some of the causes of this phenomenon of retreat. The chief of them, besides the meteorological causes that are unknown to us, was, that the glacier, in making its bed, and facilitating its outflow, contributed to its own ablation. Melting took place more readily towards the lower parts, inasmuch as, the advance being less impeded, the supply from the névés was more easily discharged.

If heavy rains supervened, they melted in the lower parts of the glaciers an enormous bulk of ice; the resulting floods, held back by the frontal moraines which opposed a barrier to their escape, deluged their embankments, and precipitated themselves

with them in masses of mud down the vales,[1] which they filled with débris, and then came to a stop, settling in the hollow parts of the valleys, where they formed a kind of coarse concrete, which assumed a certain degree of hardness under pressure. Thus were formed many diluvial post-glacial conglomerates, which are observed beneath the present soil of the valleys. Sometimes, masses of ice were rolled along with these muds; in melting they left in the dried-up deposit, pits whose presence cannot be otherwise explained.

Since the study of glaciers has become a part of science, and has been based no longer on more or less ingenious hypotheses, but upon actual observation, the moraines and erratic rocks have received considerable attention from the explorers of mountain districts; and with reason, since they afford a clear testimony to the extension of the glaciers, and to their diminution. But we must not confound the moraines deposited by the glaciers with the accumulations of glacier mud, which may be seen at a lower level than the real terminal moraines. And it is easy to distinguish a real moraine from an accumulation of glacier mud. The moraine always leaves considerable interstices in its mass. Being gently deposited, and formed of débris of all dimensions, these débris, when they are considerable, often touch only by their angles or edges; and between them there remain cavities which the sand, also brought by the glacier, grain by grain, does not fill. When, on the contrary, the moraine has been thoroughly

[1] We may see this phenomenon any day, on a small scale, at the bottom of the glaciers or accumulations of snow.

flooded by water, and borne down by it in the form of thick mud, all the interstices are filled, and though the large stones preserve their edges as in the deposit, because they have not been carried far enough for them to be rounded, and their movement has been slow, they are completely embedded in the sand, which is closely and compactly settled. These moraine muds often form very considerable accumulations, and have been confounded with true moraines.

Fig. 66.—Eastern part of the Col du Saint Gothard.

It will be readily understood that the advance of the moraine mud is not regular like that of a glacier. If the incline is steep, the mud advances more rapidly than if it is gentle. But what is the manner of its advance? It very nearly resembles that of melted lava. It rolls, because the friction on the part that touches the bed arrests the mass there while its upper part is advancing. In rolling, it leaves behind it a deposit which remains, becoming thicker as the rolling mass diminishes in volume,

and consequently loses propulsive force. To such a degree is this the case that (Fig. 67) on the gentler inclines the moraine muds have been deposited as seen

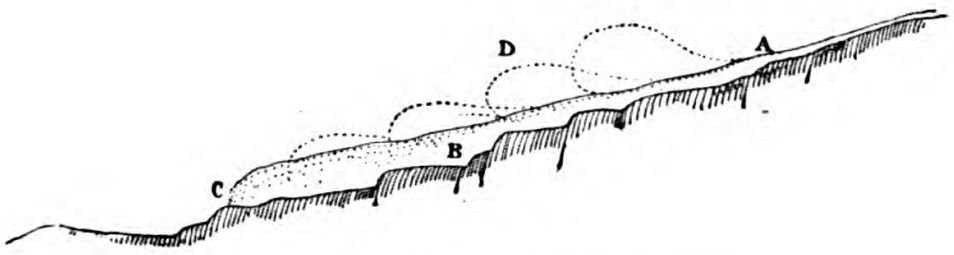


Fig. 67.—Mode in which glacier mud advances.

at A, B, C, in consequence of a series of movements, A, D, E. They have therefore contributed to render the incline from A to C still more gentle and regular.

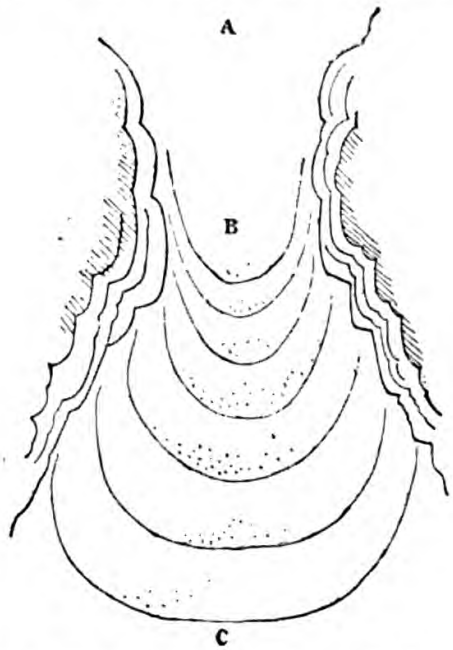


Fig. 68.—Mode in which glacier mud advances.

When the moraine muds have been formed above a gorge, Fig. 68, A, and in consequence of the incline have traversed a defile, B, in great volume, they

spread through the lower valley, C, in the form of a cone, leaving the largest stones above, and transporting the sand lower down.

The moraine muds prepared the way for the torrents and alluvial sediments by commencing the regulation of the inclines, filling up the more abrupt irregularities of surface in the bottoms of the valleys, and breaking through dikes whose ridges the plastic glacier had often crossed without greatly lowering them.

Thus Fig. 69, A, B, being a rocky dike,—a barrier crossing a valley,—the glacier C, D, would pass over

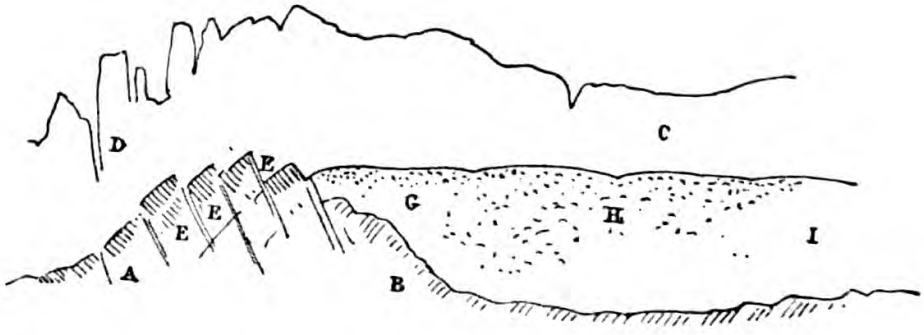


Fig. 69.—Accumulation of glacier mud.

and rasp its upper part, but would not produce any violent fracture of the dike; it would limit itself to continually removing certain asperities, tearing away portions, such as E, which opposed its passage: but when the glacier had retired, and enormous warps of glacier mud, G, H, I, descended, the pressure exerted by these yielding masses was considerable; the water they contained filtered through the fissures of the rocks that had been dislocated by frosts, and the dike was often broken through, as a retaining wall might be.

This result occurred, especially at points where

there was a junction of rocks of various natures and different degrees of resistance.

Below Sembrancher, the valley descending to Martigny was barred by a ridge of lias, shored from below by a protruded mass of porphyritic gneiss. The great glacier that descended from the Grand-Combin, Mont Colon, Mont Blanc de Cheillon, those which, along the Val d'Orsières, came down from the eastern slopes of Mont Blanc and joined the first, at the head of le Catogne, long passed over this barrier to unite with the great glacier which followed the valley of the Rhone. But when these glaciers had retreated towards the heights, the *débâcles* brought down at the point of junction enormous accumulations of mud which, arrested by the dike, reached even as high as its ridge,[2] and ultimately made an outlet for themselves by violently breaking down the dam from top to bottom, and scattering its materials far and wide, even to Bovernier.

We also find immense deposits of glacier mud on the slopes which rise from the valley of Sallanches to Saint Gervais; mud produced by the thawing of the glaciers, which having passed along the valley of Chamonix, crossed over the Prarion, traversed the col de Voza and came down upon this valley of Sallanches.

Part of the lateral moraine of this great glacier was carried down in the form of mud as far as the valley, when it was divested of ice.

[2] The traces of the mud reservoir are still clearly visible along le Catogne and on the slopes of the hills to the north-west of Sembrancher, at the chalets de Vence (3700 feet high) whereas the lowest part of the existing gorge is 2276 feet above the sea level. The mass of mud was therefore, at least, 1400 feet thick.

But it was chiefly at the expense of the clayey schists that this mud was produced in enormous masses, which have been transported to very considerable distances.

Glacier mud often filled up the lakes that had been formed after the withdrawal of the glaciers, in the hollow parts of their beds. Generally the mud was brought by the *débâcles* of the steep lateral glaciers.

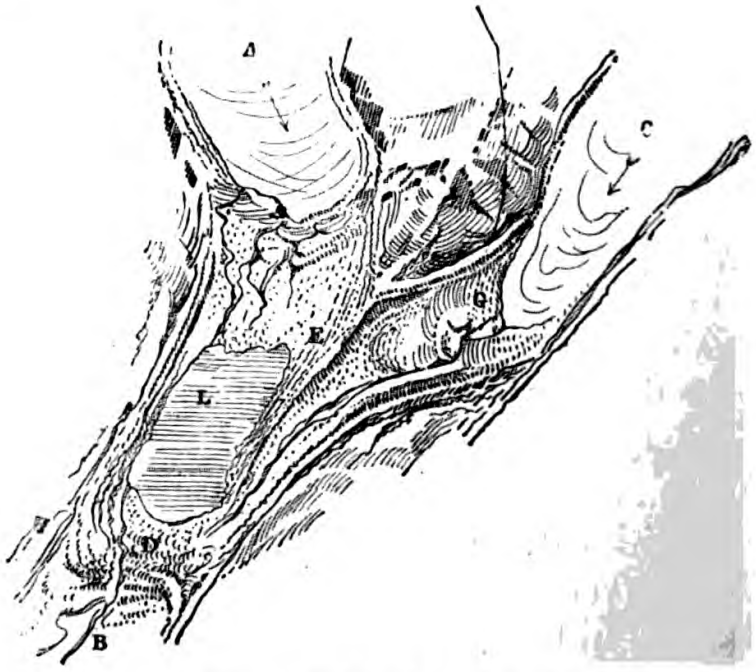


Fig. 70.—Formation of a moraine lake.

Let A B, Fig. 70, represent a trunk glacier having left at one of its stages of retreat a frontal moraine at D; a lateral glacier, C, having deposited the medial moraine E, its lateral moraines, and (on retiring) the frontal moraine G. A depression in the valley A, B, and the ancient frontal moraine, D, produced a hollow for the lake L. A sharp thaw supervened, the frontal moraine G and the medial moraine E were borne down

and filled up the lake with mud, leaving only the passage for the torrent along the right margin of the valleys.

If the lake in the trunk valley extended considerably above and below the lateral valley, the glacier muds issuing from the lateral valley would have cut it transversely in two; that is, of one lake would have made two, separated by a bank or dike. This may be observed at Interlaken. The glacier muds issuing from the valleys of Lauterbrunnen and Grindelwald, have separated the lakes of Thun and Brienz, which originally were only one. The alluvial

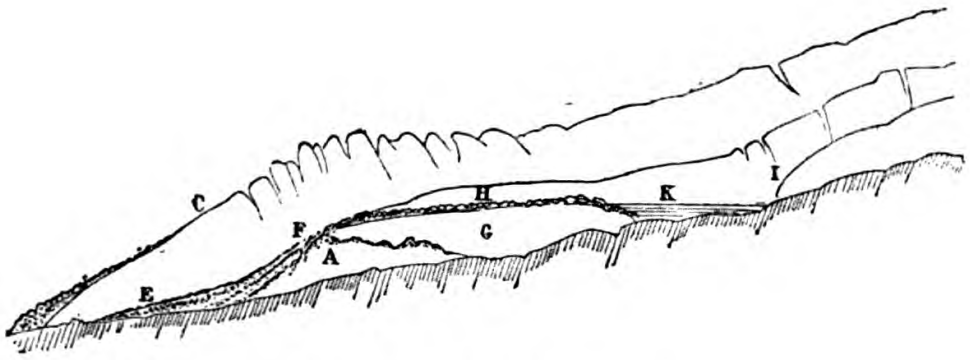


Fig. 71.—Formation of a moraine lake.

deposits from torrents have completed and levelled the obstruction.

Independently of the flooding caused by the abundance of rain during the warm seasons, the moraine mud is often occasioned by an occurrence at the base of the glaciers which presents itself even in modern times, though on a smaller scale.

At the glacial epoch, as in the present day, there were periods of relative increase and decrease in the glaciers. If therefore, Fig. 71, a glacier having deposited a frontal moraine, should happen to increase and pass beyond the moraine A, as in section B, C,

then, if it once more decreased, it would deposit the moraine débris E, F. When by ablation it had reached the moraine A, the latter would preserve the terminal ice, G, from being melted. Moraine débris would be deposited at H, on this ice, and the ablation would take place at I, higher up; so that beneath the frontal accumulations H, there remained a mass of ice G, which would also contribute to hold back the water proceeding from the melting of the glacier, which formed a reservoir, K. The effect of these waters would be to cause a rapid melting of the mass of ice, G, and with the help of the rains a time would arrive when the weight pressing on the former moraine A, would be so considerable that the whole would be borne down to a lower level in the form of mud of greater or less thickness, mingled with portions of the ice, G.

As already remarked, we often observe in these large deposits formed by the moraine mud, and which have roughly filled up the bottom of the valleys, or diminished the slope of the declivities, certain conical cavities of some depth. These cavities are due to blocks of ice which the masses of mud carried down with them, especially in the case represented in Fig. 71. The blocks that have been carried down immersed in the mud, and keeping their place in it, slowly melted while the mass was drying; and their melting has produced these basins. Fig. 71 *bis* represents an accumulation of mud A, B, in which a block of ice, C, is immersed. The block in melting naturally left a conical hole, *a b c*, which will remain visible if the débris brought down by torrents have not filled it up.

Such glacier mud which filled certain parts of the

valleys, and which had glided down the slopes, supplied those pebbles, stones, and sand which the torrents afterwards swept down with them. Hence was a first stage in the trituration of the moraine materials.

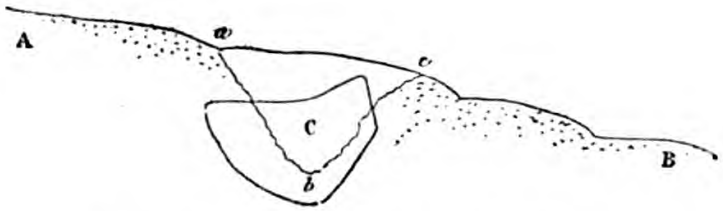


Fig. 71 *bis*.—Conical cavities in glacier mud.

VII.

FORMATION OF THE TORRENTS.

We have given only a general glance at the glaciers; it will be necessary to return to the subject, and to examine the causes of the regularity with which they discharge their waters—a regularity to which there are only occasional exceptions.

It has been ascertained that when the heat is great, or warm rains are prevalent, the torrents increase in volume; the discharge, however, does not correspond with the apparent amount of melting or of rain-water. At night, when the air is clear, above an altitude of 7000 feet, all the waters that furrow the surface of the glaciers in the form of small rivulets freeze again, and the murmur of these rills is succeeded by the most profound silence, while the torrents which issue from the glaciers continue to discharge a quantity of water nearly equal to that which they pour forth at night after a fine hot day. The glacier, therefore, serves as a kind of sponge, which at need retains the excess of water up to a certain point, or furnishes it from the reserved store. In the winter the torrents almost cease to flow, or are sensibly diminished; nevertheless, those which issue from the great glaciers, and when the tempe-

rature sinks to 4° Fahr. below zero, continue to discharge a certain quantity of liquid, issuing from a concealed reserve; since the melting on the surface of the glacier is null, and the ice, which was yielding and plastic during the warm season, has become brittle, *fière*, and has its temperature lowered from 32° to 23° Fahr., and even more, as far as a certain depth.

Having had the misfortune to fall into a "crevasse de fond"[1] (one that penetrates through the entire depth of the glacier), from which I was rescued, thanks to the devotion of my guide, Baptiste of Macugnaga, and the help of four mountaineers whom he found at Mattmark—though after a sojourn of more than three hours in this crevasse on a block of ice which had arrested my fall—I had full leisure to study the phenomena of the regelation and exudation of the glacier mass.

This crevasse, like almost all the *crevasses de fond* that traverse a glacier descending on a gentle slope, was wider at its base than at its upper orifice, and the entire fissure was nearly perpendicular to the incline, as shown in the section, Fig. 72. The zones of the ice *a b* (see B, Fig. 72), as soon as a rupture takes place, exert a tractive power in the direction *a b;* but at *c* there is resistance, resulting from

[1] In the Glacier de Schwarzemberg, at an altitude of 9500 feet, July 11th, 1870, from two to six o'clock p.m., about forty feet below the surface of the glacier.

[2] My fall having been arrested by a small block of ice A, caught between the walls of the fissure, it was easy for me to estimate the width of the separation of the latter towards the bottom, which, however, was invisible to me, the glacier being more than a hundred yards thick at this point.

friction, and there is no tractive action, whereas the part *d* continues advancing. This is why these *crevasses de fond*, on a plane slightly inclined, tend at first to open widely near the bed, and to be more and more inclined in a direction opposite to the acclivity, but afterwards to close towards the bottom, in proportion as the glacier approaches its terminal point (see D).[3]

From the point A, which was my position in the

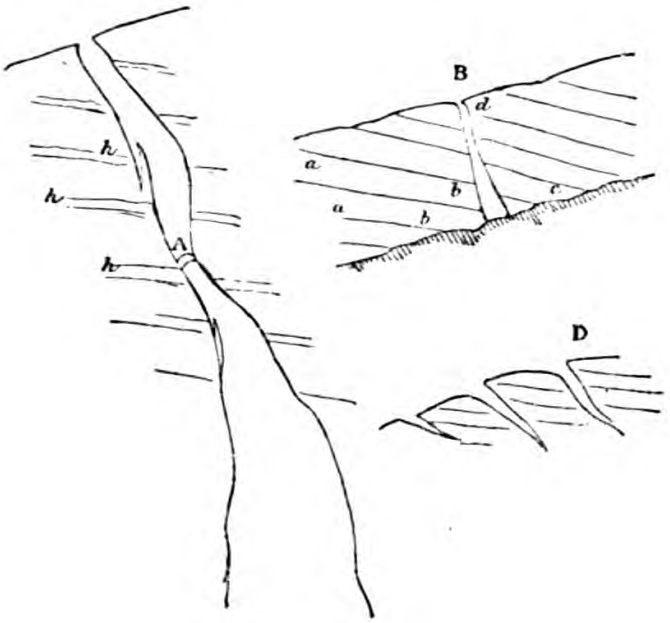


Fig. 72.—Crevasse.

crevasse, I could very well see the oblique layers *h*, which were blue and more transparent than the white mass, and, besides these zones, blocks, which were also more transparent, embedded in the white ice.

[3] See the lower part of the Mer de Glace and of the Glacier de l'Argentière, where this arrangement is very manifest, as these glaciers follow a plane which is pretty regularly inclined during their whole course. See also Fig. 57 *bis* and the accompanying explanation.

These layers and blocks, which were more transparent, affected an orbicular structure, consisting of large kidney-shaped masses of ice, perfectly limpid, locked into each other, and containing smaller pieces of a spherical form. From these transparent and globular parts of the glacier issued at certain points exudations more or less abundant; yet these transparent parts were harder, and resisted a blow better, than the whitish parts, which did not produce exudations. The thermometer in the open air marked 41° Fahr. at three o'clock p.m., and 36°.5 Fahr. at six o'clock, the sky being much overcast; and yet, on issuing from the glacier, the exudations quickly froze again to a great extent, and formed stalactites and stalagmites around me. Most of these liquid emissions issued from vertical or horizontal fissures two or three inches in length by about an inch or less in breadth. If the fissure was horizontal, the regelation assumed the form of an inverted gutter, smooth above, but covered with tubercles below (see A, Fig. 73). If the rift was vertical, the regelated water would present the stalactites B, which would increase in an hour from eight to ten inches, so that they would become detached and fall to the bottom of the glacier, and then the operation would begin again.

But, besides these infiltrations, some would proceed from the bottom upwards, like small lateral jets issuing under pressure. Then the regelation would take the form C. This latter regelation in the air was most active, and would have considerable results. To enable the water to maintain its liquid condition in the body of the glacier, and to freeze again in the open air at a temperature of 41° Fahr., this water must

have been subject to a considerable pressure, and was enabled to freeze in the body of the glacier in

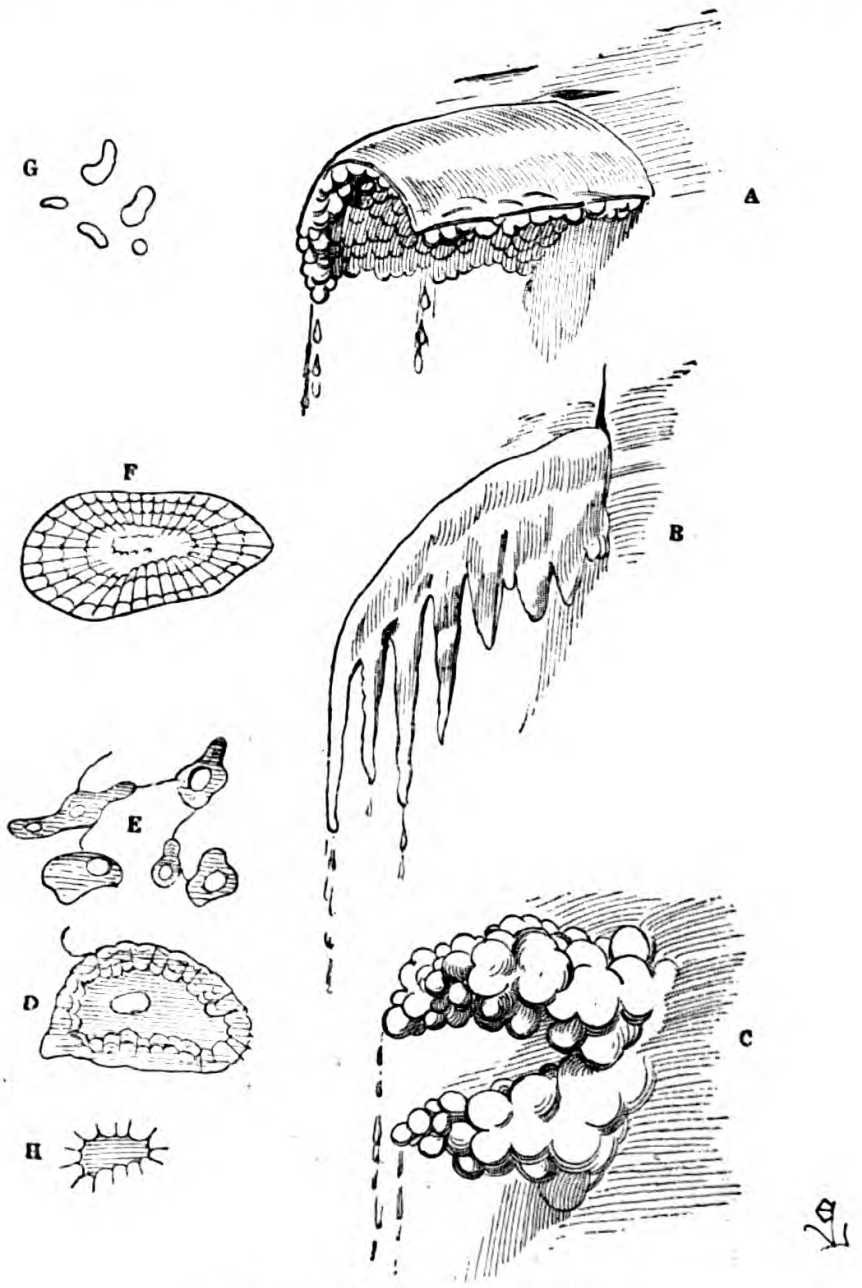


Fig. 73.—Phenomena of regelation.

consequence of the motion communicated to it by the pressure, or the effect of the pressure itself.[4]

[4] On this point I will cite a passage from my scientific friend,

Whence we may conclude that the glacier discharges from its mass a considerable quantity of water, but

M. Charles Martins, who explains this phenomena clearly :—" To understand the effect of the pressure of the glacier ice, we must first notice and explain what takes place when pure water is compressed in an apparatus similar to that employed by Professor Tyndall for ice. Let us suppose this water at a temperature near freezing point; experiment shows that *pressure* will *lower* its point of congelation; that is, the stronger the pressure the lower will the degree at which the water congeals be reduced below freezing point. This is the explanation of the phenomenon, theoretically anticipated by Carnot, and experimentally proved by Sir William Thompson, Professor of Natural Philosophy at Glasgow. Every one knows that ice occupies a volume larger than that of the water of which it is formed. Thus a bottle, and even a bomb-shell, filled with water bursts when it is frozen. But the pressure increases the amount of movement required for the expansion; that is, the forcing asunder of the particles of water when passing from the liquid to the solid state. This motion, or, if we prefer so to regard it, the force which produces it, is contained in the water itself, under the *form of heat;* when, therefore, it is subjected to a pressure, strong or slight, the ice will borrow from the water itself an amount of heat greater than if it sustained no external pressure—that is to say, if it were placed in an exhausted receiver; in fact, under more or less pressure, the power necessary to force asunder the particles will be more considerable than in a vacuum. Consequently, the temperature of the compressed water must be lower at the point of congelation than that of the water subjected to no pressure. Calculation gives $\frac{3}{400}$ths of a degree centigrade (·0044 of a degree Fahr.) depression of temperature for one atmosphere of pressure.

" A beautiful experiment of Professor Tyndall's proves the truth of this theoretical conclusion. He places a very compact and perfectly transparent prism of ice at freezing point, between two slabs of box-wood. In proportion as the prism was compressed, films of water continued to be formed in the interior. The ice melts, because under this pressure the internal temperature of the prism, not being any longer low enough to allow

that it regulates this discharge by a more or less active regelation when the water ceases to be subjected to the pressure exerted by the expansion of the ice. The crevasses serve to distribute this discharge into the torrent below, and feed it at intervals by supplies measured drop by drop. The transparent zones, separated by nearly equal spaces, are beds in which the liquid circulates at various heights in scarcely perceptible tricklings, which are compelled to follow innumerable capillary windings before finding an outlet.

When they find it they do not completely discharge themselves; the glacier, through the partial regelation of the liquid, retains a considerable quantity. Thus the glacier torrent, at its origin, is regularly measured out, and the variations in the atmospheric heat, or a certain quantity of rain water, increase it, only in a regulated proportion. In regelating the water arising from melting, or rain, the glacier absorbs a certain amount of heat. This quantity of heat, and still more effectually the pressure exerted on the capillary streamlets, keeps the water in the liquid state till it finds an issue. Being then subjected only to the pressure of the atmosphere, this water freezes in contact with the air, although the temperature is above freezing point.

Regelation was so vigorously proceeding on the walls of the crevasse, that, having seated myself on the very narrow block of ice, which had arrested my

the water to remain in the solid state, the latter passes back again into a liquid condition."—"*Les glaciers actuels et leur ancienne extension*," taken from the "*Revue des Deux Mondes*," 1867, Ch. Martins.

fall, in a few seconds my clothes were so frozen to it, that an effort was required to detach them.

The ice of the glaciers contains not only water in a liquid state, but also cavities and air bubbles. These cavities present very various appearances. Sometimes the air-bubble is contained by the ice itself (see G, Fig. 73). Sometimes it swims in a small liquid cavity (see E). These liquid cavities are fed by capillary fissures. But (see D) if it happens that the cavity is larger the air-bubble swims in a more considerable volume of water, and a geode of ice tubercles is formed on the walls. I had before my eyes some of these geodes entirely filled with ice by layers of tubercles (see F), thus exhibiting orbicular masses four to eight inches in diameter, and others, which did not contain any air-bubbles (see H), but simply compressed water; for, having bored through one of these little cavities near the ice wall with my knife—and I had ample leisure for this amusement—the water spurted in a jet from it. What, then, were the causes of the total or partial freezing of these cavities?

For the compressed water which they contained to be able to freeze, the temperature of the surrounding ice must have been depressed below freezing point; and during the three hours of my stay in the crevasse, many of these geodes had made their tubercular walls thicker. I submit the problems thus suggested to the investigation of men of science, without endeavouring to solve them. These bubbles of air and geodes were in the blue ice, from which only capillary streamlets of water were issuing. But on the wall of the crevasse there was a fine large mass of blue ice encased in the white

ice. The ice—which was perfectly transparent—of this block of triangular section with its vertex downwards, was fissured, like that which is found at the terminal point of glaciers, by planes of a straight or curved direction, locked into one another and reminding one of the combinations of certain Chinese puzzles, Fig. 73 *bis*. Each piece was more or less

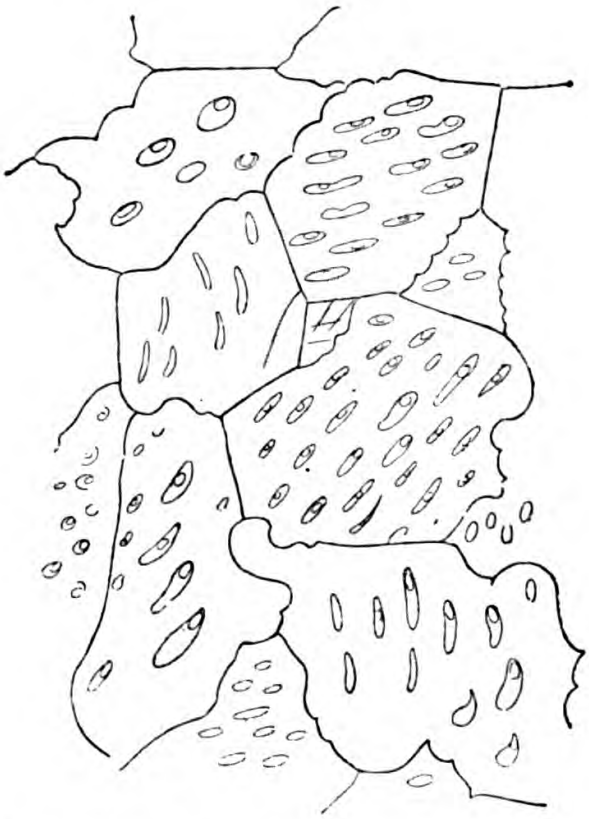
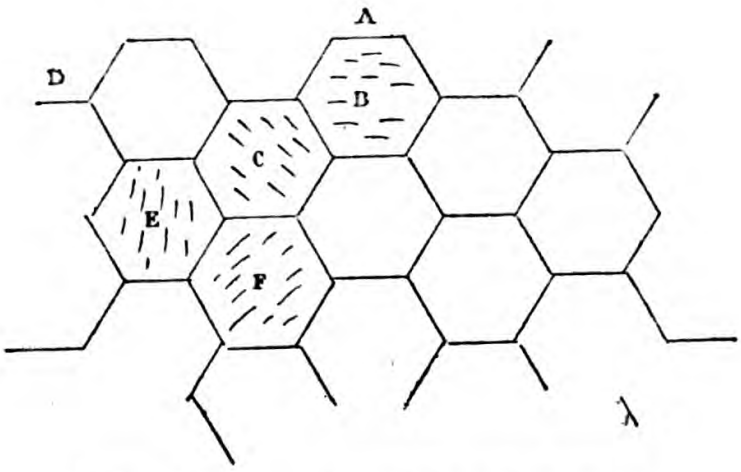


Fig. 73 *bis*.—Phenomena of regelation and compression.

interspersed with air or water bubbles, flattened in various directions, as shown in the figure.

Agassiz had observed the same phenomenon on the glacier of the Aar at depths of ten yards and more (my position was nearly forty feet below the surface of the glacier), and that distinguished geologist had concluded from it, that "every fragment of

ice is liable to displacements in the interior of the glacier independent of the movement of the mass." Perhaps not "displacement," but "individual pressure," would have been the more suitable expression. For the phenomenon of flattened bubbles of air being very perceptible at the terminal point of the glaciers, —where, evidently, we have only the lower part of the current, consequently that which has undergone the strongest pressure, the irregularity in the inclination of the flattened cells still continuing—we must conclude that this flattening is due to pressures in every



73 *ter*.—Phenomena of regelation and compression.

direction on each of these small interlocking blocks, which, being plastic in proportion as they are saturated with water, have had their cells flattened according to the direction of these various pressures. Since the blue ice consists entirely of fragments welded together and interlocked so as to fill the interstices, the form of each, and the arrangement of the neighbouring pieces, modify the direction of the pressure to which they are severally subject.

Imagine a solid (73 *ter*) consisting of hexagonal

prisms horizontally piled up; if a vertical pressure is exerted on the surface A, and the body, supposed to be plastic, contains bubbles of air, these cavities will tend to be flattened, as seen at B; but the pressure on the prisms C, will be exerted obliquely, and the air cells will be flattened obliquely.

If there is also a vertical pressure at D, the cells of the prism E will be flattened in an almost vertical direction. Suppose that at a given moment the pressure D is more powerful than the pressure A, the cells of the prism F will be flattened as shown in the drawing, and if the pressures are modified in either direction the flattening of the cells will be modified accordingly.

When in the morning, after a cold night, the surface of the glacier has frozen hard, as soon as the rays of the sun strike this surface, a continuous cracking noise is heard, as if a number of small explosions were being produced. And such is really the case. The thousands of small bubbles of air imprisoned by the recent frost expand and burst their thinly walled prison. But the innumerable bubbles of air which the ice of a glacier contains are subject to the slightest variations of temperature experienced by the glacier itself, which cannot re-freeze the water it contains except on condition of taking the heat from this water. Does not this very small quantity of heat alone produce an effect on the air bubbles, and may not the latter, reacting against the pressure to which they are subjected, contribute to impart to the glacier that kind of respiratory movement which hastens its advance? It is evident that as applied to movements oscillating between hundredths of degrees of temperature, our

instruments are coarse and our observations superficial.[5]

But we must never forget that in the production of phenomena nature proceeds by a system of means which are scarcely appreciable when isolated, and that its most striking results are due to the vast accumulation of these appliances. Just where I was the walls of the crevasse were very close together, and between them two curling splinters (*copeaux*) of ice exhibited the section, Fig. 74, approaching a cylindrical form, two or three yards long and only an inch or two broad.

This fact, compared with that illustrated by Fig. 24, shows how great is the pliancy of ice, and how a tractive action may be exerted in the mass. To get the section A, Fig. 74, it was necessary that the two walls in separating should preserve a bond, B, between them, which will have been thinned by melting, and then the wall C coming nearer to D, the plane of junction instead of being broken must have curved back on itself, as an elastic body would do. (See A.)

At the base of the glaciers nearly the whole body exhibits the transparent formation; the white parts, and those which seem to be heaped-up snow, have disappeared, to make way for blue but thoroughly bulbous ice. At the terminal point of the glacier the ice always exhibits that inlocking of pieces which is represented in Fig. 73 *bis*. And if it is exposed for a moment to the sun's rays, all these fragments which are separated by films of water can be easily

[5] We must also take into account the effect of the solar rays on the névés and glaciers, and which exert a certain *pressure*, as recent observations have proved.

disengaged. The transformation of the névé at the terminal point of the glacier is complete; the whole is one mass of ice through regelation. Between its point of departure and its lower extremity the constitution of the glacier has therefore been completely altered; from névé it has ultimately become ice by

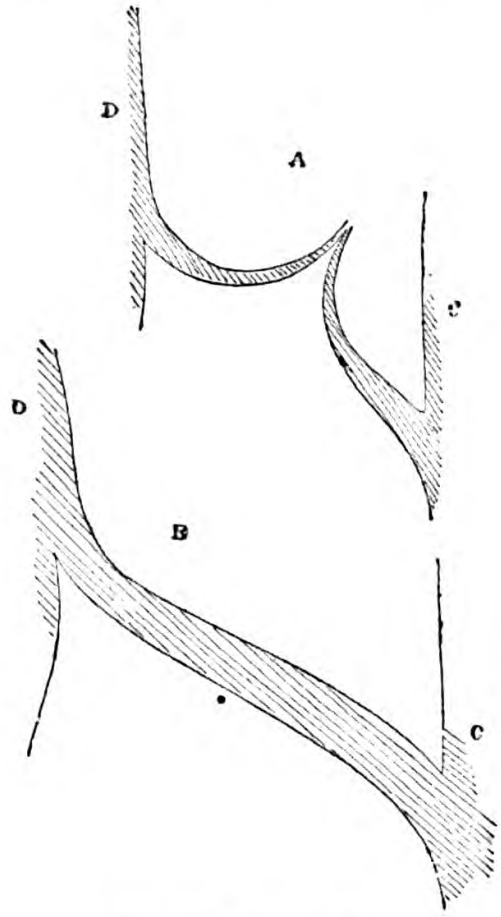


Fig. 74.—Pliancy of Ice.

melting, and by the partial regelation of what has been melted. In a word, it has partly melted and regelated, allowing only the surplus water, which it could not reabsorb by regelation, to flow away.

The further we advance down the incline of a glacier, the more numerous we find the zones of

blue ice, and the more active is the filtration. In the neighbourhood of the névés these blue bands are thin, are ordinarily oblique to the surface, and have been formed between the softest layers of névé. But even here their filtrating function manifests itself. The compressed and uniformly granulated mass of the névé allows but very little water to pass through it; and it is only when it begins to be saturated that the blue bands are formed in the less compressed layers in which this water is accumulated. The latter drives out a part of the air (we say a part, since the bubbles of air are still so numerous in the blue ice), and is refrozen. The ice is formed, and as long as it maintains a temperature not lower than freezing point it possesses plastic properties. The blue bands, therefore, would be the real transporting agents in the glaciers, whose advance increases in proportion as they are developed up to the point when the glacier, reduced by ablation, loses a great part of its power. And, in fact, the point of greatest activity in the advance of the glaciers is situated towards the middle of their course, between the névés and the terminal point.[6]

If the transparent and filtrating zones which we observe in the crevasses of the glaciers at an altitude of above 6000 or 7000 feet are due to the ice that has been formed between the periodical discharges of névés (see Fig. 58), the block, also transparent, which we see wedged in between these zones may be formed in the voids which these fallen blocks have left between them. We give this, however, only as

[6] See the very remarkable observations of Agassiz on the Aar glacier.

a conjecture; for much mystery still overhangs the formation of glaciers, and we do not pretend to dissipate it, but simply to add our observations to those which have been previously made.[7]

All the crevasses of the glaciers do not pass down through the mass in the direction of its thickness. There are some, especially towards the lower extremity, which exhibit a V-formed section; that is, which are wider at the surface of the glacier, and form two taluses more or less steeply inclined. These crevasses, called *gouilles*, are produced by the approximation of the walls, in consequence of the movement of the glacier and the melting of the edges of the opening. They often form reservoirs which preserve the water resulting from melting, and thus serve to supply water to the mass of the glacier by infiltration. It also happens, that in winter narrow

[7] We would call attention on this point to the remarks of M. Ch. Martins:—"The blue bands that traverse the white air-filled ice of the glacier are sometimes vertical, sometimes inclined, sometimes horizontal. These blue bands were layers of snow which, in consequence of very various circumstances, have been saturated by the water issuing from the melting of the layer itself or of neighbouring layers. The water drives out the air, and then freezes and converts the white ice into blue ice. . . When I visited the great plateau of Mont Blanc for the third time with my friends, MM. Bravais and Lepileur, we had, in clearing our tent, shovelled away the fresh snow that obstructed it. This snow formed blocks of considerable size lying on the névé. When three days had passed I perceived the blue horizontal bands, nearly half an inch thick, and extending to a depth of nearly one or two inches in the blocks of snow. The sun had slightly melted the edge of some layers through which water had filtrated, while others had not been penetrated by it. The blue bands are therefore layers in which filtration more readily takes place."—*Les glaciers actuels: Revue des Deux Mondes*, 1857.

crevasses are stopped up by the fall of snows which can always be distinguished by the relatively yellow tint, and which form in the mass, if the crevasses close up and are welded together, opaque bands which continue almost to the point where the glacier disappears; for the snow which falls at the surface of the glaciers below the névés, in the form in which it presents itself in our climate, never assumes the texture of the ice of the glaciers formed by the névés.

Whatever obstacles the glacier may have to surmount, or the escarpments along which it falls in seracs, it always forms again, and is welded together to resume its order of advance; and this very rapidly, i.e. at no great distance from the points at which it was dislocated by an accident of the ground. This fact is very singularly illustrated in the Rhone glacier, which, after having been utterly dislocated in descending an abrupt slope, at the altitude of the last winding on the route of the col de la Furka, immediately forms again and advances with regularity in the valley in the form of a circular arc, exhibiting concentric zones which are perfectly regular. Yet the distance between the great seracs and the terminal point is less than a mile and a quarter.

These seracs facilitate the melting by presenting innumerable surfaces to the air and sun; but they also tend to furnish a supply for the glaciers, if they are sheltered from the sun's rays. They accumulate the fresh snows which gain a lodgment between these broken masses, remain there and are welded with the mass; they present to the fogs a vast extent of regelating surface; they force the water arising from melting to take very long detours, and

these to a great extent freeze again during its windings. Thus, at the base of the seracs, when exposed to the north, the glaciers seem to renew their force; they swell out and begin to form themselves anew very energetically. It would seem, then, that the seracs can only supply the torrents to a great extent when they are so placed as to absorb the solar heat.

The experiments of Agassiz and of MM. Dessor, Dollfus, and other distinguished *savants*, have proved that glaciers present a temperature that very rarely sinks below freezing point in summer, even at a depth of about 200 feet; and that in winter, the lowering of the temperature to a certain number of degrees below freezing point operates only on the surface of the glacier, and produces a considerable effect only in the crevasses, or when the lowering of the temperature is long continued. In fact, as we observed, even in winter, the glacier (especially if its thickness is considerable) discharges a small quantity of water, while glaciers of trifling thickness become dry. During the summer, therefore, the ice has stored up a certain quantity of heat which allows a portion of the water held in suspension in its mass, to flow away, and if a very rigorous and long winter supervenes, the cold penetrates more and more deeply the mass of the glacier which thus stores up cold for the hot season; an interior temperature which contributes to the regelation of a more considerable volume of water when the spring meltings come, and proportionally hastens the advance of the glacier in consequence of the expansion produced by this regelation. In fact it is in spring that the advance of the glaciers is most energetic. Elie de Beaumont explained this phenomenon in the

Annales des Sciences géologiques, I., p. 558. "During the winter," writes this eminent geologist, "the temperature of the surface of the glacier is very much depressed below freezing point; and this low temperature penetrates, though with gradually diminishing effect, into the interior of the mass. The glacier cracks in consequence of the contraction resulting from this refrigeration. The fissures remain at first empty, and contribute to the refrigeration of the glaciers by favouring the introduction of the cold external air; but in spring, when the sun's rays warm the surface of the snow that covers the glacier, they first restore it to freezing point, and afterwards produce water at 32° Fahr. which runs into the hard frozen and fissured glacier. This water immediately freezes, disengaging heat, which tends to restore the glacier to 32°, and the operation continues till the whole mass of the glacier that had been hard frozen during the winter is restored to 32°." Elie de Beaumont calls the expansion resulting from the regelation by the name of "*augmentation by intussusception*," and it is to the expansion, which is more considerable in the spring, that we must attribute the accelerated advance of the glacier at that season.

When, after sunset in summer, the surface of the glacier freezes again, and the rivulets that furrow it cease to flow, this refrigeration does not penetrate deeply enough to allow us to suppose it to produce on the mass of the glacier the effect of expansion by regelation. This water, however, which at noon was flowing over the surface of the glacier at a temperature of 34° Fahr. has fallen again to 32° in a liquid state after sunset, and to reach the state of ice at 32° it will communicate to the glacier only an inappre-

ciable amount of heat. To regelate the water the glacial mass need only supply an equally inappreciable amount of its stored-up cold.

Now the experiments conducted by Agassiz on the Aar glacier in 1842, at a depth of from twelve to fifteen feet, during a fortnight, from the 20th of July to the 2nd of August, gave eleven days at 32° Fahr., one day at 31°.82, one at 31°.64, and one at 31°.28.

During these fourteen days the mean *minimum* temperature on the glacier had been 28°.04, and on the moraine a temperature of 32° Fahr., or, accidentally, a very little below, at a depth of sixteen feet, there might have been during the night a more energetic regelation and consequently an expansion sufficient to produce an effect on the advance of the glacier.

But this expansion itself exerts a pressure on the capillary fissures which traverse the mass of the glacier and contain water, and the pressure tends to make this water discharge itself in a liquid state through the crevasses ; so that during the night the thalweg receives no longer the water resulting from melting, but that which exudes from the glacier, which, as we have said, acts like a sponge, absorbing the water and allowing only a surplus to escape, and then contracting to squeeze out the water it has absorbed, when there is no longer a surplus.

The waters issuing from the glaciers are always turbid and charged with sand, which is entirely the result of the rasping of the glacier on its rocky bed. The mud thus formed is deposited in the bed of the torrents and tends incessantly to raise it; but it is fine enough to tinge the waters, even as far as the lower reservoirs, where, being no longer agitated, they become clear.

The snow-water, on the contrary, is perfectly limpid; and this fact alone would prove that the snow does not behave like the glaciers. The snow, however extensive in surface is immovable, melts on the spot, and has no action on the rocks it covers.

To form a glacier a very considerable accumulation of névé is required, and which is incessantly renewed; for a glacier requires an enormous supply. If the supply is diminished, the glacier disappears, and the névé, though still existing, i. e., not completely melting during the warm season, can no longer nourish the glacier. The configuration of the mountain masses is an element quite as important as their altitude in the formation of névé. If the mountains present the form of a chain with spurs—like the Pyrenees, for example—the snow, though persistent, does not find a field sufficiently extensive to enable it to accumulate in thick masses. It is precipitated in avalanches down the slopes, and melts in the spring; while on the peaks there remain only thin sloping sheets, which cannot nourish glaciers, but are sufficient to form considerable torrents.

Several other causes exert an influence on the melting of the snows at altitudes above 6000 or 7000 feet. The whiteness of the snow prevents the mass from absorbing heat; thus the inert névés (i. e., those which do not feed glaciers) melt at their margins, in contact with rocks which receive the solar heat. The water falls drop by drop from these margins, and forms rills which unite at their lowest point. At night the melting ceases, but a great many small inferior reservoirs discharge themselves, and continue the supply. While the glacier is a sponge whose aqueous product is observed only at

its terminal point, i. e., at a mean height of about 5000 feet, the inert névé yields up its water at a much higher level, but the flow of this water is so arranged that the supply is regular.

The avalanches that occur every spring cause masses of débris that have fallen from the heights as the result of the frost which penetrates the fissures and opens them, to accumulate at the base of the snows. These heaps are not moraines disposed as dams, and consisting in great part of sand produced by friction; they are fallen débris—cones of dejection formed of movable materials, the lightest having remained at the top, and the heaviest having rolled to the bottom of the cone. The water resulting from the melted snow falls and flows across these heaps of rubbish in any direction it may find; retarded by innumerable obstacles, and meeting with many slight barriers which form reservoirs that slowly empty themselves through fissures.

The cones of dejection, consisting of stones which are found below the snows, and which they form through the periodical fall of avalanches, are therefore real filters which distribute the water with regularity.

But if the avalanches have been of very considerable volume, as the result of a snowy winter, they will have rolled over the surface of these cones of pebbles down to their base in considerable masses. There, on account of their volume, they rest till great heats or warm rains supervene. When such rains occur, the very rapid melting of these masses conspires with the rain, and floods in the valleys are the result.

The snows are, therefore, a much more efficient cause of inundations than the glaciers; and, in fact, it is from groups or chains of mountains, which no longer possess glaciers but only névés, that those torrents descend whose streams, immensely increased, inundate vast districts.

Besides the perpetual snows, there are some which are accumulated during the winter, and completely disappear during the months of July, August, and September. Yet it may happen that this temporary accumulation will suffice to feed even during the summer, if not actual torrents, at least very considerable springs. And this fact is particularly manifest in calcareous formations.

The reason is that between the strata of these mountains very considerable voids often exist, in which subterranean lakes are formed, whose function it is to feed these springs. In the spring, when the snows melt, these lakes are greatly overfilled, being supplied by rills which traverse the fissures of the rock.

The source of supply being formed, these reservoirs continue to empty themselves gently, as their issues allow, and discharge their waters into the free air. We observe, on elevated calcareous plateaux, particles of snow which, enclosed in basins, have no external outlet, and which yet, on melting, leave no puddles. These snows have served to nourish the reservoirs gradually, drop by drop. But if very great rains occur, these reservoirs, rapidly filled, discharge the excess of supply with equal rapidity; so that we see springs apparently insignificant, but which, on issuing from the rock, become destructive torrents. This causes the mountaineers to remark,

when these catastrophes occur, that the inundations spring out of the earth.

Even at the present day another mode occurs in which the snows regularly supply torrents, and which is occasioned by the great glaciers of former ages.

In descending from the heights, fed by the higher masses of the primitive névés, the glaciers have glided over rocks that presented differences in nature and hardness; as we have already remarked, they have worn down these rocks, more or less considerably, in proportion to the resistance they have offered. Strata which had a vertical direction have been eroded much more than others; and hollows have been the result.

In the next place, the glaciers having disappeared and having been replaced by snows only in the neighbourhood of the summits, these, in melting, fill up the hollows in question, which are so many reservoirs of constant supply. These lakes are very often regularly stepped and divided; and they send forth their waters by issues which measure out the discharge.

Around Mont Blanc we observe many of these small lakes, occupying part of the beds of ancient glaciers, and which, in the present day, are scarcely nourished, except by snowy accumulations, some of which disappear in the hottest weather.

Such are the lakes of the Brévent, those called Cornus and Blancs (the latter are still fed by a small glacier).

These upper reservoirs freeze in winter, for most of them are situated at an altitude exceeding 6500 feet. Covered with a deep layer of snow, they are

rarely in a liquid state except in July, August, and September. During this warm period the surrounding snows and the heavy rains feed them, and they then regularly supply the torrents that issue from them. As these lakes are at successive stages, and are quite surrounded by small reservoirs, the discharge takes place at successive intervals. The most interesting of these upper lakes in the neighbourhood of Mont Blanc, are, unquestionably, the Lacs Cornus. The principal are three in number, without taking into account a number of small reservoirs, which are placed one above another, and which have been hollowed out in the strata of crystalline schists mingled with porphyritic veins.

These strata, rising almost vertically, and running from North to S.S.-West, present very different degrees of hardness, so that in making its way over the rocks, the great glacier of ancient times, which descended from the Aiguille de la Floria and the Aiguille Pourrie to the Brévent into the Val de Dioza, has worn down the softer strata much more than the harder; which, in the direction we specify, has left rocky bands in ledges strongly moutonnés, but between which at the present day these small lakes are dammed in.

A section made along the line O P of this part of the group (see V, Fig. 75) shows at *c* the lake at the higher level, C in the small sectional map X, at *d* the lake D, at *e* the lake E, and at *f* the small reservoir F. At A is the Aiguille de la Floria, and at B the Aiguilles Pourries, at G the small glacier de la Floria.

The col is near these aiguilles on the north. The section, as well as the sectional map that corresponds

with it, shows how the strata of gneiss have been worn down, while the salient parts appear at long intervals. The stratum in which the beds of the two lakes, C and E, are hollowed out, is rose-coloured, and contains garnets in small grains. We follow it in

Fig. 75.—Lakes at high altitudes.

passing between the second Aiguille de la Floria and the peak R, and we find it again on the other slope as far as the Aiguilles Rouges.

On the cols of considerable extent, we also find those upper lakes, hollowed out in the softer part of the mountains. It will be sufficient to mention that of the long col of the Oberalp, above Andermatt. Its bed has been formed in a band of jurassic rocks, bounded by gneiss, and which stretches the whole length of the valley of Andermatt. It is along the line of this band that its overflow is discharged into the valley, leaving turf beds along the col.

Besides these upper lakes there are some intermediate ones, hollowed out in the combes and amphitheatres, surrounded by peaks, now covered only with névés. These lakes, which are frequently met with in the Pyrenees,[8] are comparatively rare in the Alps. There are some of typical character on the south-west of Mont Blanc; the Lacs Jovet,[9] which occupy the bed of a very closely shut in and short glacier, that descended from the Aiguille de Bellaval and Tré-la-Tête. These lakes are dammed in by the ancient frontal moraines of this glacier, and also by the projections of the harder rocks.

But these reservoirs, however numerous, would be insufficient to regulate the course of the torrents which do not proceed from glaciers, if these torrents were not themselves habitually subjected to conditions which tend to diminish the rapidity of their discharge.

[8] The lakes de Gaube, d'Estaubé, d'Héas, d'Oo, de Seculejo, &c.

[9] The most extensive, and lowest, at a height of 6300 feet.

VIII.

COURSE OF THE UPPER TORRENTS.

It is evident that the course of the torrents varies in proportion to the nature of the strata through which they flow. If their bed passes over crystalline rocks, granite, protogine, gneiss, or porphyry, they follow all the indented detours caused by the dislocation, or wearing away, of these rocks; if they flow over lias, or slaty or clayey schists, they hollow them out deeply, descend almost in a straight line, bear down with them thick mud, and cause devastation in the valleys; then, having covered the lower parts with a grey slime, they leave the bed almost dry. If they descend through oolitic rocks, they fall in cascades along the thick beds of these deposits, and are sometimes engulfed in subterranean channels to reappear further on.

The chief function of the torrents is, not that of hollowing out deep gorges, as some have asserted, but that of filling up the valleys with the materials prepared by the glaciers, and which they bear down in their course.

The deep gorges along which the torrents sometimes pass, such as those of the Trient, the Triquent, the Via Mala, Dioza, Notre Dame de la Gorge, Berard, Val Tornanche, &c., and whose rocks they have evi-

dently worn down and smoothed, are natural rifts that existed at the time of the upheavals, and which these torrents made use of as passages, but which they did not hollow out. From the glacial epoch onwards these gorges served as headways for the water furnished by the glaciers; for, as we explained above, the

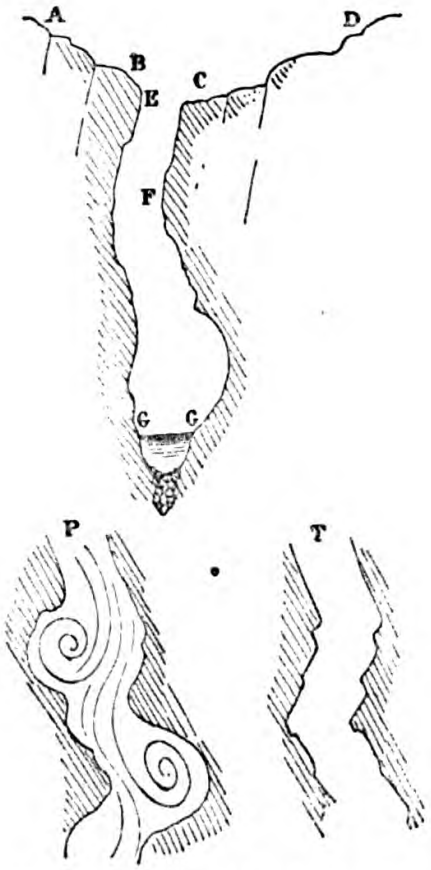


Fig. 76.—Flow of torrents in gorges.

ice did not pass into these rifts; the proof of which (Fig. 76) is the mark left by the passage of the ice above them, in the rocks at A, B, C, D, as shown by their decided moutonnage, whereas between E and F the fractures are uneven and the angles sharp, so that one might bring the two walls together and fit them into each other. Further down, be-

tween F and G, these sides are polished, enlarged by the water, and sometimes deeply hollowed out, following the curves occasioned by the current.[1] But it is not the water that has thus sawn through the hard rocks; if it had done so it would not have left the edges between E and F unworn. In fact, it is not water alone that has enlarged and hollowed out these walls; to execute this operation it has been obliged to bring sand and pebbles with it, and it is these materials which, whirled about in the current, have gradually worn down the hardest rock walls. Indeed, in horizontal section, these gorges always exhibit a succession of narrow passages and semi-circular excavations, as seen at P. The water, loaded with sand and pebbles, in whirling about as indicated by the spirals, formed these cavities which are so completely smoothed; but in hollowing out the gorges, sometimes on one side, sometimes on the other,—for the original rift always presented a series of re-entering and projecting angles (see T), and forced the current to bear now against the one side and now against the other,—the water made itself basins, in which it slackened its pace in proportion as the whirls took a wider sweep.

A phenomenon of the same kind is observed even in the torrents which flow at the surface of the slopes.

We have observed that the primitive glaciers, like those of modern times, had, when they descended over a very irregular declivity, torn away and broken the projecting rocks by pressure, and had then worn down the roughnesses that remained, leaving the

[1] Gorges du Trient.

rents on the lower side intact (Fig. 77). Let section *a b c d e* represent an inclined mass of rocks, the glacial current will have reduced this section to the form *a′ b′ c′ d′ e′*. The glacier having retreated to a higher point, there supervenes a torrent flowing over this declivity. At each broken escarpment *a′ d′ e′* it forms a cascade, at the bottom of which it finds a surface comparatively level. It hollows out the base of the escarpment, as seen at A, and, the water

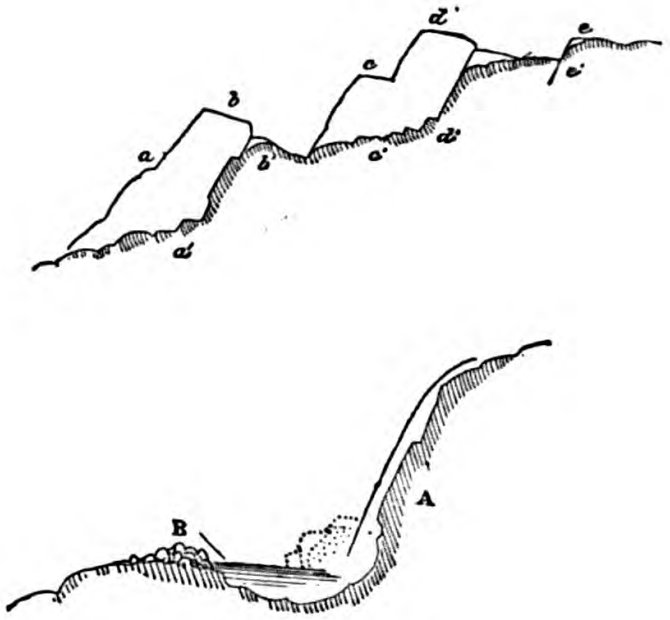


Fig. 77.—Cascades.

eddying violently at the bottom of the fall, disposes around the basin, which it is continually hollowing out, all the pebbles, B, which it carries down and which have helped it to hollow out this basin. The torrent therefore forms at the bottom of each cascade a small dammed-up reservoir, which collects the water and abates the violence of the current.[2] Thus the torrents which reach the lower

[2] See the Cascade du Dard issuing from the Glacier des

valleys after a succession of falls and shelvings, never cause such damage as is produced by those which come down direct without gradation.

It may even happen that at the bottom of these falls the whirling round of the sands and pebbles takes place in so regular a manner as to hollow out vats of considerable depth, of circular form, and thoroughly polished, which the mountaineers call *Marmites de Géants* (*Giants' Caldrons*).

There is no doubt that when the successive *débâcles* of the glacial epoch occurred, this phenomenon must have been produced on a very grand scale, and that some of those small regular and deep lakes must have been formed which are met with at the bottom of certain cascades now greatly reduced.[3]

The crystalline rocks are the most favourable to the regular flow of the torrents on account of the very nature of their formation and their hardness. On the other hand, the carboniferous schists are the deposits whose hollowing out by the torrents are most dangerous to the valleys, because they do not keep back the waters.

Let us examine, first, the torrents that flow over the crystalline rocks. Reverting to Fig. 47 and the accompanying explanation, we shall see that the crystalline rocks, the gneiss and crystalline schists exhibit oblique planes of contraction which form rhombohedrons, or at least faces cut obliquely to the declivities.[4] The waters in their flow naturally

Pélerins, and the upper falls of the Torrent de Blaitière (valley of Chamonix).

[3] This phenomenon is frequently observed at the bottom of cascades in the Pyrenees.

[4] See also Fig. 34 *bis*.

tend to follow these planes, which form junctions between the masses, leaving the hardest edges projecting, which is the case with the crystalline schists as well as the granites and protogines.[5] The result is, that a torrent which runs along a declivity over these rocks will descend in a zigzag and not in a straight line. This bed will be constantly enlarging, and, with the aid of the frost in winter, will be so deeply hollowed out as to make itself a place proportioned to its discharge, but always in accordance with the structure of the rock itself.

Suppose A (Fig. 78) to represent the bed of a lateral glacier whose ancient moraines are at M. The torrent, issuing from the lateral glacier, had already hollowed out its channel of outflow in the declivity of the mountain on whose higher slopes it had taken its place. The moraines, M, had regulated this outflow by damming up the margins of the glacier. But having retreated higher up, this glacier leaves visible the lower part, A, of its ancient bed. On this bed, whose surface is *moutonné*, the rivulets arising from meltings come from various directions to meet at the outlet, but, irregular in their channels, and bringing débris with them, they enlarge this outlet and break down its sides. The rock is disintegrated by the frosts; then a kind of half-funnel, more or less regular in form and shape, is formed, which collects the waters and unites them, and these take their course,

[5] This fact, which is so conspicuous along the banks of the torrents that flow between the crystalline schists, the granites, and the protogines, clearly indicates the greater hardness of the planes of junction in these crystalline masses. In fact we often see these rocks washed by the torrent, presenting a network of salient lines which are none other than the planes of contraction described at length in a previous chapter.

hollowing out their bed at the expense of the rock, and conforming to the general structure of its planes of junction. The ravine, however, which is wide and shapeless at its commencement, becomes regular and deep; and at the bottom the torrent deposits the

Fig. 78.—Beds of Upper Torrents.—Crystalline Strata.

stones which it bears along in its rapid course. In the meantime the cone of dejection, C, continually increases in volume (see D) and ultimately reaches the upper gorge. For a long time the torrent, through the impulse it has acquired, descends directly on the

back of the cone, forming for itself two banks of pebbles which it throws off on its margins. But a moment arrives when this cone presents so long a slope, and forms such a prominent back, that the least obstacle, a fallen rock, e. g., turns aside the current, and then it follows one of the two lines where the cone joins the declivity of the mountain, that is the slope *a b* or the slope *c d*.[6] If the acclivity of the ravine is very steep, there is a remarkable difference of level between the higher and the lower part at each angle of the ravine. Then there will be a fall of water and a level flow or slackening of speed.

On the lias and jurassic deposits, whose masses usually present wide plains, plateaux, and faults, and whose stratification exhibits beds lying conformably one on the other, the torrents flow over slopes sufficiently gentle to allow them to fall suddenly in a cascade along an abrupt escarpment. These cascades cannot produce cones of dejection at their base, the pebbles being arrested before reaching the fall. But among the micaceous, clayey, and slaty schists, which are so readily attacked by frost and moisture, the upper watercourses offer very peculiar features. These rocks, which have been so greatly affected by the glaciers on account of their yielding character, now exhibit gentle slopes, concave or convex, on which the asperities are but trifling. The snows and the waters which fall on the summits unite in the concave part of the combe; there they begin to decompose the rock, filter through its innumerable foliations, and dilute the clays; then a deep excavation takes place with almost perpendicular sides, and

[6] See in the valley of Chamonix the Torrent de Blaitière.

at the top of this excavation is formed a combe, more or less broad (Fig. 79), and whose diameter is continually increasing.[7] These torrents form at their base very large cones of dejection and consisting of materials so thoroughly triturated that vegetation soon takes possession of them. The débris of slate schists mingled with clay have often been carried down as

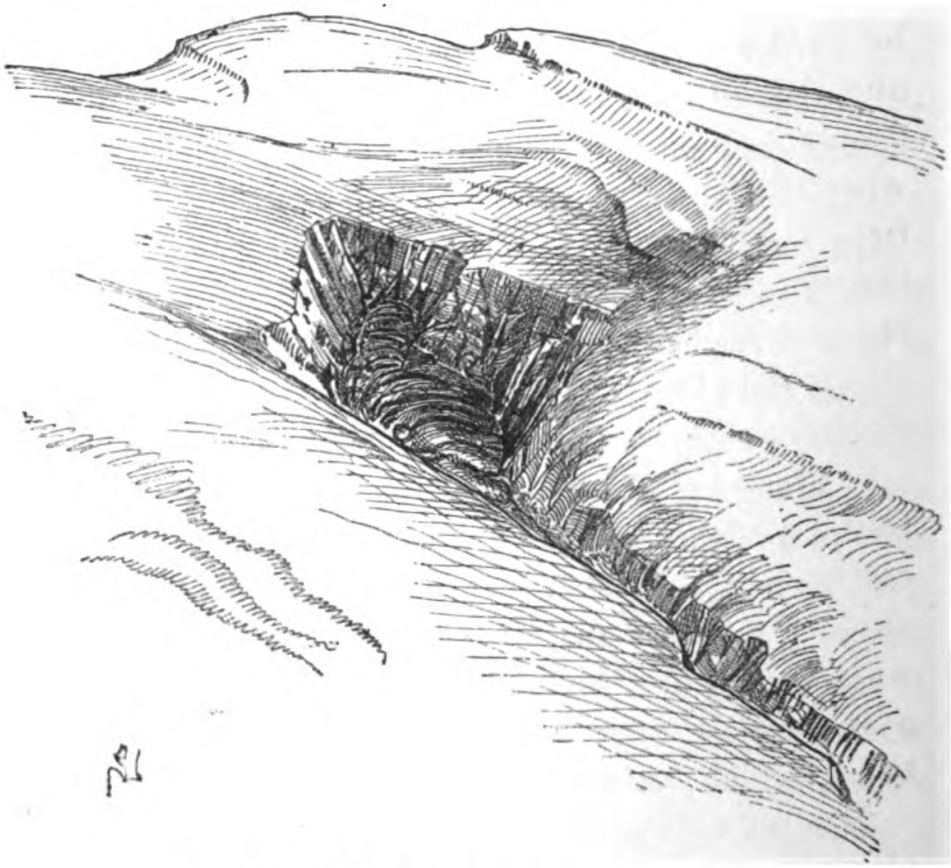


Fig. 79.—Beds of upper torrents in slate schists.

mud by the first meltings of the great glaciers, and have gone to fill up valleys of considerable extent, the outlet of these valleys not being wide enough to

[7] The combes of the torrents above les Houches on the ascent to the Pavillon de Bellevue, those of the Col de Balme, and those of the Italian Val Ferret and of Mont Joli are examples.

allow this mud to find an exit, and the phenomenon which occurs on a small scale in Fig. 79 takes place on a large scale.[8] Yet these enormous clayey masses, of which vestiges remain only at their higher level along the escarpments, have disappeared; the combes originally hollowed out by the glaciers, and then partly filled in, have been scooped out again. How did this happen? In the mud and alluvium deposited by the torrents in the valleys we see that the stream, after having brought the alluvial mass, excavated it deeply to make itself a bed, relatively narrow, and when it was no longer charged with so great a quantity of solid materials; but this watercourse allowed the older bed to remain above its present surface. In the case of many of these clayey deposits, however, this is not the case; they have been almost entirely cleared away.

What is taking place before our eyes at the present day explains this fact. Let Fig. 80 represent a combe, a horizontal projection at A, and a section along *a b* at B. The outlet, C, was not sufficiently wide to allow the schisto-argillaceous mud to flow away, and it has remained in the valley, following the section *e f*.

The rains and melted snows that make their way along the walls of the combe G H I, pass beneath the argillaceous deposit and drench its lower part, which, lubricated and oozing out beneath the load above, begins to pass away through the outlet C. In proportion as the lower stratum is cleared away, the higher part, which is drier and denser, exhibits rifts

[8] For example, in the combes of Malatra, Secheron, and at the south of the Italian Val Ferret, and the bottom of the Swiss Val Ferret.

following the lines *g h* in horizontal projection and *g′ h′* in section, and descends by ledges, as shown in the outline *i k*.

Thus the whole deposit successively quits its reservoir and is transported into the lower valleys,

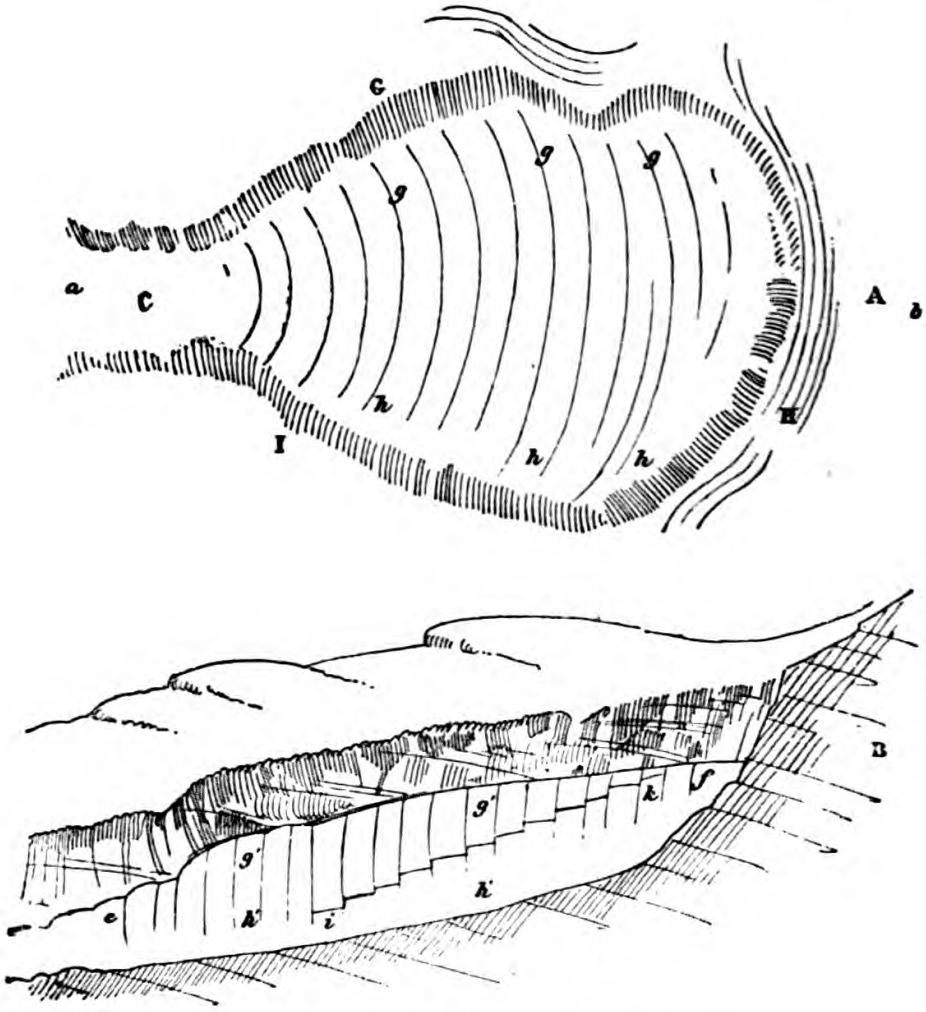


Fig. 80.—Excavation of glacier mud in a combe.

leaving in the combe it occupied only such vestiges as *g′* of its former level attached to some of the crevices in the schists.[9]

[9] This phenomenon may be witnessed in the chalk cliffs of Dieppe, which contain considerable deposits of clay. In the hollows of the chalk the clay runs off exactly as indicated in Fig. 80.

But the waters of the torrents carry along with them materials of various forms and weights, from the most filmy of clays to blocks of considerable dimensions. These materials are transported with a velocity inversely proportioned to their size. The argillaceous mud will be carried down to the lower reservoirs or the plains, or even to the sea; the sand will be deposited higher up where the currents have lost something of their force; above these the larger pebbles; and lastly, the great blocks in proportion to their size.[1] The result is that torrents rushing down very steep declivities and near the loftiest peaks, have their beds strewn with enormous stones covering the denuded rock, and that the sand and pebbles cannot stop there, while the torrents of the higher valleys transport pebbles, and those of the lower valleys scarcely anything but gravel. There is thus a sifting of the materials left by the moraines, the glacier mud, and the continual dilapidations.

But the degree in which this sifting takes place depends on the mass and the rapidity of the current. When the great *débâcles* of the glacial epoch occurred, the amount of liquid was so considerable that it carried down pebbles much further than the torrents of modern times are able to do. There was, therefore, when the great melting in the lower valleys occurred, a lower deposit of large pebbles; then, in proportion as the violence of the current was diminished, and the stores of materials were exhausted, there were deposits of smaller pebbles, and lastly of gravels and mud. The alluvium produced

[1] See "*Les Torrents, leurs lois, leurs causes et leurs effets,*" by Michel Costa de Bastelica, published by Baudry.

by the torrents in these lower valleys was, therefore, arranged according to conditions most favourable (I was going to say most scientifically adapted) to compose a well settled soil.

There are, however, exceptions to this rule, resulting from the torrent mud; for while the glaciers produced mud which was transported far from the place where it originated, the torrents also proceeded and still proceed after the same method.

When, after melting has taken place, the torrent waters which descend into the zig-zag gorges come down in abundance, they bear down numerous blocks, the ruins of undermined rock-walls, which, reaching a narrow outlet together, stop, arch up, wedge each other, and thus retard the advance of the pebbles and detritus, and form a barrier behind which sand and mud accumulates. The violent rush of water habitually produces a rupture of this improvised dam, which, in the form of mud, advances in rolling, bearing down the sides of the gorge, and goes and spreads itself in the lower parts, overflowing the bed that has been deposited. The torrent, continuing to flow, discharges on its banks the pebbles that bar the passage, and forms two dikes of stones of all sizes. This occurs at the base of all the cones of torrential deposit, and these dikes sometimes appear, from their regularity, the work of man.

It need not be remarked that the phenomena of flow in torrents rushing down a steep incline vary with the geology of the district; that where the ground is of a slight and unresisting texture the torrent hollows out ravines much deeper than when the rock offers a vigorous resistance to the waters.

Thus, even at a great distance a mere glance at the section of a ravine may indicate the geological character of the ground in which it is excavated.

The liassic and jurassic systems, the green schists and even certain cretaceous deposits present arrangements particularly favourable to a regular discharge below the loftier altitudes, contrariwise to what happens on very abrupt declivities. In these regions, and in consequence of the actual structure of the rocks, the torrents proceed through narrow gorges and along projections which are succeeded by basins of more or less extent.

These rocks present, like the crystalline rocks, planes of contraction[2] which divide the strata into rhombuses, the result of which is (Fig. 81) that the ice having first prepared the way, the thalweg of the torrent is hollowed out at A and B with a projection at C. If we draw a section through *a b*, we have the outline D. At *e* there is a fall—a cascade.

Consequently, as remarked above, there is a basin at *f*, a heap of stones at *g* on the dike, and often a second reservoir *h*, resulting from the fall which this dike produces, with a secondary heap of pebbles *i*. The torrent then finds a condition of rest,—a widening out between the margins *l*, L, *m*, L. It accumulates the pebbles *n* in the middle of this enlargement, and generally divides into two branches with a comparatively tranquil course; then falls at L, and so on through the remainder of its course. This fact may be observed in a great many narrow valleys where torrents flow.

We may mention among others, the cascades

[2] The white chalk still preserves this texture.

above Val Tornanche, which run over green schists and serpentine, and which also exhibit, hollowed out in the last rock, the *Giant's Caldrons* mentioned before.

The Pyrenees, in consequence of the nature of

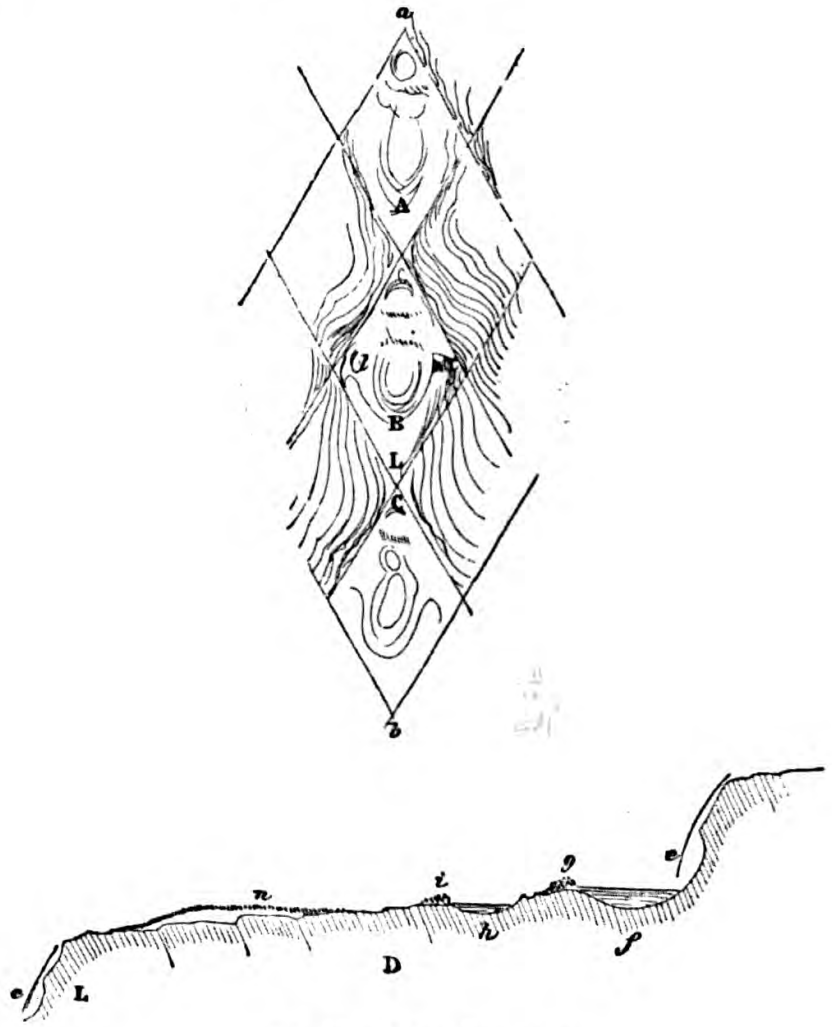


Fig. 81.—Flow of torrents.

their rocks, exhibit a very large number of such torrents flowing through narrow gorges, followed by quiet basins. The same phenomenon may be observed on a small scale in the chalk deposits. Rivulets, which in ordinary weather may be an inch or two

wide, behave exactly like those powerful torrents of the higher valleys. Fig. 82.[3]

We shall now examine the torrent in the bed it

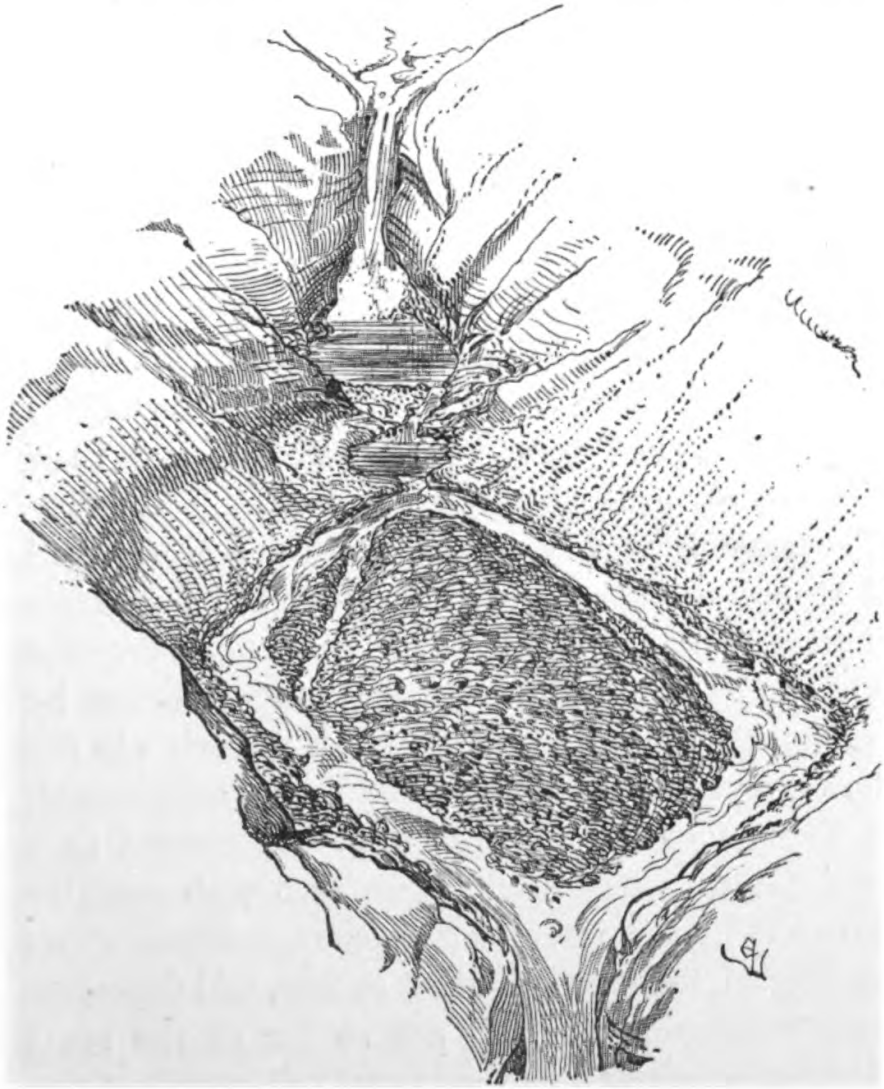


Fig. 82.—Flow of Torrents.

has deposited, and observe its action in the wide valleys which it has filled in and levelled.

[3] The chalk cliffs of Dieppe.

IX.

TORRENTS AND LAKES OF THE VALLEYS.

THE great débâcles of the glacial epoch swept down the enormous débris of the moraines into the valleys whose banks had been already eroded, and their dikes broken through at many points by ice.

These thick muddy torrents—rolling along sand and stones of all sizes, when they found an obstacle forming a dam, (for the ice had by no means brought the thalwegs into regular shape,) being retarded by this obstacle, depositing the heaviest materials in the hollows, and so running clearer to a certain extent, and finding or forcing an outlet—descended to a lower point, where they again met with moraine débris left by the retreating glaciers,—débris which they flooded, bore along in their course, and deposited again, continuing thus to act as far as the great collecting reservoirs, or the lowest valleys.

If we cast a glance at Figs. 31, 32, 33, we see that the bottoms of the valleys, or, more correctly, of the depressions destined to form valleys, in many cases presented elevations—transverse prominences on whose slopes had remained frontal moraines left by the glaciers which passed down these valleys. These transverse prominences had not been reduced

by the ice, which, to pass them, did not require to destroy them, but had been contented with smoothing them, rounding off their ridges, and filling their recesses with débris. The débâcles, which resulted from the retreat of the glaciers, filled the intervals between these elevations with muddy water, and formed temporary lakes, which were rapidly filled in by the pebbles that were brought down, and then presented a level (*palier*). The torrent would flow in a broad sheet over this level, which it raised by the continual addition of pebbles, and then hollowed out a bed for itself in it. But how, and under what conditions?

It need not be remarked that those irregularities of surface which formed dams across the valleys did not present a horizontal crest, but, on the contrary, differences of level. When the water had reached the lowest point of this crest it rushed down through the outlet. The current of the lakes was therefore rapid at the outlet and comparatively tranquil at the side; whence it resulted that the pebbles were heaped up on the margins of this current, and gradually limited its bed, beginning from the outlet upwards.

Fig. 83 represents a depression and a natural weir at A, whose lowest point is B, and where, consequently, is the outlet. A lake, *a*, *b*, *c*, *d*, has been formed, into which the pebbles are brought down. As the water escaped through the outlet B, a rapid current is set up from F to B, and the pebbles are discharged at *f*. The formation of the channel once begun, it gradually extends upstream through the continued deposit of pebbles laterally, and is ultimately complete from B to F. But at B the water has hollowed

out the passage, the level of the water is lowered, and the parts G emerge, or continue to be covered only when the stream swells considerably; sometimes there

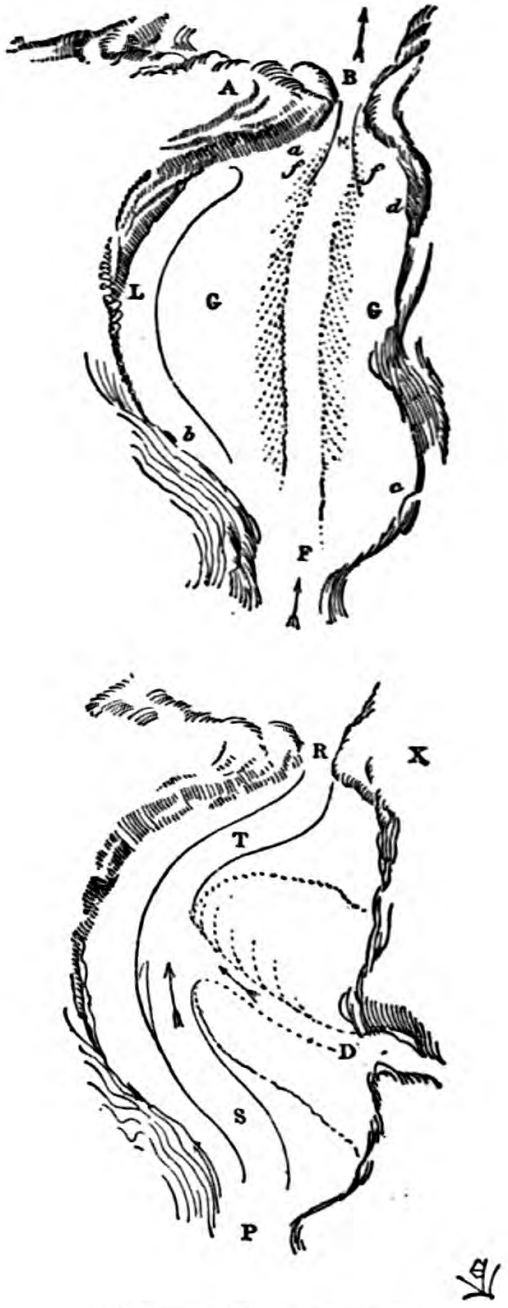


Fig. 83.—Valley Torrents.

will then remain a marsh, L, which was a secondary current filled up by the accumulations *f*, G.

But if (see X) a torrent finds issue at D, it will have deposited a cone of dejection compelling the principal current, P, R, to make a detour from S to T.

The more deeply the torrent wore down the obstacle A, Fig. 84, by dint of the sands and pebbles which it carried along, the lower did the surface of the water sink, and the higher were its banks. So that the level of the water which, when the depression was filled up, stood at A, B, would be lowered to D, C. On this account, valleys which still have rapids, in consequence of the barriers, C, that have been reduced by the waters, exhibit high banks

Fig. 84.—Valley Torrents.

along the watercourses, consisting of gravels whose expanse has been hollowed out by the current, which has thus taken its ultimate direction.

But these dikes, when they produce a cascade in the current, produce phenomena of outflow which have had important consequences. At the bottom of the fall the previous fillings in are undermined. If the dike is rocky, this undermining has no other result than forming a deep basin for the torrent, as shown in Fig. 81. But if the dike has the character of a moraine, the undermining continually tends to destroy it, and to enlarge the passage, so that at length the moraine disappears, worn away by the torrent, and the irregularity caused by it disappears. Thus, in the valley of the Rhone, we often find mere

relics of certain frontal moraines that barred the valley,—remains attached to the sides of the enclosing escarpments.

The underminings that have occurred at the base of the rocky dikes damming up the valleys have been sometimes sufficient to produce pools hollowed out in the lower alluvial lands. The result of a rapid is always an undermining on the down-stream

Fig. 85.—Valley Lakes.

side, which produces rest and slackening of the current to a considerable extent. If the dike A is rocky, Fig. 85, when the stream of water has passed over it, it will have undermined the base of this dike on the lower side, and formed a deposit of pebbles—a made dike. But the level of the stream having been lowered in consequence of the hollowing out of the passage E, the lake has con-

tinued to be deepened under the cascade, and the pebbles C D have been turned aside from C to E by the principal current D G, the most bulky being ranged from C to E. Another current has been produced at H, by the side of the culminating part of the heap of pebbles, which extended from C to I when the stream covered the weir.[4]

Similarly, if a block of stone happens to be arrested in the middle of a watercourse on a shifting bottom, the latter is undermined above, and the stone, tilting over, settles deeper into its bed, so that beds on alluvial ground tend to become regular and level. Fig. 86 explains this fact. Let A B represent a gravel-bed, and C D the surface of a current. In consequence of the undulation produced in the current by the presence of the stone E, and the eddying occasioned by the obstacle, an undermining, F, occurs below the stone, so that it tilts over, as shown by the dotted line. As long as it remains projecting above the bed A B, an undermining takes place on the up-stream side, and ultimately, in proportion to the activity of the current, the stone is entirely covered by the gravel. Below the section is shown the effects of eddies in horizontal plan. The current has deposited at *a* the largest pebbles, in consequence of its force being neutralized at this point. It follows that the large stones which settle by

[4] These observations, and those which follow, have been drawn from small rivulets which allow the conditions of their flow to be modified, and a very exact idea to be formed of the arrangement of the deposits, of their undermining action, &c. In questions of this kind the scale is of no consequence, and what has been produced on the large scale may be produced before one's eyes on the small scale artificially in a few minutes.

their weight at the bottom of a gravelly bed, instead of filling up this bed, help to dredge it by exerting those *routings up* (*souilles*), or underminings, whose result is the removal by the current of a quantity of this sand or gravel. Small stones produce at the bottom of the bed of a current of no great rapidity

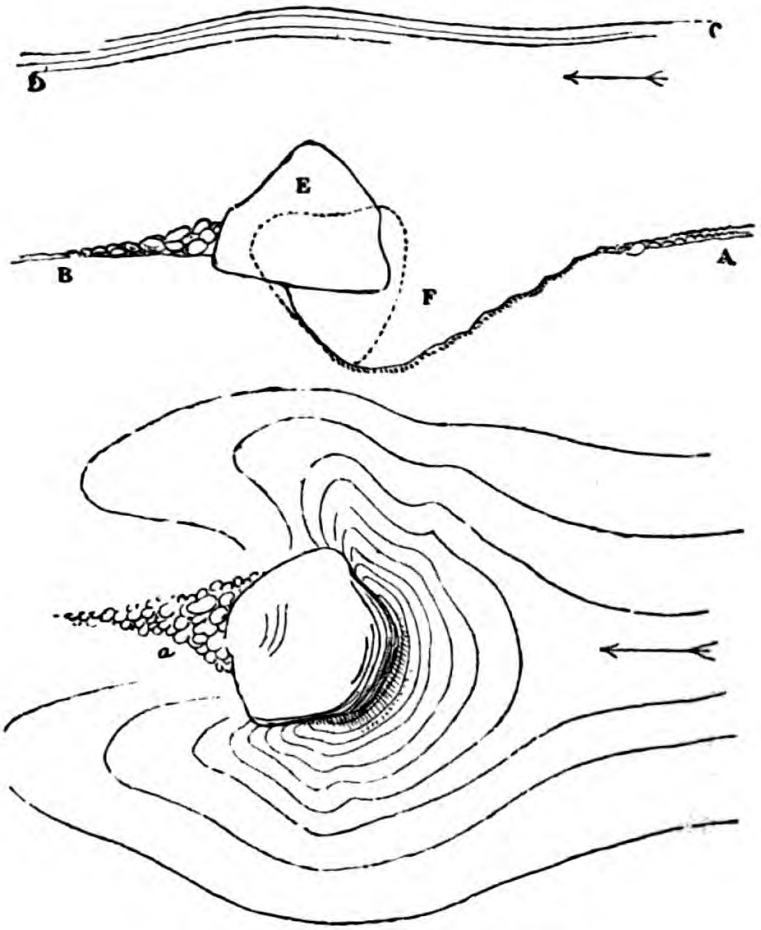


Fig. 86.—Dredging of Torrent beds.

the effect that has been pointed out on a large scale, and, by producing each its small undermining action in the very fine sand and mud, oblige the current to carry these materials further, and deposit them on its banks or in tranquil spaces. This is also the reason why the thalweg of the bed of rivers

always exhibits a layer of gravel more or less thick in proportion to the strength of the current, but always free from mud. The gravel maintains the level of the thalweg, and, if the waters are greatly swollen, it is carried away to be replaced by a fresh supply, in proportion as the flood decreases.

When a torrent met in a valley an ancient frontal moraine barring its course, it formed a lake, passed over the ridge of the moraine, soon broke through it at its weak point, and poured forth its waters lower down; but in the meantime it hollowed out the gravel below the moraine, at the most active point of its flow (Fig. 87).

Suppose A B (the dotted lines) an ancient frontal moraine. The waters overflowing this moraine between these two points have, as in Fig. 85, undermined the bed at C; but as the débris of the moraine were borne along by the current, they formed a slope and filled in the most concave part at C. Then the longer declivity of this current tended to hollow out the bed farther on, i.e. at D; and subsequently, as the reservoir was extended, the torrent diminished its speed, deposited its gravel on the down-stream side, and produced an elevation of its bed at E,—an elevation which the torrent crossed at one point with difficulty, to resume the course given it by the slope of the ground lower down. This is what is shown by the section S along *a b*.

But if a tributary entered at G, it would deposit its cone of dejection, H I, and present another obstacle to the course of the principal torrent. There would then be an eddying and a counter-current in the reservoir D, which would produce at

the bottom of the bed the curves shown by the horizontal projection and the section s.

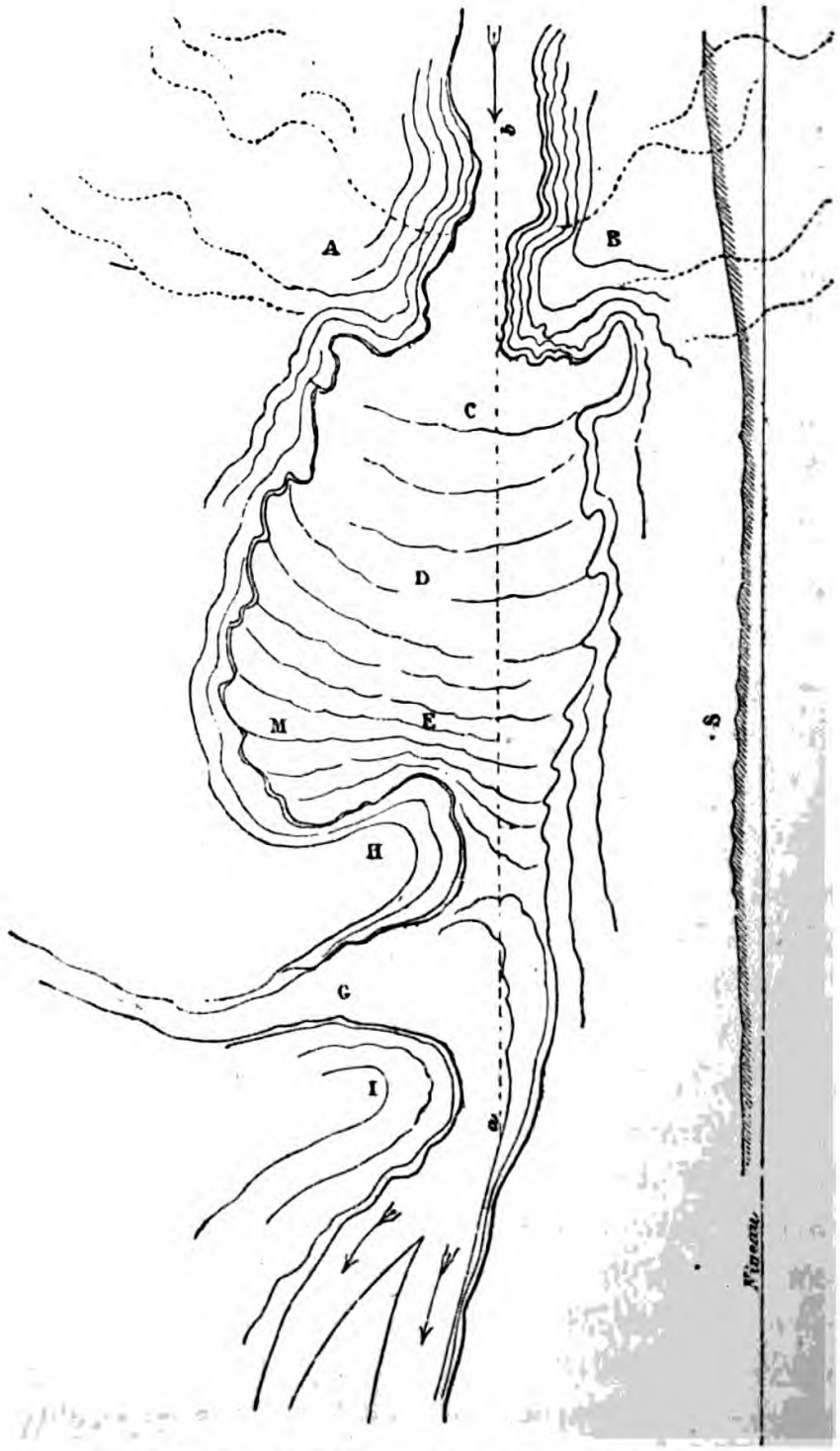


Fig. 87.—Course of a Torrent through moraine deposits.

At every flood portions of the moraine would be carried away, and would proportionally fill up the reservoir; a more and more regular channel would be established in this alluvial ground, and the retained water, except a marsh at M, would disappear.

The valley of the Rhone furnishes a great many examples of this phenomenon, which is owing to the successive resistance and ruin of the frontal moraines left by the retreating stages of the great glacier.

But we must try to understand the processes employed by nature in filling up the broad valleys, levelling their bottom, and forming the scarcely

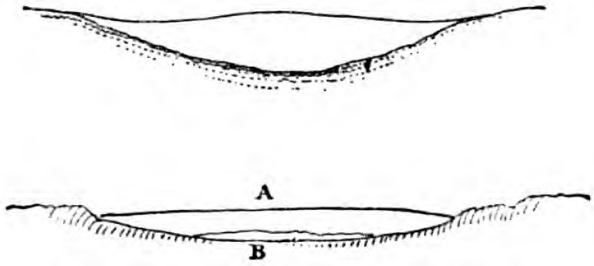


Fig. 88.—Flow of Torrents.—Section.

sensible inclines, which extend to great lengths, and present an almost horizontal transverse section.

We have seen that the current of the glaciers bulges out in the middle and presents a convex transverse section, and that its rapidity is greater along its longitudinal axis than on its margins or its bed. It is the same with a current of water in this last respect, but its transverse section does not present exactly the same form as that of a glacier. If the current is rapid and the bed smooth, the middle is convex; there is a lateral depression and a rising on its margins. To make my meaning better understood, let Fig. 88 represent a very rapid torrent, whose bed

is smooth; the water, being neither compressible nor elastic like ice, pressure, joined to the acceleration of the current in the middle, causes the stream to spread against the sides and throw off the pebbles on its banks. If, on the contrary (see A), the current, pursuing a gentle slope, carries with it materials in suspension, the action of *colmatage*, i. e. the deposition of these materials on its bed, gives the transverse section a continuous convex curve.

In fact, the deposition of materials on the bed of a torrent depends on its rapidity. If it is very rapid, it distributes the materials on the side; if its course is slow, it deposits them in the middle. This deposit ultimately reaches the level of the surface and forms islets; then the torrent erodes one of its banks to find sufficient room for discharge. The waters, which constantly bring down with them a considerable mass of débris, and deposit it at an early stage, always exhibit a convex section. We shall return to this point farther on.

At the bottom of the valleys the torrent proceeds as on the steepest inclines. It produces there, as on these inclines, a cone of deposit, which it tends to increase continually, until an accident causes it to break through the dikes which it has raised for itself to find a bed lower down. Fig. 89 shows the section of a valley in the state in which a glacier has left it.

The first torrent begins by depositing a cone of dejection, section *a b*, and, following it, *c d*. An accident causes it to break through the dike it has made for itself at *d*, and it makes its bed at *e*. It goes on to raise its level and banks to *g h*. A second accident makes it break through the dike *g*, when it

runs along *i;* its banks are at length raised to *l m;* then it finds its way at *o*, and, thus passing from one side to the other of the valley, it ultimately fills it up completely and regularly, without the necessity (which has been sometimes supposed) of its rising to very high levels. The result of this process is still manifest in the fact that the torrents of the valleys, when their course has not been artificially modified, always run along one of the escarpments, passing from one to the other without ever taking a middle course. Great rapid rivers, such as the Rhone, follow the same law exactly, running along one of the two

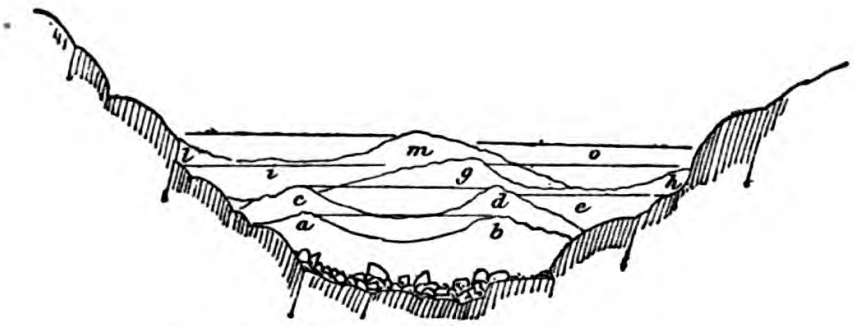


Fig. 89.—Mode of deposit by the Torrents.

slopes of the valley which they occupy. But the valleys do not always follow a straight course; many present elbows and windings. Let us then now examine in horizontal projection, not in transverse section, how cones of dejection are formed according to the arrangements of the banks, so as always to produce the same result, i.e. a progressive levelling. What are the causes of the accidents which break through natural dikes?

In the first place, the formation of cones of dejection presupposes an extraordinary swelling of the waters, which at the decline of the glacial epoch

must have been constantly occurring, except, perhaps, during the winter. Let us suppose the soil of a valley prepared by the ice, and then by the earliest

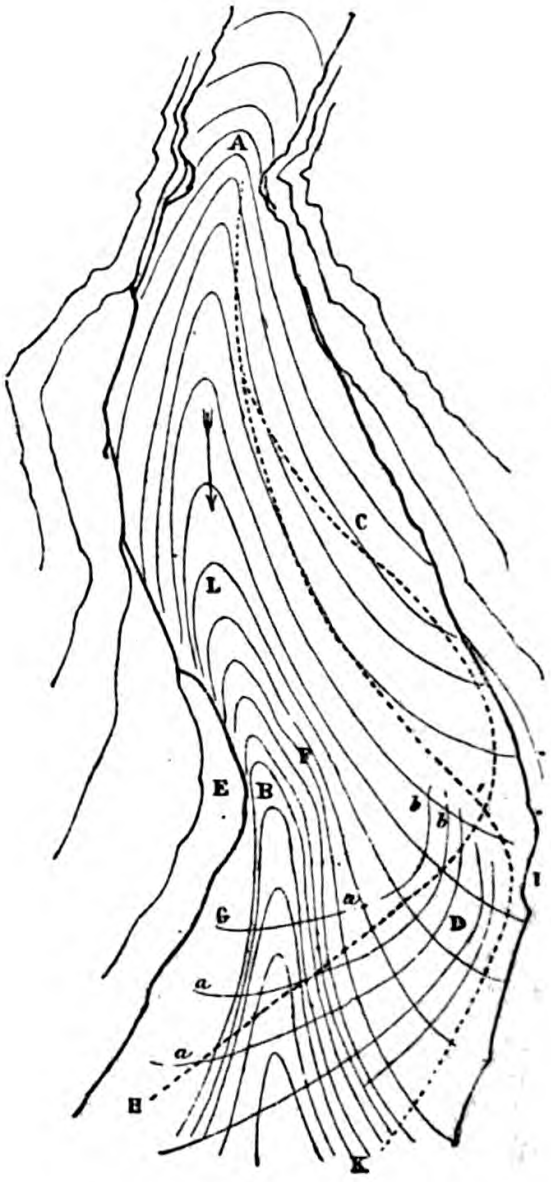


Fig. 90.—Hollowing out of Torrent beds.

deposits of mud and the glacial agglomerates that have begun to fill in its bed. (Fig. 90.)

There are no serious obstacles to the course of the

waters proceeding from thawing, which in vast sheets fill up the bottom of the valley and bathe the escarpments. The current brings with it mud, fine gravel, and stones. The contour lines of its bed are as shown in our drawing. The current being rapid at A, on account of a narrow gorge, and the water always seeking the shortest passage, the main strength of the current is from A to B, forming a concavity in the bed beneath this line of the plane of waters. The stream, repelled from C towards D, rises and deposits stones and gravel in a cone of dejection. The base of this cone approaching the point B, confines the torrent, which, obstructed by its own deposit and the obstacle E, hollows out its bed more deeply to pass on swiftly, and with a fresh impulse rushes straight on, to begin again at G H what it had done at C D; but as it continues to bring down gravel and pebbles, and the cone of dejection increases from C to F, the passage of the torrent at B is so much more obstructed. Then begins an evolutionary process. The sides of the bed F B that had been under water roll down at B and raise the level, and the torrent is obliged to extend its range at the expense of the fallen materials; but in proportion as it hollows out this bed towards point F, and beyond it, it finds higher and higher accretions, and these roll down readily in proportion to their height above the level of the lower bed; and a time comes when the axis of this bed is directed straight against the escarpment I, to resume its course at K, and perform a similar evolution lower down; but this state of things changes once more. The current then deposits a cone of dejection along the curves *a b*, whence ensues a superabundance of materials at D and a

giving way of the submerged banks D. Then the thalweg of the bed tends towards G, while it is constantly approaching C, filling in the space L, so that the thalweg follows the line A C H. Thus, even when completely submerged, the thalweg of the torrent tends to lengthen itself by sedimentary deposits.[5] The longer it is, the more gentle is its slope, and the more regularly the deposits are formed, the current being less rapid.

Now let us come to a more recent period. The waters are relatively less abundant in summer, and in winter the deposits emerge and are covered only at the melting of the snows and during the autumnal rains. The swollen waters discharge more gravel and pebbles on the shores of the torrent, then they subside, and the torrent returns to the bed it has hollowed out for itself. But as the whole valley is no longer constantly submerged beneath the stream of a current, it follows that the torrent is always bringing into its bed, but especially on its margins, masses of gravel, while it only accidentally spreads this gravel and these pebbles over the parts that have emerged. The stream thus tends to fill up its bed, and to raise its margins. A swelling of the stream supervenes; it overflows its banks, carries along the materials that filled the bed, and arranges them as a cone of dejection. (Fig. 91.) A, B, represents the course of a torrent which, in consequence of floods, has formed

[5] I would mention once more that I have long studied these phenomena on the small scale in the numerous rivulets that run in the sands of the valleys, producing a rising of the waters by small artificial weirs; and these experiments on a small scale have explained to me many phenomena which were afterwards clear and simple on the large scale.

the cones of dejection indicated by the contour lines, *a*, *b*. The longitudinal lines, *c*, *d*, show the direction of the slopes along which the gravels have run,

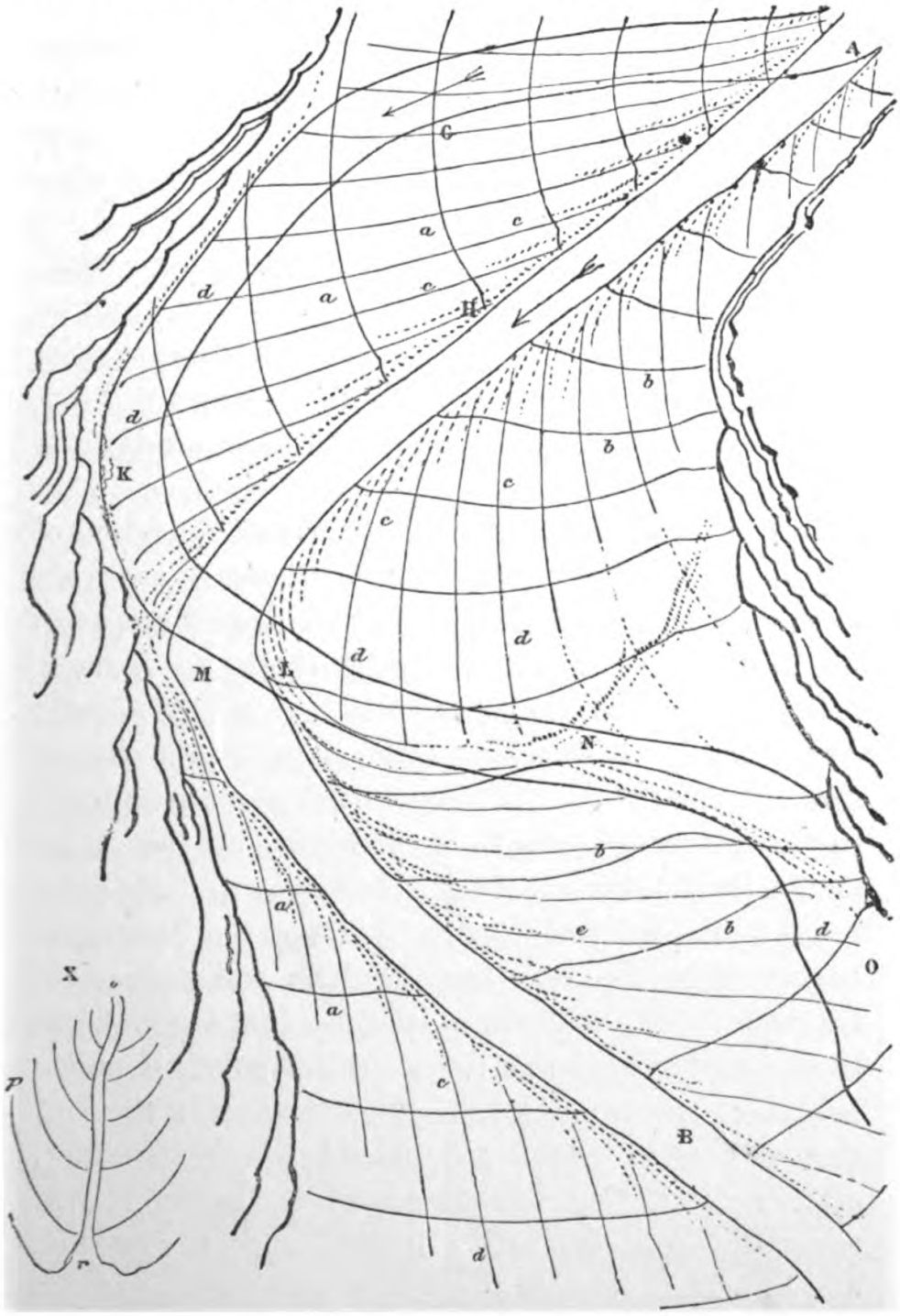


Fig. 91.—Hollowing out of Torrent beds.

the coarsest being arrested near the banks of the torrent, and the finest at the base of the cones, except some pebbles that have been swept onward.

By dint of elevating the cone through the deposit of gravel and raising its bed, the torrent, taking advantage of a swelling of the stream, breaks down the bank it has made and seeks the lowest point—the steepest incline. Our figure will clearly show what then takes place. If a cone of dejection is a portion of a regular cone whose base is perpendicular to its axis, it is evident that all the lines drawn from its apex to its base are equal, and that, consequently, whatever be the line along which the torrent flows, it will always make a circuit of the same length on an equal incline.

But it is not thus with the cones of dejection of rapid torrents. These portions of cones are very much elongated (see x). Their base is an ellipse of which the current that generates them is the major axis. It follows, then, that the line *o p* is shorter than the line *o r*, and that the slope *o p* is steeper than the incline *o r*. This is why it so often happens that the torrents which have formed a cone of dejection quit their generating bed, *o r*, to flow more rapidly over the incline *o p*. Well, on our figure, the torrent deposits are so arranged, in consequence of the rapidity of the current, that the line A G happens to be shorter than the line A H, the points G and H being on the same level. The torrent is then induced to wind round A G instead of A H. In fact, after a flood that has deranged its banks it will some day quit its bed A H, and sink a new one at A G. Then it naturally follows the meeting of the cone with the escarpment of the valley. But finding an impediment at K, it tends to make a sudden turn,

eats away the left bank L of its older bed, forms a dike of gravel at M, proceeds to rejoin the lower point N, and naturally follows the declivitous plane of the second cone from N to O. The bed M B is gradually filled in, is extinct, or simply forms an arm filled only during the great floods.[6] The above explains how it is that the more the valleys are filled in and consequently levelled the more do the streams meander, lengthen their course, and consequently slacken their currents.

Yet there occur—and at the time of the great glacial meltings they were still more marked—phenomena of flow of a more complicated character though ending in the same result.

In the widened valleys, which were already filled in by mud and torrential deposits, the great floods which formed a sheet of water completely covering the ground, hollowed out, on subsiding, a number of currents whose course was determined by accidents of the ground, through the general sheet of water, and which were more rapid than the general flow.

These currents tended to follow straight lines, as far as the slopes of the valleys would allow. They proceeded as shown in Fig. 90, and formed a bed composed of cones of dejection greatly elongated, confused with each other and intrenching one on the other, overlapping one another like scales, and thus filling in the valley by beds successively deposited, with perfect regularity, and according to a law which it is not difficult to explain.

[6] In the course of an hour or two any one may observe these phenomena along a rivulet flowing over fine sand, between firm banks, with a very little care in damming up and setting free the water so as to produce a succession of regular discharges and swellings of the stream.

Fig. 92 represents a valley, covered with a sheet

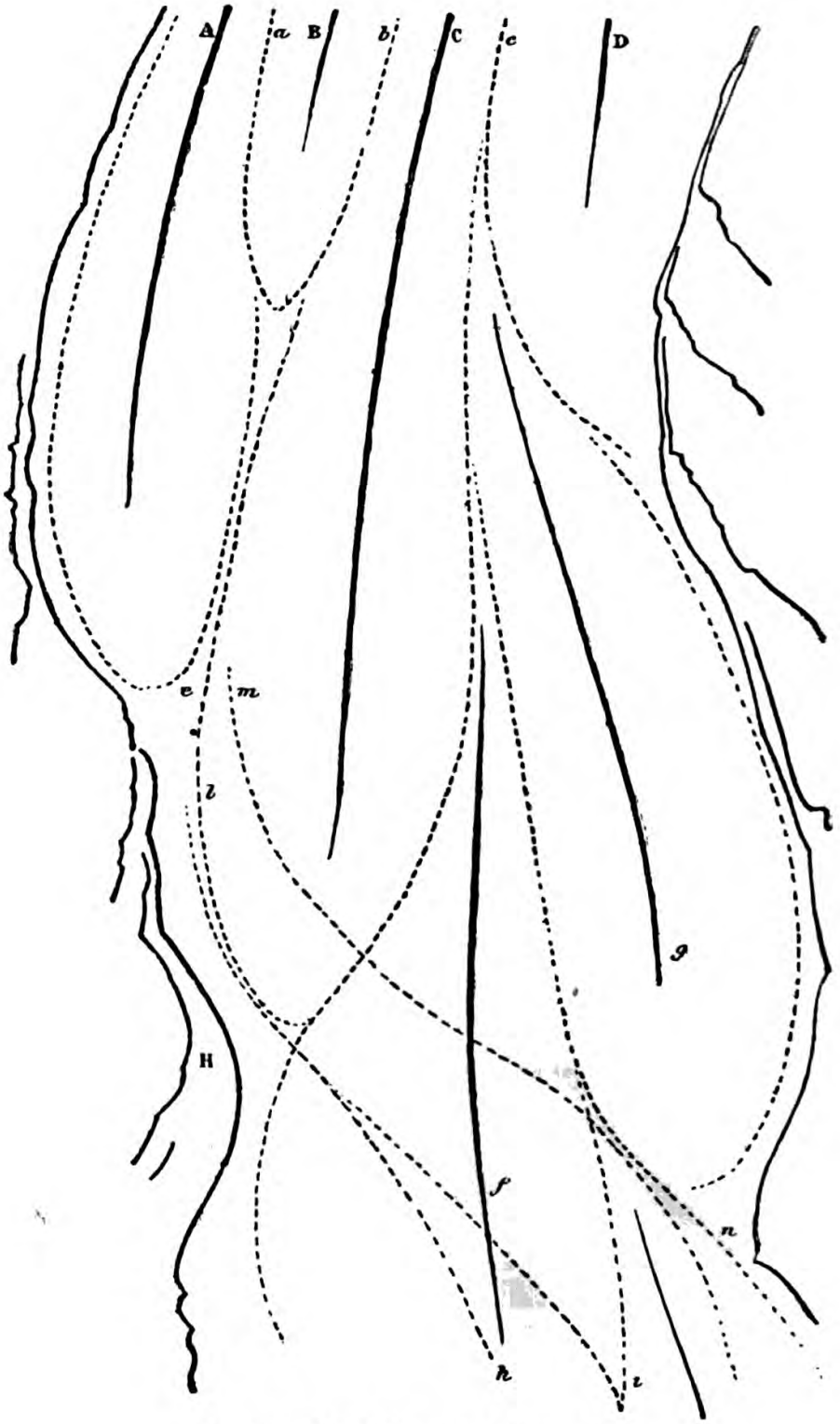


Fig. 92.—Hollowing out of Torrent beds.

of running water, with four torrential currents, A, B, C, D. These deposit each a cone of dejection in proportion to their strength. In depositing them they form meeting lines, *a b c*, which are more deeply hollowed out, and which become, in their turn, torrent beds, *a e*, *b e*, *c f*, *c g*. These new currents deposit their cones of dejection which are considerable in proportion to their violence. But the current *a b e* rushing against the escarpment H, and not being able to throw down the obstacle, betakes itself, as we saw before (Fig. 91), towards the current *c f*, and ends by joining it in the line *l h*, or, rather, *l i;* for the torrent *c f*, has ultimately taken the declivitous line formed by the cones of dejection of the torrents *c f*, *c g*. A curve is formed, and forming in its turn the cone of dejection following the line *m n*, in the up-stream direction, it will be soon obliged to abandon the line *l i*, to follow the new bed *m n*. All these separate rapids in the advancing stream tend, therefore, to unite in one, and to excavate the future bed of the torrent, which will pass from one side of the valley to the other.

It need not be remarked that many local circumstances cause these torrent courses to vary indefinitely; moraines and barriers of other kinds causing particular accidents in their passage: but the general law always resumes its authority.

We have said a few words respecting the arrangement of the materials brought down by the torrent according to their volume. The heaviest are, as might be expected, deposited, or run aground first, unless the impetus resulting from their weight carries them further; those of moderate size facilitate their progress by having their angles rounded, and

are transported to a great distance if the current is rapid ; the smallest reach even the lower lakes, or the low valleys, if reservoirs, or shelving parts, do not stop them.

A valley torrent (Fig. 93) presents, as Fig. 88 shows, a convex transverse section with an elevation at the margins, or one simply convex. The stones that are too heavy are arrested on the bed, whence, as Fig. 86 shows, they are buried deeply in proportion to their size if the bed is gravelly.

Stones which are not heavy enough to resist the current are rolled to the sides, in consequence of the repellent force of the waters. They stop when their resistance overcomes the strength of the current.

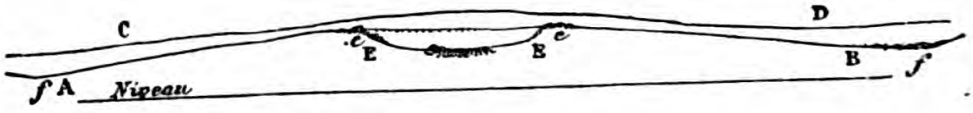


Fig. 93.—Process of Alluvial deposit.

If a flood occurs, A B being the section of the cone of dejection, and C D the level of the flooded stream, in transverse section, which is invariably convex, the pebbles are thrown off at *e*, and the largest stones run aground, those of less size are carried over the slopes of the cone, and at *f* reach the lines of junction of this cone with other cones, or with an escarpment; —lines of junction which are destined one day or another to become the bed of the torrent thus *paved* with pebbles, which (as we saw, Fig. 86) will maintain the level of this bed, and will dredge out the mud.

So that the cones of dejection which rise above the stream always exhibit the largest pebbles along the

bed of the torrents and at their bases. But we must investigate the longitudinal section of the cones of dejection and the torrents that have formed them, and the laws that produce that section.

Torrents fill up or undermine; they undermine when they are subsiding, they fill in when they are swelling. A torrent in its normal state hollows out its bed; when it is swollen it forms a cone of deposit, and raises the site over which it flows. But it began by finding a natural course through the rocks, or a firm sedimentary slope; this slope may be longitudinally convex or concave.

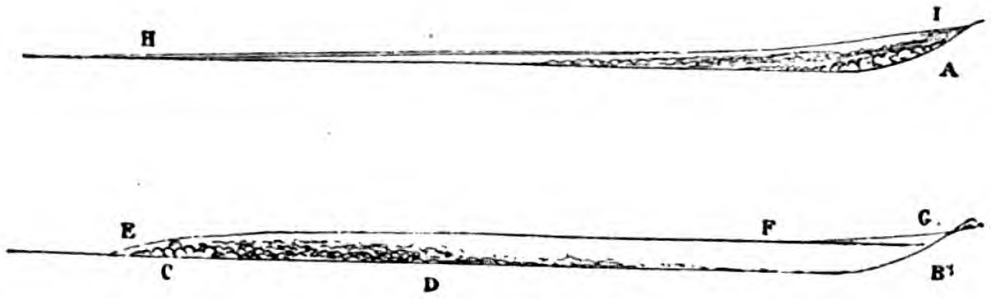


Fig. 94.—Cones of dejection.

When the torrent flows along a gorge, the undermining power is the only one that acts; but when the torrent issues from the gorge, the depositing power acts in its turn, and the torrent forms its cone of dejection. The profile of this cone is determined by the energy of the torrent. If its force is inconsiderable (Fig. 94), the great stones on issuing from the gorge A are arrested in proportion as they can resist the strength of the current, they form the apex of the cone, and the sediments take a concave section; the materials being sorted and deposited according to the same law; the heaviest first, then the lighter

ones, and the sand at the base of the cone. But if the power of the torrent is considerable on issuing from the gorge B, the heavier materials hurried along by the impetus they have acquired, tend to pass beyond the lighter, and are deposed at C only, when the extent of the current diminishes its swiftness. Materials of less volume, and less violently impelled, are deposited at D, and the cone of dejection assumes the outline E F; it is convex.

When the force of the torrent decreases, a concavity is produced at G, and, returning to a stable condition, the torrent hollows out its concave bed over the whole section of the cone, whatever be its convexity, because in its normal state it sifts its materials; that is, deposits the heaviest first, and those of less volume successively, according to their weight; then, although the cone of dejection presents the curve F E, the bed of the torrent exhibits that marked I H. The torrents of more or less liquid mud, or the currents of heavy material form chaotic deposits, that is, presenting various dimensions; the torrent, when it has reached its normal state, sets up a sifting process in these materials. When an extraordinary flood takes place the normal torrent may accidentally become again charged with a mass of material; and it is thus that we observe in its deposits alternations of gravels regularly arranged according to their volume, and then chaotic beds where large stones, gravel and sand are mingled without order.

One cause is incessantly tending to bring disorder into the deposits of currents; namely, the tributary or lateral torrents, which in the mountains are very numerous, and whose fall is more precipitous than

that of the main torrent. These tributaries bring down great stones, which, falling into the bed of the main torrent, impede its advance, and sometimes oblige it to make a détour and erode the banks opposite the mouth of the affluent, or if the bank resists its efforts, compel it to narrow its bed, to grave it so much the more deeply, and to acquire a strength in that part capable of carrying along further the materials that impede its course. Thus nature is able to cope with all eventualities, by the rigorous observance of her own laws.[1] Meantime, it happens that the tributary torrent sweeping down materials in considerable quantity rushes into the main torrent with such violence that it cuts across it, attacks the opposite bank, pierces it if a natural or artificial dike, and spreads itself out in the valley beyond this bank. These effects, which are often enough produced in the mountains, and which were even considerably more frequent formerly, cause the most serious disturbances in the regular course of the main torrent, and form pools or marshes, which, however, the main torrent fills up at last more or less rapidly, according as it carries along with it more or less gravel. In fact, the main torrent, when it has resumed its normal course, issues forth from its bed to some extent through the breach made in its embankment, and bears with it sand, which, as the water is tranquil in these submerged parts, is deposited, and ultimately fills the gap.

The very admirable works of Cézanne, Belgrand, and Costa de Bastelica on torrents and watercourses

[1] See M. Cézanne's work on watercourses and torrents.

render a further notice of this subject unnecessary: to say more would take us beyond the limits of our purpose. We shall terminate our observations on torrents by some words on the lower lakes of the valleys.

Though very numerous after the glacial epoch in the valleys whose bottoms consisted in fact only of a series of lakes one above the other, they are rare in the present day. Only the largest have been preserved; the others have been filled up, or are being filled up before our eyes, by the incessant contribution of materials carried down by the torrents. Where these torrents entered the lakes a cone of dejection—a delta—is formed. This delta is continually increasing, especially when floods occur, emerges on the upstream side, and ultimately fills up the lake as far as its issue. We can recognize many such filled-up lakes in the valleys that surround Mont Blanc, and which now have only one retaining its lacustrine character—Lake Combal in the val Veni; and we can foresee the ultimate filling up of this, which in the course of a century has lost more than a third of its surface.

But besides the lakes that have been produced by the natural hollows of the valleys, and which the torrential deposits have as yet not been able to fill up, such as are most of the Swiss lakes,[8] there are some which have been caused by the damming up of waters by a moraine dike. Lake Combal, which has just been mentioned, owes its existence solely to the fact that the great moraine on the

[8] The Lakes of Geneva, Neufchatel, Thunn, Brienz, Lucerne, &c.

right hand of the Italian glacier de Miage has barred the valley. But there the phenomenon is a simple one; it is often presented under more complicated conditions.

A lateral glacier descending at B, its medial moraine C, Fig. 95, joined a trunk glacier T. The latter having retired, the lateral glacier B deposits a frontal moraine A, which blends with the left hand lateral moraine of the trunk glacier whose

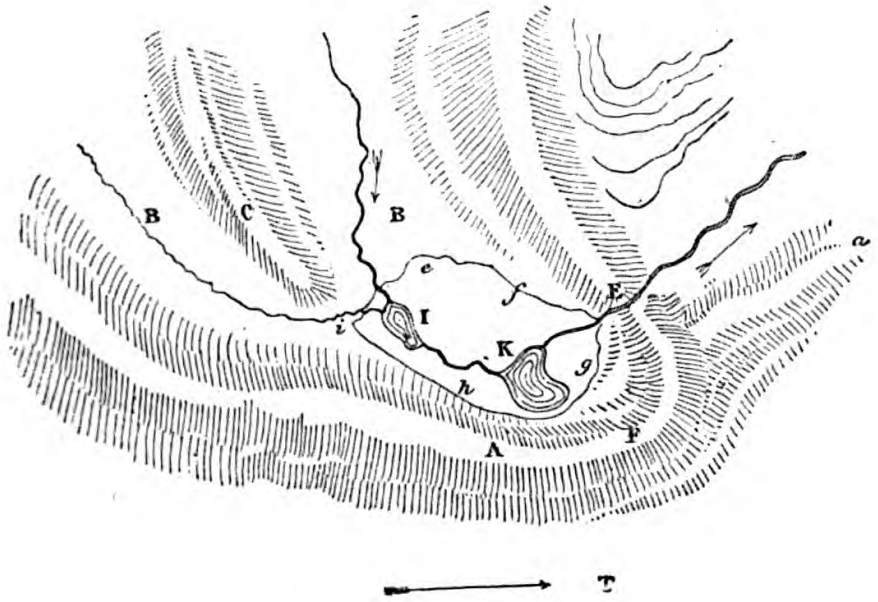


Fig. 95.—Moraine lakes.

vestiges we find at *a*. In melting, the glacier B forms a lake—an embanked accumulation of water *e*, *f*, *g*, *h*, *i*. This lake excavates for itself an issue at the point E, the weakest part of its dike—that at which the materials brought down must have been, by the very position of the glacier, deposited in least quantity—while at A F the dike is very strong. It is therefore laterally, and not according to its natural direction B T, that the current finds an

outlet. But one or more reservoirs I K, have remained, for the bed of the lake *e*, *f*, *g*, *h*, *i*, was below the level of the outlet E.

The rains,—the torrent itself,—have ultimately brought sand and pebbles that have partly filled up the bed, while the current of pure water was excavating its bed E more and more deeply, without making any deposit there. The last vestiges, I K, of the great lake *e*, *f*, *g*, *h*, *i*, are therefore destined to disappear. The phenomenon here described has been studied in the valley of the Vorder-Rhein below Flims, and above Trins. There, numerous streams flowing over the bed of an ancient glacier, meet the ancient frontal moraine of this glacier, lateral to the trunk glacier of the Vorder-Rhein; one of these streams still forms two small lakes.

But this valley of the Vorder-Rhein presents at many parts in its course, subjects of remark of the highest interest in reference to the phenomena of the flow of torrents.

Where the Hinter-Rhein flows into the Vorder-Rhein, below the valleys of Trins and Tamins, the valley, which is wide, exhibits traces of enormous accumulations of glacier mud and moraines, and of thick alluvium deposited by the torrent waters which were loaded with materials, as also of very regular successive excavations of these accumulations by torrents of a comparatively recent period, Fig. 96. At M are vestiges of moraine mud reaching a level higher than the existing bed of the valley (see at *m* the section C along A B). These deposits have been, to a great extent, swept away by the torrent waters which have formed the alluvium *a b;* subsequently the torrent, reduced in

volume and become clearer, has hollowed out its bed *a e;* then, when still further reduced, the bed *a f;* then the bed *a g;* lastly, the bed *a h*, in which it now flows.

Thus, after having excavated, filled in, and levelled the bottom of the valleys by enormous deposits of pebbles and sand, the torrents, less charged with

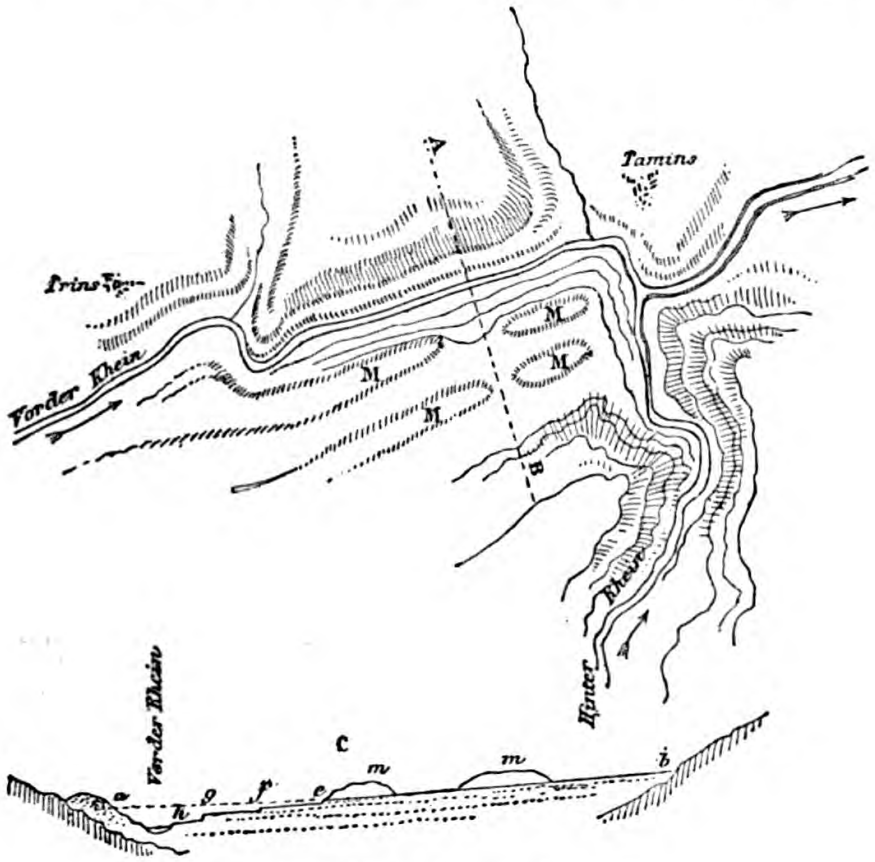


Fig. 96.—Valley of the Vorder-Rhein.

materials, and diminished in volume, having lost the viscous character which the materials with which they were freighted gave them, begin a work of a contrary character. Henceforth they hollow out the ground they have formed, transporting to a lower point the sand and pebbles that had been stored up; they reduce the level of their bed, and

make its form regular; yet, if considerable inundations occur, they recommence their earlier stage of operation, once more deposit materials, and sometimes even change their bed, excavate it again elsewhere, or in its former course; and thus we see produced on a small scale, in the present day, the phenomena which were exhibited on the grand scale after the glacial epoch.

It is difficult for us to form an idea of the level attained by the primitive torrents in the upper valleys, and of the quantity of deposits which they must have swept down at a later date. Thus, in the lower part of the Val de Valorsine, above the Auberge du Châtelard, and following the course of the valley as far as the Tête-Noire, and beyond, we meet long bands of rock (the coal measures and anthraciferous strata) which, worn by the passage of the ice, form hills mammillated on the surface. The higher levels of these hills are about 500 feet above the torrent as it now runs, and yet, among the higher mammillations of these rocks we find heaps of rolled pebbles of schist and granite which came from above, and clearly indicate that the torrent rose above this level. It must have subsequently swept away all the boulders which it had deposited below these rocks,—all the sediments which certainly filled the valley as far even as the ridge of the rocky eminences which are now cleared. The erosive action of the torrents must therefore have been very powerful in the higher valleys. The waters have swept away a great part of the mud and torrential deposits that owed their origin to the first débâcles; and after having filled up these valleys they have cleared them out, and transported

the materials into the lower valleys, and levelled their thalweg.

But there are at the lower extremity of the valleys of the Alps large deep lakes, terminated towards their outlet by moraine deposits and erratic blocks, which forbid a doubt of their bed having been filled by glaciers. Such are the great lakes of the Italian slopes, and such is even the Lake of Geneva. These lakes may be classified as those occupying a *cluse*, and those in a "combe;"—lakes occupying a *cluse*, when they have found a depression, followed by a dam, through which they have made themselves a passage;—lakes in a "combe," when they have collected waters in a reservoir quite surrounded by heights, i.e. in an amphitheatre. There are, indeed, some lakes which present both characters, e.g. the lake of Lucerne.

Beyond the *lacs de cluse* the alluvium of the torrents is so considerable that it would have been sufficient, and even more than sufficient to fill them in. After the glacial epoch had culminated, therefore, the muddy waters, loaded with gravel, descending from the higher valleys, must have covered these lakes and deposited farther on the débris they were carrying. The question is a very difficult one. For to have enabled the waters of the torrents to be sufficiently abundant to sweep down these enormous alluvial deposits, the ablation of the glaciers must have been already greatly advanced, and the slopes of the great valleys above these lakes must already have been to a great extent freed from snows. Why, then, did not these transported materials stop at the bottom of these depressions? how should they have been carried farther?

I would remark at the outset, that I agree with M. Studer and most of the Swiss geologists in regarding it as impossible that glaciers should have excavated the beds of these lakes to depths of three, four, or five hundred yards below the sea-level. From what was stated above on the action of ice as the result of a long series of observations *in situ*, it may be concluded that, while the glaciers exert a lateral action powerful enough to tear away salient rocks and widen valleys by a rasping process, they produce a comparatively feeble effect on their bed; that, as their plastic nature enables them to follow the inequalities of the ground, they do not and cannot operate on their beds as a gouge, but simply wear it down—polish, and lubricate it, as we might say. How can we suppose that, on issuing from the upper valley of the Rhone, the glacier, which could then find plenty of room, should have excavated the bed of the lake of Geneva to a depth of 300 yards below the present surface, while it respected the St. Maurice dike above, and while the enormous glacier, which came down from Mont Blanc with a pressure proportioned to 6000 or 7000 feet, abstained from disturbing le Prarion, and was obliged to rise and pass over that dike of schist, though it was closely banked in at that point? How can we suppose that the glacial currents, which in the present day lend themselves to all the irregularities of the rocks and pass into narrow defiles, as into sluices, to expand beyond them over wide surfaces, and which operate in the gorges only by way of lateral rupture and erosion, when these are favoured by the dislocation of rocks exposed to the disintegrating effects of weather, should have possessed

an excavating force of such intensity at a particular point in their course, when they could find lateral space?

These beds of the great lower Alpine lakes were depressions produced by the thrusting back and folding of the strata. The ice filled them, rose above, and passed beyond them; but even when, in consequence of ablation, the glaciers had abandoned the plains and retreated up into the higher valleys, there must have remained in these depressions—these "*holds*"—wide and deep accumulations of ice, covered with moraine débris—accumulations which it took a long time to melt. There must often have been a separation between the "glacière" and the glacier that had fed it,[9] and this "glacière" having become inert—not continuing to advance—received on its surface the mud torrents caused by débâcles, thus furnishing them with a levelled bed, so as to enable them to pass on lower down.

This view has already suggested itself to many savants. "We suppose," says M. Desor,[1] "that, when they first invaded the district, the glaciers advanced with sufficient rapidity to enter the lakes before the torrents had had time to fill them up completely. When, at a later period, the glaciers retired, the ice would not have entirely disappeared from the deep parts; portions of it would remain at the bottom of the valleys, which, covered by great beds of gravel, would keep their position there during the interglacial period. Later on, when the second invasion took place, the glaciers would have pushed forward their moraines over these ancient

[9] See Fig. 71.

[1] *Le paysage morainique*, by Desor, p. 77.

substrata of ice, and would thus have been able to heap up those erratic deposits beyond the region of the lakes without the latter having been filled up by them."

It seems difficult to find a better explanation of the preservation of the depressions which contain the great lower Alpine lakes, as similar phenomena on a very small scale are still produced, and we observe detached masses of ice, covered with gravel, remaining in the depressions, and allowing currents of water and warps of mud to pass over their surface and continue onwards. Ultimately these masses are melted, and a small lake will remain at the bottom of the glacier.

It is quite possible, however, that the great glacier currents have sometimes eroded and excavated the softer strata in the lower districts, while they left the harder parts as they were, since they have operated, and still operate thus in the higher regions of the mountains; but this action could not produce any considerable excavatory effect at the bottom of the great depressions which contain the lower lakes.

X.

CAUSES OF THE INCREASE AND DECREASE OF THE EXISTING GLACIERS OF MONT BLANC.

Towards the close of the last century the glaciers of Mont Blanc had retreated upwards to a considerable extent. It is asserted, on the authority of a chronicle of the twelfth century, that at a much remoter period the passage was made on mules from the Priory of Chamonix, by the col du Géant, to Cormayeur. Without discussing these traditions, which cannot have the value of scientific observations, we will limit ourselves to calling attention to facts that have been clearly and carefully verified.

The long and severe winters which, between 1812 and 1817, alternated with rainy summers, considerably increased the névés, and consequently the glaciers around Mont Blanc. Towards 1818 they reached a very low level. In 1820 the glaciers du Miage and de la Brenva, in the Val Veni, continued advancing, while the glaciers of the northern slope were stationary. The latter even sensibly diminished between 1821 and 1826. Then they resumed their progressive movement till 1837, when we observe them again diminishing, but resuming a certain amount of increase up to 1854, with some oscillations. From that date they have continued

to diminish down to the present year, 1877. Yet on some other parts in the Alps, especially above Zermatt, the glacier de Gorner continued to increase from 1818 to 1851. From that date this glacier has been undergoing oscillations, as well as most of those which come down from the Bernese Alps on the north-west slope. During these last years, from 1868 to 1877, the glaciers des Bois, de l'Argentière, des Bossons, du Tour, de Bionassay, the French glacier du Miage, de Tré-la-Tête, the Italian glacier du Miage, de la Brenva, du Mont Dolent, de Saleinoz, and du Trient, have been continually diminishing to a very marked extent. During this period the glacier des Bois has retreated 200 yards, the glacier des Bossons 150, and their surface has been visibly depressed. Below les Ponts the level of the Mer de Glace was only ten or twelve yards beneath the ridge of the moraine; now it is more than twenty yards. The ablation has, therefore, been considerable. The surface of the névés has been proportionally lowered, especially in the south-east aspect.[1]

[1] I will add to the above data those collected by my learned friend, M. Charles Martins. "Sometimes a glacier advances in a single year with a quite exceptional rapidity. Thus, after the rainy summer of 1815 to 1817 the glacier de Distel, in the valley of Saas, in Valais, advanced fifty feet in a year, that of Lys, on the opposite side of Monte Rosa, nearly 160 feet; that of Zermatt progressed seventy-three feet in 1853.

"But the most remarkable glacier in this respect is the *Vernagtferner*, at the head of the Oetz valley, in Austrian Tyrol. In the summer of 1843 it was forming a junction in its advance with the little glacier de Rofen, from which it is now separated by a projecting mass of rock. These two uniting in a single mass were descending rapidly into the valley. The inhabitants were frightened. They knew by tradition that in 1600, 1667, and 1772 this

To explain why these oscillations do not take place in so limited a district as Switzerland and Savoy exactly in the same manner, we must suppose that the direction of the winds that bring the snow

glacier had advanced with equal rapidity and had dammed up the course of a rivulet and changed it into a lake. The lake had afterwards broken through its barrier of ice and had swept into the valley, causing great damage there. The authorities of Inspruck, in consequence of the prevalent rumour, named a commission, which ascertained the rapidity with which the glacier was advancing. In 1842 it advanced 656 feet in sixty-seven days, or about 9·79 per diem, less rapidly in 1843 and 1844; but in the summer of 1845 it advanced 32·5 per diem. This was a veritable slipping down of the whole mass. The water opened itself a passage under the ice on the 14th of June, and from this date to 1848 the lake filled and emptied itself nearly twice a year. This glacier, like all the others, must have commenced its period of contraction in 1854; but it has perhaps not returned to its former condition, for after its aggression in 1667 it took thirty-four years to return to its usual limits.

". . . . In the Valais, during the rainy years and summers of 1812 to 1818 the Rhone glacier had advanced so much that two geometricians, MM. Pichard and Marc Secrétan, calculated that it would take 774 years to reach from the bottom of the Valais to Soleure. Less than eight centuries! A mere minute on the dial-plate of geology. I have made another calculation. Let us suppose the winter in the plain of Switzerland to retain its present character, but the summer to be less hot, so that the mean temperature of Geneva should be 41° Fahr. instead of 48°.5, as at present. The limit of perpetual snow would be also lowered and stand at 6400 feet above the sea level. The glaciers of Chamonix would descend below this new limit by a quantity at least equal to that which exists between the present limit (8800) and the lower extremity. But at present the lower end of the glaciers is at 3770 feet; with a climate 7°.2 Fahr. colder it would be 2460 feet lower, i. e. it would be at 1312 feet above the sea level, and consequently at the level of the Swiss plain."

Les Glaciers actuels et période glaciaire; extr. de la Revue des Deux-Mondes, 1867.

is an element of some importance in causing the increase and decrease of glaciers. (See Figs. 13, 14, 18, and 19.) A current of air continually blowing from the north-west will deposit considerable masses of snow beyond the ridges on the opposite slope. The winds persistently blowing from the south-west are favourable to the accumulation of snows on the north-north-east slopes; as are those which supply the glaciers that descend into the valleys of Zermatt and Saas, while the same current, passing along the range of Mont Blanc in the direction of its length, cannot produce deposits to the same extent.

But the massif of Mont Blanc, by the very character of its geology is subjected to marked oscillations in the state of its glaciers. The primitive plateau, which has suffered very deep excavation in consequence of the tendency of the protogine to be readily disintegrated in a vertical direction, and thereby allow huge bare cliffs and lofty crags to jut out above névés and ice, thus presents wide dark surfaces which reflect the sun's rays and rapidly melt the ice and névés.

The glacier currents, being deeply embanked, are subjected to higher temperatures that cause them to melt with a rapidity proportioned to the diminution of the frozen surfaces, so that the ablation is effected in an increasing ratio the smaller the volume of the glacier. When, on the contrary,—as in the massif of Monte Rosa, e. g.,—the upper plateau does not exhibit such marked depressions, but presents itself in the form of an immense ice-covered plain, slightly inclined to the north, there is no reflection from environing rocks, and the glaciers continue fuller, even after a period of hot summers.

Amphitheatres, which are so favourable to the accumulation of névés, such as those of le Talèfre, Leschaux, and le Géant, in the massif of Mont Blanc, but which are surrounded by deep escarpments that reflect the sun's rays, produce a considerable extent of thaw during the fine days in June, July, and August; and the temperature in these great combes is then very high. It falls at night below freezing point, and the regelation of the waters that have saturated its surface produces an expansion which pushes forward the mass of the glacier so much the more rapidly in the lower beds. Embanked by rocks, or by moraines, the reflection from which is still more effective than that from the rocks, the melting increases with the distance from the sides. Thus, in a hot dry summer, the reservoirs are emptied, and the glacier currents sink; the ablation is rapid; the terminal point of the glacier retreats upward in its bed.

The long cold winter of 1870-71 produced no effect on the decreasing progress of the glaciers of Mont Blanc; the proportion of ablation was the same as that of the preceding years. But we must not forget that this cold season was followed by a warm, dry spring, and that the summer was very fine and the autumn a prolonged one.

In 1871 no snow fell at Chamonix before the end of December. During the winter of 1874-75, the snows were very abundant in the valleys, they were thirteen feet deep at the village of le Tour and at Nant Borant; but these snows were less in proportion on the peaks, which perhaps during their fall were uncovered. The glaciers continued to diminish during the summer of 1875, and the

snows in the valleys melted during the month of May, which was very warm.

During the winter of 1874-75 more than ordinary accumulations of snows were noticed on the cols of St. Gothard and of the Simplon, and on the 15th of June the snow was still a yard or more deep at the Maienwand, above the Hôtel du Glacier du Rhône.

The warm rains at the end of this month, which caused such disasters in the south of France, quickly melted these snows; and in August the snows that had long remained on the chain of the Brévent, those of the Bonhomme and the col de la Seigne had almost entirely disappeared. In the month of July, which was very rainy, there was not a single day of clear weather in the neighbourhood of Mont Blanc. These rains had caused the lower snows to *melt* even more than those of June. Yet the avalanches at the end of the winter had been so considerable that even in September, at the bottom of the lateral couloirs of the Mer de Glace, there were enormous accumulations of snow, which certainly could not melt in the interval before the return of the cold season, and which, if the winter of 1875-76 were snowy, would blend with the glacier, and thus restore the small tributary glaciers which are so necessary to the supply of the principal currents, and which greatly contribute to their increase.

In fact, as soon as a lateral glacier ceases to be connected with the main glacier, when it becomes detached and retreats towards the heights, it sends only its melted waters to the main glacier, and these rushing into its bed tend rather to dissolve than to feed it. But if the junction is restored by

avalanches which are successive and persistent,—that is, which do not melt in summer,—the lateral supply of the glacier recommences; and if there is a renewal of such supply at many points, the glacier may be rapidly increased by these lateral contributions; and as most of the glacier currents of the massif of Mont Blanc are bordered by a great number of channels of this kind issuing from lateral glaciers, if, after many snowy winters, these lateral glaciers blend again with the main current, the increase will be rapid, in fact almost sudden. Such

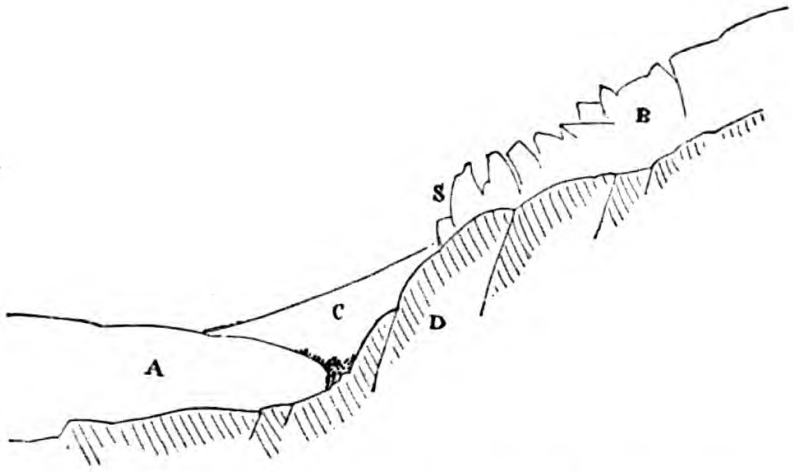


Fig. 97.—Junction of lateral glaciers with the trunk glacier.

are the glaciers de l'Argentière, the Mer de Glace, du Miage, and de la Brenva. Most of the glaciers of Mont Blanc are therefore subject to very marked oscillations, more rapid than those experienced by the great glaciers of Monte Rosa and the Bernese Alps.

How is the welding effected? Let Fig. 97 represent a trunk glacier A, and B a lateral glacier: if the snows resulting from considerable avalanches have accumulated at C, so as to form a heap volu-

minous enough to resist the summer melting, if this mass remains, the séracs s of the upper glacier B, instead of falling and being broken along the rocky escarpment D, coming down on the talus, C, as on a bed, unite with it; and the glacier B, which has itself been increased by a greater abundance of névés, henceforth becomes one with the glacier A. As the sun's rays no longer strike on the rock wall D, this again becomes the true bed of the glacier, and cannot be a cause of the séracs, s, being melted.

The disconnexions which occur after hot summers and winters of little snow, between the trunk glaciers and the lateral glaciers, are one of the causes of rapid decrease for the former; for it happens that these lateral glaciers no longer discharge their séracs on the trunk glaciers, they have a separate existence, and cease to furnish any but a liquid supply. Still it must not be forgotten that the glaciers move, and that their mean annual speed at the longitudinal axis is 100 yards: this speed being, moreover, quicker in the higher parts than near the terminal point, and greater at the middle than at the margins.[2]

[2] The hut which Hugi built on the lower glacier de l'Aar in 1827, near the promontory of the Abschwung, had, in 1830, descended 109 yards, in 1836, 780 yards; and in 1840, M. Agassiz found it 1561 yards from its original place. It had therefore descended about 109 yards yearly. In 1840 Messrs. Agassiz and Desor took up their station on the glacier de l'Aar, and built on an erratic rock borne by the ice, the hut known as the *Hôtel des Neufchatelois*, where they lived during an entire summer. In order to investigate the laws of the speed of the glacier, which they were endeavouring to define, these observers planted a series of stakes in a straight line corresponding with two fixed points. The displacement of these landmarks was to indicate the movement, and the distance between the relative positions of the stakes was to mark the amount of the glacier's descent in the

When therefore a lateral glacier has retreated, has ceased to be welded with the trunk glacier, and after a snowy winter, a considerable cone of avalanches forms at A B C, Fig. 98, this cone, at the end of the warm season, will, in consequence of the motion of the glacier, occupy the surface *a b c*. If there is a fresh import of avalanches, the base of

time that elapsed between two observations. But when Agassiz came the following year to ascertain the position of the stakes, he found them all lying on the ice. This preliminary experiment only showed him that the surface of the glacier had sunk at least five feet, the length of the stakes. The persevering geologist then drove into the ice poles of about five yards in length, which he cut off level with the surface. In 1841, one of these poles was standing two yards out of the ice, and at the beginning of September it showed three yards above the surface. The ablation of the surface had, therefore, been three yards. After that the learned observer marked a fresh line of six staves, placed apart and in relation to the margins of the glacier at verified distances. When he returned the following year, the staves had considerably advanced their line, which from straight had become curved—convex in the direction of down-stream. This result proved both the movement and the greater speed in the middle. But these experiments tended, moreover, to demonstrate that the speed diminishes in proportion as we near the end of the glacier; that is, that it is less in the lower than in the upper parts (see in the *Monthly Atlantic*, January, 1864, the article by M. Agassiz). Professor Tyndall has verified this fact with scientific exactness on the glacier du Géant. He fixed three stakes, A B C, on the axis; A was placed up-stream; B in the middle, 595 yards from A; C, down-stream, was 533 yards from B. The daily speed, measured by the theodolite, marked:—For A $20\frac{3}{4}$ in.; B, 16 in.; C, $12\frac{7}{8}$ in.

The upper parts were, therefore, constantly approaching the lower parts, and this difference in the speed may amount to eight inches per day for a length of 1100 yards of the glacier.

See *Les Glaciers*, by William Hüber, Major of Engineers of the Swiss Confederation. The author has admirably arranged all these observations; see also *Heat, a mode of Motion*, Tyndall.

the new cone will be D E F, which will again change its form in the following summer; and thus the junction between the two glaciers will take place obliquely in the direction of the current. But the annual speed I K along the axis of the glacier being 100 yards, and that L M only 30 yards, the speed O P of the axis of the more elevated lateral current will be 110 yards. The lateral glacier will soon form a

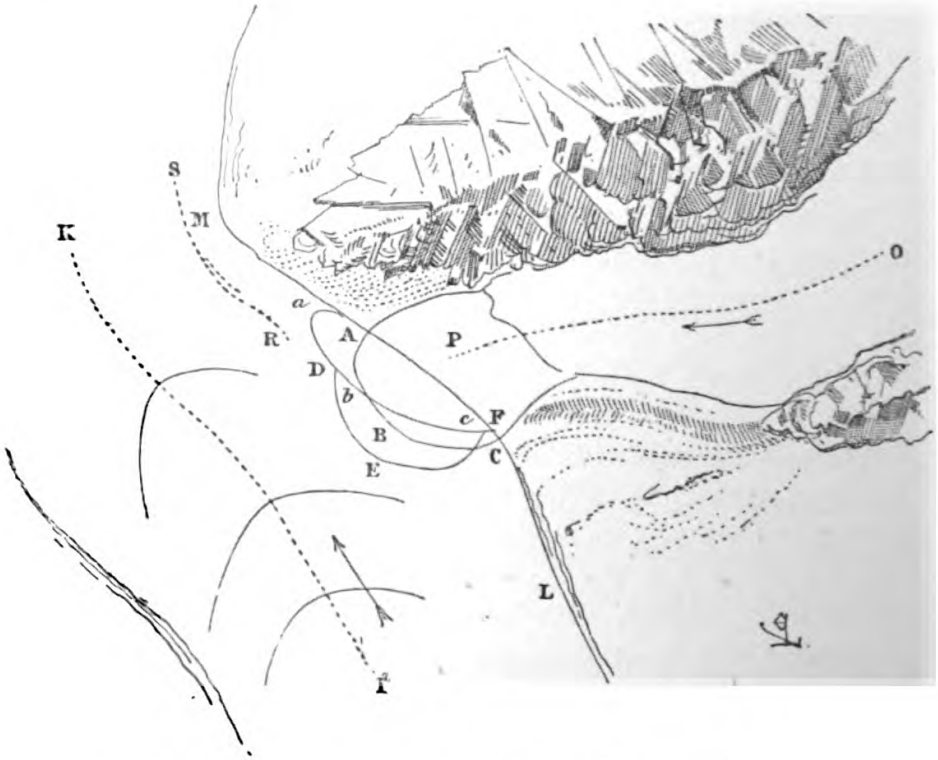


Fig. 98.—Junction of lateral glaciers with a trunk glacier.

special current, which will not mingle with that of the trunk glacier; and the proof of this is, that this current will have its medial moraine R S, and its special crevasses, down to the point of ablation. This current will find room, and will force the trunk glacier to raise its surface in order to discharge only the same quantity of ice in a bed narrowed by the

interference of the lateral current. We can understand, therefore, how a series of several snowy winters and wet summers may lead to a pretty rapid increase of flow in glaciers which, like those of the massif of Mont Blanc, receive many affluents, so soon as these affluents are reunited with the trunk glacier, or rather make their way beside it.

Besides, the abundant falls of snow fill the crevasses, not as sand would do, shovelled into a cavity, but by blocks. It must be remembered that on the elevated parts the snow always falls, driven by a more or less violent current of air, and never descends perpendicularly.

According to the laws which we have previously indicated, Figs. 13, 14, and following, the edges of crevasses present an obstacle to the wind; and there the snow deposits itself in greater quantity than on the even parts.

Suppose Fig. 99 to represent the section of a crevasse: the wind following the direction A B, the snow deposits itself conformably with the two sections C D. If the fall is abundant, the bulging mass D gives way from its weight, and carries down the mass C; then the operation recommences. These blocks often remain held between the walls of the crevasse,[3] and there form a stop-gap, which fills with snow, as seen at E. Then over a certain length, the crevasse no longer appears to extend to the bottom, though it really does so. These pits receive the thawings in summer, which, refreezing, convert the snowy deposits into ice, union is effected, dilatation

[3] We have remarked the presence of these blocks of snow in the crevasses of nearly all the elevated glaciers.

takes place, and in swelling, these kind of wedges, set between the crevasses, perform their part in the motion of the glacier.

But if after a very snowy winter there supervene a dry, warm spring, as in 1875, and then a very rainy June, accumulations of snow four or five yards in thickness at an altitude of 8000 feet are quickly

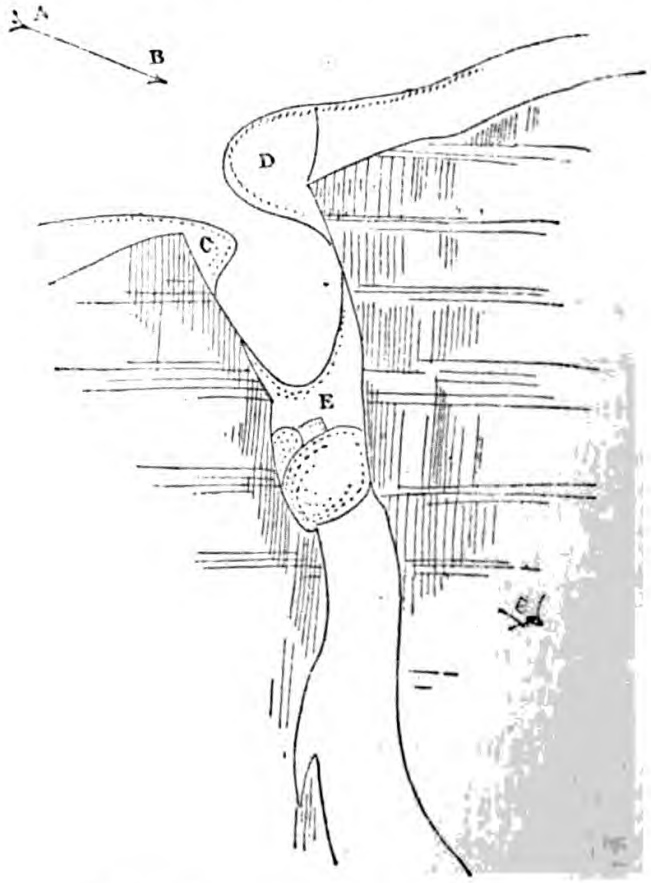


Fig. 99.—Filling up of crevasses by snow.

melted. The warmed ground produces by radiation a rapid thaw; the snow becomes soft throughout its thickness, and the rains easily carry it down. Enormous accumulations find their way in a few hours into the lower valleys, and spread in floods over wide districts.

If, on the contrary, the winter lingers, if the spring is late and wet, the snows remain until the end of June, losing little of their volume. The heats of July thus induce considerable evaporation and frequent storms, during which the new snow frequently descends to the altitude of 6500 feet, and after which the temperature falls. At the end of July the days sensibly shorten, and if the sun shows itself, its inclination leaves great surfaces in shadow around the summits which preserve their snows. In September the nights are already long and cold; the snows of the previous winter are thenceforth preserved, and will protect the accumulations of the ensuing winter. In proportion as the mass augments, the causes of thaw diminish; in proportion as the frozen accumulations absorb and re-freeze the vapours, their augmentation thereby increases in inverse ratio of their thawing.[4]

Canon Rendu, now Bishop of Annecy, asserted in 1840,[5] that all vapour contained in the air must be condensed at the surface of a vast extent of névés, such as those of Mont Blanc. The observations of Messrs. Ch. Dufour and J. A. Forel have shown that, when there is condensation, it is only the excess of vapour over and above the point of saturation of the air at the temperature of the ice, that can precipitate itself on the latter; that the air, if it is very dry, can carry off a certain amount of moisture at the

[4] On this subject we refer our readers to the interesting observations of Messrs. Ch. Dufour and J. A. Forel, professors at Morges, *Recherches sur la condensation de la vapeur aqueuse de l'air, au contact de la glace, et sur l'évaporation*, which we have already mentioned in Chapter III.

[5] *Théorie des glaciers de la Savoie*, Chambéry, 1840, p. 27.

surface of the glacier, but that the evaporation of the snow or of the ice never raises its tension more than 0.181 in., or its content in watery vapour to more than 65.6162 grains per cubic metre (35.31 cubic feet); so that while the condensation may be considerable, the evaporation will never be so.

General observations confirm those of detail, which the learned professors of Morges have made with minute care, and which they have frequently repeated, to secure a reliable mean.

We have frequently remarked that after sunset, when the sky is very clear, there appears a kind of halo of extreme rarity above the most elevated névés, which has not exactly the tint of the sky, is of more roseate hue, and even sometimes displays itself in very slight nebular films above the snow. This is easily accounted for; the vapour contained in the warmed atmosphere condenses at the surface of the snow, and is being deposited there.

But this phenomenon was observable also during the night and in varied circumstances.

On the 12th of September, 1875, in bright weather, the north and west winds were battling at an altitude of 1600 feet, as was shown by some clouds which were eddying about the summit of Mont Blanc—the moon was rising behind the mountain.[6] The summit, during the whole time it concealed the moon from view, exhibited a line of bright light, which regularly followed its contours at a certain distance. The light clouds appeared to slide over this envelope without in the least disturbing it. But when they

[6] At 9 p.m., between the summit and the Bosse du Dromadaire.

were resting on this motionless envelope, the latter became still brighter and thicker.

The phenomenon was observable without change, until the moon appeared near the summit.

The névés therefore withdrew from the clouds, which were at a certain height above them, a quantity of vapour which they condensed at a distance from their surface—a distance which I estimated at about twenty yards.

All who have traversed mountains know that the mists, which in the morning fill the valley, roll along the slopes when the sun rises, slowly mount them, then, reaching the altitude of the glaciers, disappear in a few moments. In the evening of clear days, in settled fine weather, the converse occurs. The clouds which have collected about the summits descend at the moment of sunset, appear to settle gently on the glaciers, and soon after completely disappear.

The glaciers, therefore, absorb a great portion of the water contained in the atmosphere, appropriate it, and convert it into ice. It is evident that this property of absorption tends to increase them in the direct ratio of their surface and their volume, and that the causes of ablation augment in proportion as the glaciers diminish, while the causes of increase augment in proportion as the glaciers assume greater volume. After long, snowy winters and wet summers, the glaciers are under conditions favourable to their continued augmentation, because they better resist the causes of melting, and absorb a more considerable quantity of water, which they can regelate or retain, as we have seen. But when, in consequence of dry winters and summers, they begin

to decrease, the causes of ablation become more and more considerable. In order therefore that, after a period of decrease, glaciers may swell anew, and be able to advance in the valleys, there must occur a series of snowy winters and wet summers.

It was ascertained that, in 1874, throughout the western part of Europe, the springs and streams had reached a minimum of flow that had not been marked for a very long while; and this diminution was justly attributed to a series of dry winters without abundant snows, and to hot summers.

In Switzerland and Savoy the wind which causes the rapid disappearance of the snows in spring is the south-east wind, called the *Föhn*. It is the *sirocco* coming from the African deserts. This warm, dry wind absorbs the snows—devours them, as the mountaineers express it. If the *Föhn* does not blow in spring, the snows remain very late, and the sun has not the evaporative action of the warm current of air. If the summer is wet and the autumn premature—which often happens after wet summers—the fresh snows fall on those which have not been able to thaw, névé forms, and the glacier augments. The fall of one or two degrees in the mean annual temperature, and a moist condition of the atmosphere, may therefore produce a considerable increase of the glacier. It is not so much the quantity of water fallen that produces this increase as the permanently moist condition.

Storm rains rapidly thaw the lower extremities of the glaciers, and I do not think that the hail and snow which then fall above an altitude of 10,000 feet, and even lower, compensate the ablation under the present conditions. But the spring

rains that in the plain appear mild, are only snow above 6500 feet. If these rains continue late, and if they should last during the entire summer, as happened in 1816, snow largely accumulates in the elevated plateaux and in the upper amphitheatres, and there is no melting. The store of snow is thus tripled, allowing that in ordinary seasons the winter store is expended by the summer melting. That is, in lieu of a summer waste there is a store accumulated during two winters and a summer. It is evident, therefore, that if there occur a series of cloudy, wet summers, there will be such an accumulation in the glacial reservoirs as to swell and extend the currents with an irresistible force.

While, as we have endeavoured to explain, an infinitesimal variation in the temperature of the glacier suffices to produce its movement, a scarcely apparent modification in the atmospheric state equally suffices to occasion the great glacial oscillations.

XI.

DESCRIPTION OF THE MASSIF OF MONT BLANC.[1]

It is desirable to follow up the observations of a general character that have been given in the preceding chapter by a special application of them to the massif of Mont Blanc, such as we now see it after the lapse of ages, and to indicate in a kind of detailed review the still existing traces of the changes to which its present form is due.

When from a distant lofty height we regard the massif of Mont Blanc, its aiguilles, so high and sharp, and its deep sunk valleys disappear; and the whole presents a rounded mass with a flattened conical summit that very little exceeds the neighbouring summits. The whiteness of the névés gives the mass an apparent relief greater than it actually possesses; and when by means of the camera lucida we get a defined outline of it, this outline scarcely exhibits any perceptible undulation. As regards its general form therefore,—its chief lines,—the massif has hardly changed since the date of its upheaval, and the deep sunk ruins exhibited by its flanks, are, relatively to the mass, only inconsiderable erosions; those gigantic aiguilles are mere vestiges scarcely appreciable in the general outline, and yet the

[1] See the general map.

quantity of materials carried away awes the imagination ; it has filled long and broad valleys and under the form of pebbles and sand has spread over extensive districts.

We shall begin the description of the Massif by that of the most important of its slopes, inclining towards the N.N.-West and bordered by the valley of Chamonix.

That valley begins towards the north-east, at the col de Balme, and extends to the village of les Houches ; it should be divided into two levels, one, the highest, which extends from the village of le Tour to that of l'Argentière ; the second, which from les Tines descends to les Houches.

Between l'Argentière and les Tines there exists a perceptible narrowing, at the bottom of which the Arve has hollowed a narrow bed, and flows noisily through the heaped-up rocks. At the place occupied by the village of le Tour, the widened level long contained a lake hollowed out in the inferior jurassic strata. The Arve pursues, on the thick inclined accretions that have replaced the lake, a relatively tranquil course, which it does not regain except at les Tines until it reaches les Houches. At that place the Arve again rushes down a steep narrow gorge between the jurassic beds and coal measures to spread itself in the valley of Sallanches, where, after the glacial epoch, a wide basin formed a second lake filling the entire valley.

During the glacial period the glaciers du Tour and de l'Argentière, as well as the current that descended from the col de Balme, found in the lower part a narrowing of the valley which hindered their passage ; moreover, the Mer de Glace, the glaciers

des Aiguilles, des Bossons, and de Taconnaz, of great volume, descended at right angles into the valley of Chamonix, where on the opposite slope were likewise gliding the glaciers des Aiguilles Rouges, and of the chain of the Brévent. The upper surface of these currents rose to an altitude of at least 6500 feet,[2] and finding near Sallanches a narrowing of the valley and an elevated dike—the Prarion—overflowed it by the cols de Voza and de la Forclaz-Prarion and discharged themselves into the valley of Sallanches, into which also descended the glaciers issuing from the Val des Contamines and the Val de la Dioza.

The glaciers du Tour and de l'Argentière, thus obstructed in their course by the narrowing of the valley, and by the masses of ice which blocked the valley of Chamonix, had to find a way out. A depression at the eastern base of the Aiguilles Rouges, afforded them this issue towards the north, across the granitic and anthracitic beds of the valleys of Valorsine and Salvan; and passing through the col des Montets, these two glaciers united therefore to fall directly into the valley of the Rhone, at Vernayaz, and met on their way part of the glacier current descended from le Trient, which, closely embanked opposite the Tête-Noire, and being unable to find sufficient issue, raised its surface enough to clear the col de Forclaz, and thus descend into the valley of the Rhone, at Martigny.

The current that passed through the col des Montets was again fed by the glacier which, from le Buet, descended the Val de Berard, and by the lateral glaciers de Fins-Hauts and d'Emaney (col de Barberine).

[2] About 3300 feet above the village of Chamonix.

It will be remarked that while the col des Montets is situated nearly in the direction of the glacier de l'Argentière, the glacier du Tour, on the contrary, is confronted by the dike des Posettes and de l'Aiguillette, and could only pass through the same col des Montets by uniting at the foot of the glacier de l'Argentière, and by turning abruptly to the left. Thus it manifestly raised its level until it completely covered the summit of l'Aiguillette, deeply wearing and tearing its slopes, consisting of inferior jurassic beds and coal measures, with conglomerates of gneiss and granite.

This fact makes it evident that during a long period the great combe of the col de Balme was completely filled with ice, and that the summit des Posettes barely emerged above it. And indeed, except the part forming the ridge of that summit and of la Croix-de-Fer, all the slopes of the mountain which, from la Tête-Noire to the col de Montets, separate the valleys du Tour, du Trient, and de Valorsine, are deeply eroded and moutonné by the passage of the ice; and then, the waters of the upper Arve fell at Vernayaz into the valley of the Rhone, instead of descending into the valley of Sallanches. There is still to be seen above the Aiguille du Chardonnet, along the slopes that border the glacier de l'Argentière (right bank) the mark of the level of the glacier which, though already at the decline of the culminating glacial period, still passed over the col des Montets (Fig. 100).[3] At the present time the glacier de l'Argentière has fallen to C; but from B to A is seen a well-marked erosion, then moraine deposits, which indicate in the most evident

[3] This view is taken from Plan-Praz.

manner the higher level of the glacier during a long period of time. The altitude of the point A is about 7000 feet. Lower down, at D, there is evidence of a second level of the glacial period; but at that time the glacier no longer traversed the col des Montets; it united with that of du Tour, not without difficulty, at the glacier des Bois. Then also the lateral glaciers E separated from the trunk

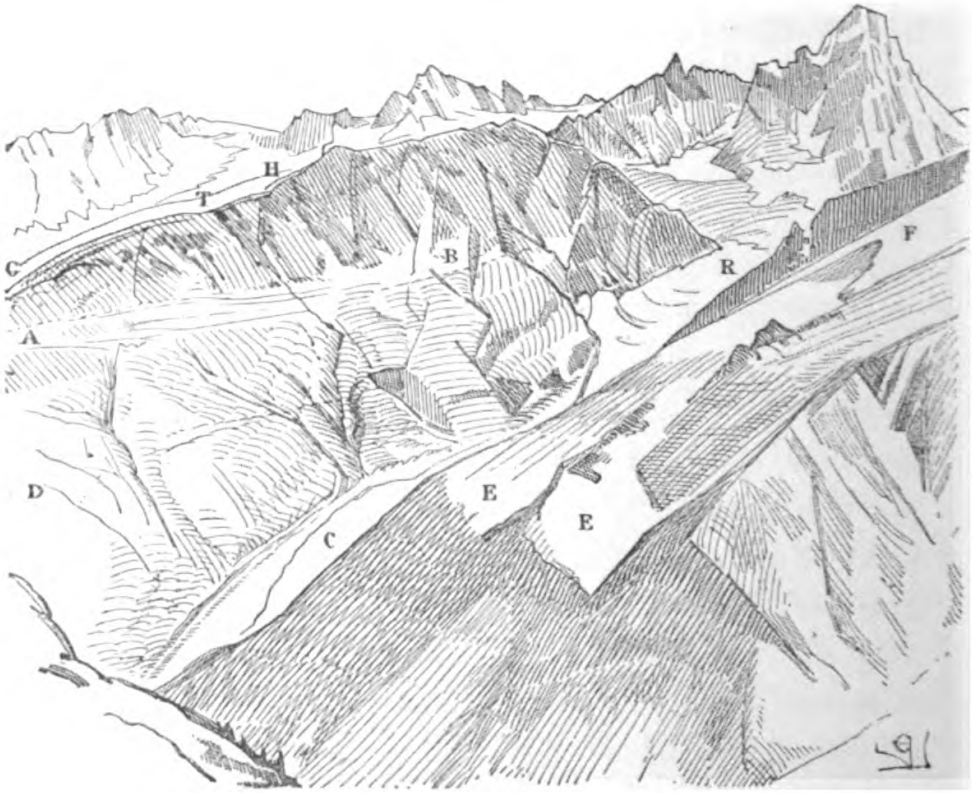


Fig. 100.—The Glaciers de l'Argentière and du Tour.

glacier, and existed individually. Of these glaciers there now only remains the glacier F (glacier de Lognan) separated from the glacier north of the Aiguille Verte by a ridge of rock (les Rachasses, R).

When the glacier de l'Argentière reached the level B A, the glacier du Tour, T, overflowed the ridge G, and wore it down, then at a later period deposited

there its left lateral moraine. But during the culminating period of the glacial epoch the ridge G H was beneath the ice. This ridge being deeply moutonné, the current of the united glaciers (du Tour and de l'Argentière) no longer having sufficient depth and volume to pass les Montets, accumulated in the narrow of the valley, below the village of l'Argentière, compelled the glacier des Bois to make a sudden turn in order to leave them a passage, and to rasp the northern angle of the spur of Montenvers, to clear a way for its stream, whose surface rose to the altitude of 7500 feet, that is near 4000 feet above its present bed at the source of the Arveiron, as evidenced by the moutonné rocks and moraine débris found at la Filiaz, above the Châlet de Montenvers. The broad glacier des Aiguilles, now divided into three small glaciers—those of Nantillons, Blaitière, and les Pèlerins, but which then reached the upper level of the trunk glacier de Chamonix, leaving exposed only la Tapiaz, or Plan de l'Aiguille, and fed the trunk glacier that again received the enormous glaciers des Bossons, de Taconnaz, du Bourgeat and de la Gria. During a long period these united currents flowed over the dike of le Prarion,[4] which closes the valley on the west, not finding sufficient issue by the narrow gorge that separates le Prarion from l'Aiguillette and from la Montagne de Fer; since the glacier that descended through the Val de la Dioza hindered its course. Then these gigantic currents, fed from all sides in the depression that formed the valley of Sallanches, with difficulty descended through the Val de Cluses into the valley of

[4] As evidenced by erratic blocks of protogine on the Prarion and strongly marked moutonnage with small lakes.

Bonneville, widening that valley by bearing away considerable masses of the rocky sides.

As the forces producing the phenomena of the glacial epoch became less intense, the Prarion (6458 feet) emerged, and the current of the valley of Chamonix continued to widen the gorge of Châtelard, and of les Chavants for freer passage. In these gorges the raspings of the ice attest the tremendous force which it must have exerted to facilitate its passage. It was then that the glacier current deposited the fine erratic blocks to be seen as we ascend to Merlet, and on the very slopes of the Gorge du Châtelard.

As the melting continued, the trunk glacier formed by the glaciers des Bois, des Bossons, and de Taconnez, was arrested at the entrance of the gorge, at les Houches, and there deposited a frontal moraine. A wide torrent, in two streams, continued to descend the gorge, filling that in which the present torrent and that of le Châtelard flow.

At that time, the right moraine of the glacier des Bois, continually augmenting, tended again to bar the course of the glaciers of l'Argentière and le Tour. These glaciers, which had lowered their level, were no longer able to pass the obstacle, and deposited their frontal moraine along the right lateral moraine of the glacier des Bois, below le Bochard, at the place where the village of Lavancher now stands.

Then as the retreat became more marked, the lateral glaciers des Aiguilles, and those of la Bourgeat and la Gria, ceased to be in communication with the trunk glacier. The glacier des Bois no longer joining that of les Bossons, deposited a first retreating frontal moraine at the very foot of les Bossons; later on, a second frontal moraine near

the village of les Barats, and lastly, a third on the side of Chamonix.[5]

Then its right lateral moraine reached above the Châlet de la Côte, where there is a fine block of protogine; its left moraine, higher, because of the transverse declivity of the glacier towards the south, followed the slopes of Montenvers and came bending round on Chamonix.[6] This glacier had a medial moraine, as it now has, whose deposit we still perceive above les Praz-d'en-Haut.

At the same time, also, the glacier de Taconnaz became disconnected from the glacier des Bossons, and the latter, left to itself, rapidly withdrew its frontal moraines, but long continued to block the valley so completely, that it compelled the Arve to hollow out the opposite slope in order to pass.

The vast glaciers of l'Argentière and le Tour, however, were continually depositing moraine heaps along the right lateral moraine of the glacier des Bois, and that as far as the entrance of the gorge. Melting more and more rapidly, the glacier du Tour separated from the glacier de l'Argentière, and in the same way deposited its frontal moraine opposite the right lateral moraine of the glacier de l'Argentière.

A small lake, retained by these moraine banks, formed below the village of l'Argentière, and another below the village of le Tour.

These lakes were filled by the successive débâcles, and the modern epoch began.

In the Val des Contamines, to the west of the

[5] The remains of this frontal moraine are very evident on the left bank of the Arve, particularly in the garden of the Hôtel d'Angleterre.

[6] Very visible traces of this moraine exist at the foot of the present Montenvers route.

massif, the glacial phenomena presented less regularity because of the narrowness of that valley, the various character of the slopes, and geological disturbances.

This valley, bounded on the side opposite the massif by elevated ridges, among which stands highest that of Mont Joli, is terminated to the south by the Bonhomme, which is connected with the culminating points of the massif on that side by ridges whose altitude reaches a mean of 7000 feet and exceeds that in several places.

Thus, at its upper extremity, the Val des Contamines presents a very vast amphitheatre whose floor is very elevated, whose sides are very steep, and which was singularly adapted for the accumulation of névés. Moreover, in the massif itself, deep and closely approaching furrows, having a direct western aspect, would send into it glacier currents of very great volume. These currents are now those of Bionnassay, the French Miage, la Frasse, and Tré-la-Tête. None of these however, except the last, are nourished by névés of any considerable extent; but, excepting that of la Frasse, they descend into narrow gorges that shelter them from the sun.

Accordingly, in the Val des Contamines, glacial action manifested itself on the mountain masses with unusual energy, affording us a striking example of the tremendous effects of the ice on the rocks. The geological formation of this extremity of the massif presents besides, a considerable variety of strata, and we thus see how the ice acts on each of them.

The inclines confronting the massif opposite Saint-Gervais are partly occupied by lias intermingled with bands of quartzite and variegated schists; next

appear the jurassic beds, and further on the argillaceous and variegated schists (verrucano[7]). At Nant-Borant are lias and incoherent slaty schists, then above them occur lias, cargneules, sandstones, and conglomerates. Opposite, upon the slopes of the massif, there follow the variegated schists, the calcareous schists and the anthracite beds above Saint-Gervais, then again the lias, succeeded by gneiss, as far nearly as the col du Bonhomme.[8]

These strata, being of different densities, offered an unequal resistance to the glaciers, and produced features of the most remarkable character.

During the glacial epoch the Val des Contamines was filled with ice almost to the summit of Mont Joli, and this deep current joined with that which descended from the valley of Chamonix along the Prarion by the col de Voza; and even when the decrease began, the glacier de Bionnassay, blocked by that which descended the Val des Contamines, still joined the glacier de Chamonix, through the col de Voza and the place now called the Pavillon de Bellevue. There happened in this valley that which we have observed in the valley of Chamonix—the ice lowered its level, the glaciers separated, the spurs emerged. Then, the Val des Contamines became filled with vast warps of glacier mud that attained a height of nearly 4000 feet, and again these mud warps were swept down by torrents.

There are few places where the moraines are of a more interesting character than in the Val des Contamines; the thaws having been relatively rapid,

[7] Verrucano.—The name in Alps for certain rocks corresponding to our Rhætic beds. (F.S.)

[8] Col du Bonhomme, or rather Croix du Bonhomme, 8050 feet. —Summit du Bonhomme, 8840 feet.

these moraines were very much less drenched and borne away than they were in the valley of Chamonix. In the Val du Bonhomme, a glacier descended from the Aiguilles de Bellaval, found a resting-place at the present Lacs Jovet, joined with the glacier du Bonhomme at the Plan Jovet and turned abruptly northwards, passing by a narrow gorge to Nant-Borant. At that place this current was blocked by the glacier of Tré-la-Tête, which was then of sufficient volume to pass over the dike on which is situated the Châlet du Pavillon, but which also descended on Nant-Borant.

Lower down, the glacier de la Frasse spread itself in a great sheet; then, by two ravines advanced on les Contamines and formed a second barrier. Still lower down the French glacier du Miage formed a third barrier athwart Saint-Nicolas de Veroce, and lastly, the glacier de Bionnassay intercepted the current of the valley opposite Bionney. These frequent dams in a narrow valley raised the level of the trunk glacier to an altitude of about 7000 feet between Nant-Borant and les Contamines.[9] Nevertheless, as these glaciers, with the exception of that of Tré-la-Tête, had not very considerable resources of névés, their melting took place much more rapidly than in the valley of Chamonix.

They withdrew up their respective valleys in a comparatively short space of time, and the lateral glacier of Tré-la-Tête alone continued to descend in the Val des Contamines as far as below Notre-Dame de la Gorge, when the glaciers du Plan Jovet and du Bonhomme were already greatly reduced. The gla-

[9] The altitude of Nant-Borant is 4750 feet; that of les Contamines, 3940.

cier de la Frasse, however, had left athwart the Val des Contamines a little above that village, two lateral moraines which formed a dam after the glacier de Tré-la-Tête had withdrawn. A lake long remained between Notre-Dame de la Gorge and these moraines, which were partly degraded by the torrent in hollowing out a passage. This lake was fed besides by the Nant-Rouge.[1]

The original glacier du Bonhomme had divided into two parts, separated by a fine medial moraine, which descends the valley as far as the lower side of la Balme.

But the glacier de Tré-la-Tête had itself also formed a dam in the upper valley by the deposit of a high moraine (left bank) which for a long time converted the Val du Bonhomme above Nant-Borant into a marsh.

Continuing its retreat, the glacier du Bonhomme withdrew towards the summits, and the part of that glacier which occupied the existing amphitheatre du Bonhomme, joined with the glacier that descended from the Aiguille de Bellaval, and, depositing a frontal moraine above the existing cascade of la Balme, formed a lake at the site of the Plan Jovet, a lake which was filled up at a very late period.

Lastly, the glacier de Bellaval, separated from that of the amphitheatre du Bonhomme, deposited a frontal moraine which formed the existing dam of the Lacs Jovet. During a long period, i. e. till the Val de Bonhomme was cleared of ice, the great glacier de Tré-la-Tête descended directly into the valley opposite Notre-Dame de la Gorge, as shown

[1] See the general map.

by the deeply marked "moutonnage" of the rocks on the right bank of that glacier, up to above the Châlet (Pavillon).

The lateral moraines of the glacier du Bionnassay are very interesting to study; we can count as many as six on the left bank of the Val de Bionnassay, and at the foot of the existing glacier, which indicate the periods of decrease of this glacier at a comparatively recent epoch.

These closely occurring parallel moraines, marking a successive lessening of the glacier current, are nearly equal in height and bulk, which indicates rather sudden retreats followed by periods of halt (Fig. 101). The examination of this glacier leads to other curious observations. It shows how the glaciers withdraw towards the summits by stages or levels. Thus, in our figure the active glacier is at present halting at A.[2] But there remains at B a terminal glacier mass now inert, inasmuch as it is no longer joined to the trunk. This mass B melts without further advancing. The solution of continuity took place at the narrowing point of the moraines and on a ledge.

At the period when this glacier extended into the Val des Contamines fronting the village of Bionney, after the great glacial period, its upper level was at N, and the entire amphitheatre C was full of névés.

In the Val de Bionnassay itself, and even below that village, we see four lateral moraines deposited by the glaciers on its right margin, when its terminal point was at Champel. On account of the narrowness and the aspect of the valley this glacier

[2] This drawing was made in 1871. The mass B no longer exists, and the terminal point A has still further withdrawn.

had a long duration, as proved by the enormous

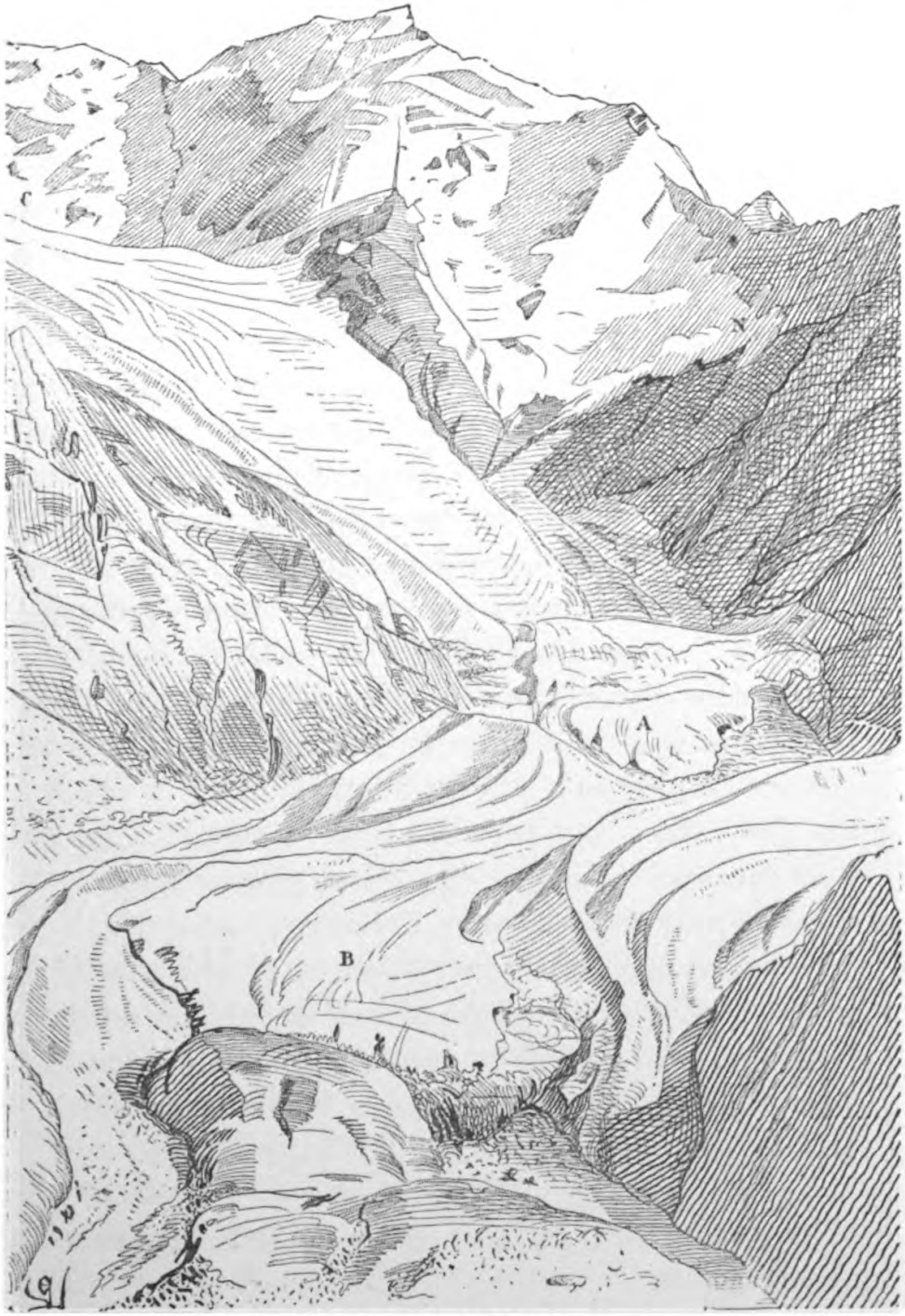


Fig. 101.—The Glacier de Bionnassay.

débris of its frontal moraine at the outlet of this valley into that of Saint-Gervais.

When we pass the col du Bonhomme, we find ourselves on strata consisting of conglomerates, lias and sandstones, with some later beds,[3] which are a most interesting study, and on which the ice has hollowed deep grooves by reducing the more friable rocks; passing on we reach the Cime and Col du Fours,[4] which have been so thoroughly rasped and rounded by the ice, that this wilderness presents the aspect of a denuded plateau, which is the starting-point of ravines, shallow at first and faintly marked, then deepening more and more, and exhibiting their escarped sides of sombre grey as they descend towards le Chapiu.

Nothing can equal the desolation of this solitude, once covered by ice that has now disappeared.

Here we may leisurely examine the bed of the glaciers, for ten years ago some were still existing round the Cime des Fours. Long after the glacial epoch, the whole space comprised between the Cime des Fours and the Col du Bonhomme was one great glacier that descended on the one side to le Chapiu, on the other into the Val des Mottets. The Val des Mottets is below the great glacier named on our map the glacier de Saussure,[5] and which is situated at the southern extremity of the massif of Mont Blanc. During the glacial epoch the desolate Val des Mottets was completely filled with ice that flowed through a narrow gorge hollowed in the lias and the slaty schists as far as Chapiu.

[3] La Bonne Femme.

[4] 8890 feet. Here are found beds of mica schists, carboniferous schists and lias.

[5] This glacier is called *Glacier*, or *Grand Glacier*—a vague designation. M. Ch. Martins has proposed to give the name of Saussure, and we accept the suggestion of this distinguished savant.

The level of this glacial reservoir rose as high as the col de la Seigne, whence we descend into Italy by the Val Veni. A lake formed itself at the end of the Val des Mottets that was filled up by the glacier mud and the moraines carried down there. In consequence of its aspect, the glacier des Mottets rapidly melted and occasioned débâcles, whose alluvial deposits we find as far as below the town of Saint-Maurice.

The slopes of the massif of Mont Blanc into the Val Veni and the Val Ferret, which are on the same line, are much more abrupt than on the side of Chamonix, and the glaciers, nourished by névés of narrow extent, do not descend so low. The most considerable of the lateral glaciers of the Val Veni are those of the Italian Miage and of la Brenva. At the height of the glacial period, these glaciers of the Val Veni passed over the col de Chécouri, and barely left emerging the summit of Mont Chétif; for the narrow issue, whose outlet is at Cormayeur, in the valley of Aosta, was clearly insufficient for the flow.

It is not even certain that this gorge was then clear, and it appears to have been especially deepened by the débâcles breaking down the rocky dike connecting Mont Chétif to Mont Saxe. Thus the glaciers of the col de la Seigne, l'Allée-Blanche, Miage, le Brouillard, le Fresnay, la Brenva, and Toule in the Val Veni; those of le Frély, Rochefort, les Grandes Jorasses, Fréboutzie, Triolet, and Mont Dolent, in the Italian Val Ferret, all fell into a narrow depression without issue. They filled it, and, finding on the other slope mountains of feebler resistance, they bore down their ridges and passed over them. But this glacial reservoir must then have attained an altitude of

nearly 8000 feet. Finding a weaker part between the Monts de Saxe and Mont Chétif, their enormous pressure broke through the dike and they began to descend regularly towards Aosta in an opposite direction; that is, by uniting their currents at Entrêves.

The steepness of the massif, however, and the unusual narrowness of the gorges in which the two glaciers of le Miage and la Brenva descended, have so sheltered these two currents—notwithstanding an aspect favourable to ablation—that their terminal point even now reaches the Val Veni, where the two glaciers make a turn in the direction of Entrêves, and deposit very considerable lateral moraines. That on the right of the glacier de Miage has blocked the valley and retained the up-stream waters which form Lake Combal, whose issue had to sink its way in the inclines of that moraine which rested against the slopes confronting the massif.

The moraines of the Val Veni are of considerable dimensions, and in great measure consist of enormous blocks; a feature which is accounted for by the steepness of the massif and the comparatively unresisting character of the protogine of the summits, laminated in many parts, and mingled with crystalline schists and veins of serpentine and diorite; moreover, the base of the upheaved mass apparently rests upon thick rolled-over beds of jurassic and liassic strata, which, readily decomposing and forming inclines, enabled the falling fragments of the upper crags to reach the bottom without being broken by repeated shocks.

We can now exactly estimate at numerous points, the different heights reached by the glaciers in the Val Veni at the decline of the glacial period,

for these glaciers left the marks of their ancient levels. We take an example among several.

When we have passed Lake Combal down-stream, and find ourselves a little above the Auberge d'Avizaille, turning by the side of the glacier de Miage, we have before us the Aiguille du Châtelet (altitude 8213 feet), and, farther off, the Monts de Brouillard. This Aiguille de Châtelet is rasped to its very summit by the passage of the ice. This summit was therefore covered by the glaciers. Now the ridges of the opposite mountains do not rise above an average of 7500 feet: they are completely moutonnés, and dotted with those characteristic tarns which indicate that a glacier current has had a long duration.[6] Therefore, the glaciers which descended the inclines of the massif of Mont Blanc entirely filled up the Val Veni, and overflowed the opposite chain. Fig. 102 gives this Aiguille du Châtelet, with its ice-worn summit. Next, at A B, the level at an epoch in the lowering of the glacier du Fresnay, which then joined the glacier du Brouillard[7] and that of Miage; then, a second level of lowering, D F, in the same conditions; still later, a third level of lowering, D E *f* F. Then the three glaciers were beginning to separate. Lastly, the moraine V, which indicates a definitive period of separation.

In the present day the glacier du Fresnay halts at G; the glacier du Brouillard at nearly the same level. At P are seen its bed and its right lateral moraine M, which joins with the left moraine of the glacier de

[6] The most considerable of these tarns, or small lakes, is the lake of Chécouri.

[7] See the general map.

Miage. The glacier de Brouillard united with that of Miage when it reached the level C H. When it

Fig. 102.—The Aiguille du Châtelet (val Veni).

separated from it, it descended in the direction of the line H I; sinking again, it traced the line L K.

At R is seen the great right recent moraine of the Glaciers du Miage and du Brouillard united. At T the earlier moraines, and at s the traces of the still more ancient one, covered by the moraine T.

The ruins of the slopes of the massif in the Val Veni, absolutely devoid of vegetation, thus enable us to observe the glacier in its successive phases of decrease, with periods of halt. The Aiguille du Châtelet (protogine) nakedly exhibits its crystalline system, worn and rasped by the ice, with some parts torn away, for the most part blunted, rounded and hollowed; while the first summit of the Monts du Brouillard x (10,988 feet), having emerged from the glacier current at the first clearing away of snows, exhibits those angular ruins, dislocated in parts, which distinguish the summits of ridges changed, not by the passage of ice, but by the sudden variations of temperature.

But for a long period the glacier of the Italian Miage completely barred the Val Veni, encumbered below by the ice descending from the glaciers of le Brouillard, le Fresnay, and la Brenva, and even then, when already these three united glaciers flowed by Cormayeur, in the valley of Aosta, the glacier de Miage was compelled to surge over the dike of the opposite chain, to the south-west of le Mont Chétif, by the col de Chécouri, thus descending direct to Cormayeur through Dolone.[8] The defile between Cormayeur and Entrêves must have been encumbered by ice to a very late period, and the glacier de Miage long kept its elevated bed without following the Val Veni; for the deep traces of its

[8] See the general map.

passage are very evident, and the erosion produced by the ice testifies to the most energetic action.

The ablation of the great glaciers was evidently more rapid on this slope of the massif of Mont Blanc than on the other; but it is perhaps easier on this side to ascertain and to class the periods of decrease, followed by periods of unaltered level, than it would be on the Chamonix slope.

As the elevated margins of the glaciers bore stones in vast quantity along the escarpments, they marked their level on the hardest rocks by a series of deep erosions, and also by leaving in the cavities débris that appear to be built in; and hence on the rocky walls of the glaciers that descended in the Val Veni may be perceived the successive lowerings of those glaciers. There were, however—and this we consider is a point to be insisted on—periods of decrease more or less gradual, but uninterrupted, succeeded by a condition which maintained itself without either serious diminution or augmentation; since it must have required a great many years to hollow out tracks such, e.g., as those so evident at H I in Fig. 102, or, again, those D E *f*. There were, therefore, after the culmination of the second glacial epoch, great thaws during a certain lapse of time; then a halt,—a second period,—during which the ice preserved a constant level; then a third period—a fresh halt—and so on up to the historical epochs. We allow that these conclusions are not calculated to simplify the explanation of glacial phenomena on our globe, but they result from facts which every one may verify. There is no part of the massif where the effects of ice action on mountains can be better appreciated than in the Vals Veni and Ferret. The effects of

bearing down and disruption are terribly evident. Acting like a battering-ram through their weight or concussion, or as a rasp, the glaciers carried away entire portions of the mountain and shaped their bed. Opposite the Auberge d'Avizaille, the glacier of le Fresnay and the small glacier of le Châtelet exhibit a mass of ruins of which it is difficult to form an idea,—rugged escarpments resulting from violent ruptures. Fig. 103 shows this glacier now much reduced. At A are the slopes of Mont Rouge;[9] at R the level which united the glaciers of le Fresnay and le Brouillard. At that time the aiguilles B C D were standing out.

At E are the rocky slopes of Mont Blanc, which, denuded on this side, are constantly disintegrating. When at last the ice-masses were limited within the depression which now constitutes the Vals Veni and Ferret, they had their outlet, as has been said, in the valley of Aosta, through a narrow gorge, where are now situated the baths of la Saxe; but for a long period there was a lake at the forking, on the site of Entrêves. After leaving that village, the Val Ferret rises considerably, in an opposite direction to that of Val Veni, and keeps along the back of le Géant, les Grandes-Jorasses, the Aiguille de Leschaux, and Mont Grenetta, reaching the col Ferret above the glacier du Mont Dolent. The schistose upheavals of the opposite slope are deeply rasped by the passage of the ice; which, during the height of the glacial period, surged over that dike as it passed through the col de Chécouri, opposite the summit of Mont Blanc, in the Val Veni.

[9] This view forms a continuation of the preceding one. (See the general map.)

The great glacier of the Val Ferret overflowed the

Fig. 103.—Southern side of Mont Blanc.

crest of the Mont de Saxe, and fell between that chain

and Mont Cormet into a bed of triassic deposits, which it hollowed out to rejoin the Val de Cormayeur below the dike. In fact, the ridge of the Monts de la Saxe does not exceed 7668 feet (highest point), and the higher traces of the great glacier of the Val Ferret

Fig. 104.—The Vals Ferret and Veni.

(glacial epoch) are found at the foot of les Grandes-Jorasses at above 8200 feet. A view of the Vals Ferret and Veni, taken from the col Ferret (8320 feet), Fig. 104, perfectly explains how the

glacier masses, descending the slopes of the massif of Mont Blanc, would pass over the opposite heights. Our figure exhibits at A Mont Chétif, behind the summit of which passed the ice masses descending direct from Mont Blanc near Avizaille; at B the rupture opening into the valley of Aosta; at C the steeps of les Grandes-Jorasses; at D the col de la Seigne, and at V the upper Val Veni. The acclivities of the massif, still more abrupt in the Val Ferret than in the Val Veni, caused the glaciers—which, after the culmination of the glacial epoch, ceased to unite in the valley in a descent to Entrêves—to halt suddenly along the opposite slopes, and not to make the détours of the glaciers of le Miage and la Brenva. Separated by the ablation of the trunk glacier, they banked up their frontal moraines along those opposite slopes, and so completely blocked up the valley that the upper stream had to pass beneath their bed on its descent to Entrêves, and that a series of small lakes was formed between each of these glaciers.

This is indicated in Fig. 105 (section of the Val Ferret on the line of the Grandes-Jorasses, the hamlet of la Vachey and the Châlets de Sécheron).

This section shows that during the great glacial period the accumulations of névés followed the slant A B and passed over the opposite schistose acclivities. When the glaciers decreased in magnitude, the glacier that descended from the Grandes-Jorasses, and which is now reduced to the thin deposits of le Tronchey, presented the longitudinal section A C and deposited a high frontal moraine at C. The torrent coming from the Val Ferret, le Dolent, and the glacier of Fréboutzie and le Triolet, had therefore to force a passage at P beneath the ice, not without leaving a

lake opposite the Châlets de Fréboutzie. In the upper part of the valley above this lake the united glaciers of le Triolet and le Dolent deposited a thick frontal moraine across the valley that formed a small lake. It was only at a late date that these two glaciers separated.

After having passed the col Ferret we descend into the Swiss Val Ferret, whose axis is on a line with

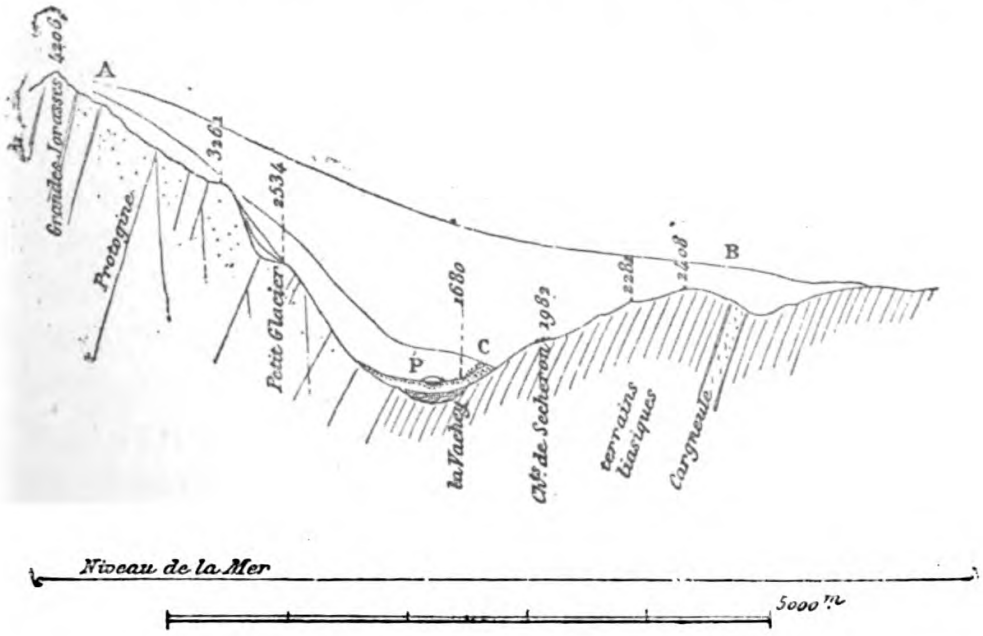


Fig. 105.—Section of the Italian Val Ferret.

that of the Italian Val Ferret, extending northwards as far as Sembrancher. Past the Col Ferret the protogine ceases to appear, and the slopes of the massif consist of gneiss alone on an upturned base of liassic strata. In addition to the lateral glaciers of the massif, this valley received that which descended from le Grand-Golliaz. Thus was produced, near the village of la Folly, opposite the glacier of Laneuvaz, descending from the massif, a considerable widening in the valley, which, after the glacial epoch, contained a lake soon after filled by the mud

of the acclivities, consisting, on the slope confronting the massif, of liassic strata and of grey argillaceous calcareous schists.

With respect to the glaciers of the massif on this side, since, with the exception of that of Saleinoz, they only possess upper névés of small extent, their terminal point is situated at a great height, and they have only an inconsiderable development.[1] On the other hand, the slopes of the massif present a steep escarpment in the shape of great pyramidal planes of sheer descent, without projections, and with an aspect formidably stern.

The great trunk glacier currents that descended from the col Ferret and le Grand Golliaz met at Orsières another glacier current that came down from Vélan and le Grand Combin ; then these three trunks met at Sembrancher a fourth current, which also descended from le Grand Combin, from Mont Colon and Mont Blanc de Cheillon.[2] This fourth trunk was of considerable volume, and obstructed at right angles the trunk glacier which followed the eastern slopes of the massif of Mont Blanc. Moreover, below Sembrancher, the end of the massif joining the Pierre-à-Voir absolutely barred the passage. As a result of these circumstances, the accumulation of ice in the Swiss Val Ferret must have been enormous, for it will be observed

[1] The terminal points of the glaciers of Laneuvaz, Truzbue, and Planereuse are scarcely below 7900 feet, while the terminal point of the glacier of Saleinoz was, fifteen years ago, at an altitude of about 4900 feet. At present it is much higher—5900 feet.

[2] The principal remains of this current are, the magnificent glacier d'Otemma, de Breney, and de Getroz on the right bank ; those of le Mont Durand, de Zessetta, and de Corbassière on the left bank.

that on no other side of the massif did glacier affluents of such volume exhibit themselves. Accordingly, all the ridges of the heights, between the massif of Mont Blanc and the Val de Bagne, which abut on Sembrancher, rising towards the south-east, were submerged beneath the ice, and, owing to their feebly resisting nature, were profoundly rasped and smoothed.

Everything favours the belief that these currents, uniting at Sembrancher, without finding issue, passed to the west of la Pierre-à-Voir, and fell into the valley of the Rhone through the Pas du Lens upon the prolongation of the argillaceous schists upheaved at this place. What cannot be doubted is the prodigious accumulation of the ice at the confluence of the valleys of Orsière and Bagne—an accumulation which, in ruining the rocky walls by abrasion, formed an immense amphitheatre. But below Sembrancher the northern point of the massif of Mont Blanc becomes lower, the protogine ceases to appear, and the gneiss and liassic strata crop out. The ice took advantage of that declivity, and of the break of continuity of the rocks, to force itself another passage in the extension of the current descending from the Val de Bagne, and ultimately to fall above Martigny. In this gully the ruin produced has a formidable appearance. The dike was not lowered sufficiently, however, for the flow of the torrent. At the first débâcles a lake therefore formed itself above Sembrancher—a lake whose level rose as high as the village of Verségère, and whose length was thus four miles and a half. Then only could it pass the liassic dike of the point of le Catogne, already lowered by the passage of the

glacier current. By the thawing of all these glacier affluents prodigious masses of mud accumulated in this reservoir, which ultimately broke down the dike to the level of the present valley of Sembrancher, thus enabling the torrents to flow. The lake was emptied, and there only remained a deposit of alluvium.

The effort of the ice, in accordance with the local circumstances we refer to, produced between the heights of Catogne, la Pierre-à-Voir, and les Six-Blancs, effects which it is well to examine, for they sufficiently manifest the importance of the glacier agencies whose force certain geologists dispute. But at the moment of their culmination these glacier currents could not rest satisfied with the tedious flow they found to the west of la Pierre-à-Voir at an altitude of 5500 feet (Pas du Lens), and on the dike opposed to them by the liassic upheavals between le Catogne and that Pas. Besides, the formidable current of the Val de Bagne alone took advantage of this issue, and the eastern current of the massif of Mont Blanc, obstructed—unable to flow on—forced a passage in the extension of its affluent from the Val d'Entremont, cutting the point of the massif, and thus separating le Catogne from the massif, across the protogine, the porphyritic schists and the gneiss. A fault or a depression in the mountain evidently facilitated the passage which the ice widened with prodigious force in advancing to fall above Martigny, and thus join the trunk glacier of the Rhone. The hindrance, however, which the elevation of the massif offered to the passage of that arm only allowed the ice to flow by gliding over a ridge whose altitude was nearly 5000 feet; so that from Orsières (2800 feet) the current had to mount

and thence descend to the Borgean (1970 feet). We have seen that the plasticity of the ice enables it to advance, despite these differences of level in the bed which contains it.

When, however, the ablation began, the eastern current of the massif laid bare the highest part of its bed below Catogne, and was forced to join the current of the Val de Bagne, depositing enormous lateral moraines on the eastern slope of le Catogne and the western slope of les Six-Blancs. Later on, the disjunction being effected, the glacier of the Swiss Val Ferret and that of the Val d'Entremont, still united, deposited a vast frontal moraine at Orsières. When the disjunction between these two glaciers had taken place, that of the Swiss Val Ferret withdrew its terminal point to its junction with the lateral glacier of Saleinoz, depositing a frontal moraine at Praz-le-fort, where it formed a small lake.

On the bed of the ancient glacier which passed between le Catogne and the massif—a bed, as mentioned just now, with an up-and-down incline—some small lateral glaciers existing on the two acclivities, and more particularly on that facing the north, whose remnants still exist, formed moraines that eventually barred the narrow valley and retained a small lake above Orsières—Lac Champey, which still remains (4815 feet), but which is continually filling up with accretions of sand and pebbles.

Le Catogne is in every respect one of the most interesting of mountains to examine. It forms a pyramid with a regular triangular base, and three distinctly-marked planes, whose isolated summit rises to 8500 feet. Its eastern base exhibits an acclivity of lias; thence to the summit that side is of

porphyritic gneiss; towards the north-west is a band of protogine, its direction being, like that of the massif, from N.N.E. to S.S.E.; next comes a band of gneiss.

Not only are the junctions of these rocks distinctly apparent, but the aspect of their ruin is different, although the whole mass presents a general character in its planes and arêtes. In some parts the lias sediments in contact with the porphyritic gneiss have acquired great hardness, and have even better resisted atmospheric effects and the action of ice than the gneiss itself. This is very perceptible on the arête,[3] which, from Sembrancher, bears towards the summit in a direction from N.N.E. to S.S.W. This compact arête is not again found on the other incline of the Val de Sembrancher, where the lias deposits assume much greater breadth.

The summit of le Catogne, whence we have a lengthwise view of the entire massif of Mont Blanc, is an excellent observatory for verifying the position of all the summits of the massif (N.N.E. part), and for examining the peaks of le Grand Combin, Mont Blanc de Cheillon, and le Vélan, which are only twelve or thirteen miles distant.

We have seen (Fig. 12) that the massif of Mont Blanc originally presented a plateau widening towards its N.N.E. extremity, and that towards that end the protogine, compressed, formed an overlap, which the crystalline schists encased at a mean altitude of 9800 feet; that nevertheless the protogine still appeared along these crystalline schists.

As a result of this primary formation, the massif, instead of at that end presenting névés environed by

[3] See the general map.

amphitheatres, as in its middle part, constitutes very elevated plateaux, whence descend three principal glaciers, which are—towards the east, the glacier of Saleinoz, in the Swiss Val Ferret; the glacier of le Trient, in the valley of the same name; and the glacier of le Tour, in the upper valley of Chamonix.

Although the glacier of le Trient is not fed by a névé of very considerable extent, that névé, being at a great elevation and having only gentle inclines, enables the glaciers, whose aspect is the north, to descend rather low (5180 feet). With respect to the glacier of Saleinoz, which presents analogous conditions, there exists below its rather flat-lying névés, whose altitude is about 9800 feet, a narrow gorge which shelters it from the southern exposure.

As regards the glacier of le Tour, its terminal point is now very high up, while its névés, although at a great altitude and flat, do not cover a very extensive surface.

But these three principal glaciers and the less considerable intermediate ones, all have their origin, as just mentioned, in a plateau whose mean altitude is 10,500 feet, and whose surface is surmounted only by peaks and ridges of barely 800 or 900 feet in height. The Aiguille de l'Argentière alone—the queen of this part of the massif—attains an altitude of 12,830 feet.

But precisely because this end of the massif takes the form of a plateau in its upper part, the effects of the glacial period on that surface were tremendous. The snows completely covered it, only a solitary peak here and there being left outstanding. Hence

the erosive action of the ice manifested itself at a great elevation and over surfaces of vast extent.

In order to realize the tremendous force of this action, we must visit the now almost extinct glacier of Orny and les Ecandies, whose ravaged beds exhibit rocks bare, rasped, and smoothed, together with moraine heaps, left as a work of clearing would be which had been suddenly stopped.

The altitude of the ice on the highest declivity of the Glacier de Saleinoz was about 9850 feet, that is upwards of 1300 feet from the existing level of the glacier at this point. Hence the plateau extended

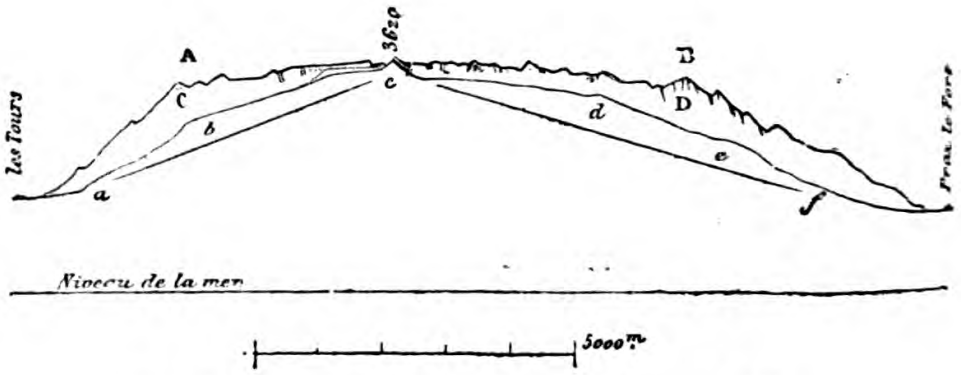


Fig. 106.—Section on the Glaciers of le Tour and Saleinoz.

beyond its present limits. The area of its surface has been reduced by the gradual ruin of its declivities and widening of the issues through which the glaciers first began their movement. The ravines produced by the continual flow of the ice in descending from the plateau have gradually encroached upon its surface, and (Fig. 106[4]) of a section given in the outline A B have produced the section *a b c d e f* (bed of the existing glacier) while leaving remains C D which form the rocky banks of these glaciers—banks which

[4] Section on the line of le Trient and the Glacier de Saleinoz.

are profoundly disintegrated. But while the accumulation of snow on the plateau from A to B, at an altitude of 11,500 feet, was very considerable, it was much less on the diminished plateau *b d*; and the glacier currents descending from *b* to *a* and from *d* to *f*, warmed as they were by radiation from the upstanding rocks C D, became subject to causes of ablation more rapid in proportion to the decrease of their bulk. Supposing that in the course of time the excavation of the beds reaches the two lines *c a*, *c f*, the accumulation of névés will, in spite of the altitude, be too inconsiderable for the nourishment of glaciers. Thus while the great amphitheatres of the central part of the massif, though at a lower mean altitude, will still supply stores of névés large enough to feed glaciers, the parts of the massif which form a plateau will constantly tend to reduce the source of supply through the erosion of the margins of that plateau.

We mentioned that the Glacier du Trient, obstructed in its course by the great glacier current which, descending from l'Argentière and le Tour, passed through the Col des Montets, followed the Val de Valorsine and fell into the valley of the Rhone by Salvan, must, during the height of the glacial epoch, have overflowed the Col de la Forclaz and descended in a straight line to Martigny. But when, diminished in size, the great glacier of the Val de Valorsine had its terminal point near Barberine, the Glacier du Trient on its side left prominent the Col de la Forclaz, and forced a passage in the narrow gorge which, from the Val du Trient, descends to the Tête-Noire. The narrowness of this gorge which the glacier was unable to clear out at the level of its bed, produced a lake at the site of the existing

hamlet of le Trient, a lake now filled with pebbles and sand.

Thenceforward the torrent of le Trient deeply hollowed out its bed as far as Vernayaz in conjunction with the Nant from the Val de Valorsine.

When the Glacier du Trient passed through the Col de la Forclaz, it excavated its bed in a narrow belt of lias embraced between bands of gneiss on its left bank and of micaceous schists on its right bank. As regards the torrent that passed down at Vernayaz, it had its passage in a rent produced between beds of the gneiss and the micaceous schists, which occurred along the right bank of the old glacier whose current slid on the anthraciferous rocks of Salvan, there deeply furrowed by its passage: the course of the ice being parallel with the strata.

The glacier mass which descended the Col de Balme and united with le Trient below la Croix-de-Fer had taken advantage of the junction of the lower jurassic beds with the micaceous schists separated by some belts of *cargneule* to hollow out a bed closely embraced at its base.

The N.N.E. extremity of the massif of Mont Blanc, as well as the S.S.W. extremity, exhibits a great variety of rocks and of violent ruptures, which plainly show the effort of the upheaved protogine to force its way through the beds of the strata existing before the upheaval. Hence those ruptures—those breaks of continuity that have formed the very narrow and deep gorges in which the torrent streams have found a passage.

The terminal point of the great trunk glacier current of the valley of the Rhone had long since retreated towards the higher parts of that valley,

when the glacier current of Valorsine and Salvan still descended opposite Vernayaz, as proved by the moutonné rocks of its bed above that village, and as far as the level of the alluvium.

But the frontal moraine of this glacier was swept by the diluvial drifts of the Rhone; and we can now only see the vestiges of its lateral moraines which lie buried beneath the alluvial deposit.

This general review of the acclivities of the massif of Mont Blanc would be incomplete were we not to penetrate into the very heart of the mountain, in order to realize some of the phenomena manifested by the partial dilapidations which it has undergone.

In examining the general map of the massif, any attentive observer will be struck by the polygonal arrangement of the ridges which connect the summits.

At the very centre of the massif, the largest of the glaciers of Mont Blanc—the Mer de Glace—is fed by the névés of three vast amphitheatres, which are:—to the north-east, the Glacier de Talèfre; to the south-east, the Glacier de Leschaux; to the south-west, the Glacier du Géant and de l'Allée-Blanche, separated by the Rocher du Rognon. During the glacial period these three amphitheatres long formed a wide plateau, which was successively degraded only in the least resisting parts, and which afforded a regular flow to the glacial currents.

Thus, the Aiguille du Moine joined the arête that from the Aiguille de Talèfre descends as far as the great moraine de Beranger. In climbing along this moraine we see the gigantic ruins which mark the rupture of that ridge, and how the eastern acclivities of the Aiguille du Moine were profoundly rasped

by the ice when the line of connexion was broken. Similarly, from the Peak du Tacul, we still observe above the névés of Leschaux a buttress which, taking a north-easterly direction, formed a line of connexion between this peak and the Aiguille de Talèfre; so that the Glacier de Leschaux formed a great level covered with névés at an altitude of about 11,500 feet. From the Aiguille du Géant, the remains of an arête stretch in the direction of the second Aiguille du Plan. This arête was broken opposite to the present séracs of le Géant, to permit the discharge of the névés of the great glacier, which is limited on the south-west by Mont Maudit and on the north by the Aiguille du Midi.

Similarly also, the mountain exhibited a plane of junction between the Aiguille de Tré-la-Porte and the Aiguille du Moine, then a second between the Aiguille Verte and that of Greppon.

We have pointed out the importance of those durable arêtes,[5] which are merely the hardest parts of the crystalline masses along the planes of contraction; and it will be observed that these arêtes or planes of retreat of the crystalline masses present themselves in particular directions over the entire extent of the massif.

Thus, at right angles to the great axis, commencing northwards is a first arête which, from the point of Orny, takes the direction of the Col de Balme. Advancing south-westwards, a second arête connected le Tour-Noir with the Aiguille du Chardonnet, extending to above l'Argentière; and a third ridge marks a line from the great Aiguille de Triolet to the Aiguille Verte. The fourth ridge united the

[5] First Chapter.

Grandes-Jorasses, the Pic du Tacul, and the Aiguille de Charmoz; the fifth, the Aiguille du Gèant to the Aiguille du Plan; the sixth includes Mont Blanc de Cormayeur, Mont Blanc, the Dôme du Gouté, the Aiguille du Gouté, extending to the Prarion; the seventh, the Aiguille de Sarsadorège, the Aiguille de Tré-la-Tête, and the crests impending over the glaciers of la Frasse, and of the French Miage. On the south-west of the massif the parallelism disappears.

These ridges, situated at nearly equal distances, namely, varying between 11,500 and 14,800 feet, all take a direction N.N.W. or S.S.E. There is a second series of characteristic arêtes, though of lesser importance, which take a direction from north to south. They are as follows (always beginning with the north end of the massif),—from the Point d'Orny to le Catogne; from the Aiguille du Tour to its neighbours; from the Aiguille Verte to the extremity of les Rachasses; from the Aiguille de Talèfre to the Aiguille de Leschaux; from the Pic du Tacul to the Aiguille du Géant; from the Aiguille de Blaitière to that of de Greppon and to la Filiaz.

From the summit of Mont Blanc northwards, three of these ridges are very near together, that of les Grand Mulets stands out of the névés, and is in a line with les Monts du Brouillard, situated on the southern slope. We again find one of these ridges which, from the Aiguille du Gouté, is apparent as far as the Aiguille Grise. In horizontal projection these ridges form with the first, an angle of about thirty-five degrees.

The third system of arêtes is nearly at right angles to the first; that is nearly parallel to the

great axis, taking a direction from E.N.E. to W.S.W., and forms with the first system an angle of about seventy-five degrees. Faintly marked at the very centre of the massif, it becomes, on the contrary, very strongly marked at its two extremities.

Thus a long ridge of 10,000 yards starts from the Aiguille du Chardonnet ending above the Lac Champey. A second starts from le Darrey to form the right bank of the glacier de Saleinoz. Short arêtes, following this direction, connect Mont Dolent with l'Aiguille du Triolet; the Aiguille de Talèfre with the neighbouring summit towards the E.N.E. (11,962 feet); the Pic du Tacul with the Aiguille de Talèfre, with rupture where the Glacier de Leschaux passes; la Tour-Ronde with les Flambeaux; the acclivities of Mont Blanc du Tacul with le Rognon, &c., and at the extremity, the Aiguille de Bellaval with the Croix du Bonhomme.

On examining the map, we perceive that a number of arêtes of the third order are in that direction.

Lastly, there is a fourth system of arête lines very limited in length, which run from east to west. We see these arêtes extending from the Pointe d'Orny to le Châtelet, above the town of Issert; to the north of the glacier du Tour; between the glacier de Saleinoz and de Laneuvas; from the Aiguille de Talèfre to the séracs of the glacier de Talèfre; from the summit of les Rachasses to the summit of le Bochard; from the Aiguille de Leschaux to Mont Grenetta; to the Grandes-Jorasses (crest); to Mont Maudit (eastern slope); to the Tête Carrée (eastern slope); to the Aiguille de Tré-la-Tête (western slope);

from the two sides of the glacier de la Frasse; to the south crest of the slope of the glacier de Tré-la-Tête, &c.

The partially disintegrated crystalline masses uniformly exhibit their planes according to the four directions just indicated. And the fact may be especially observed along the northern and southern

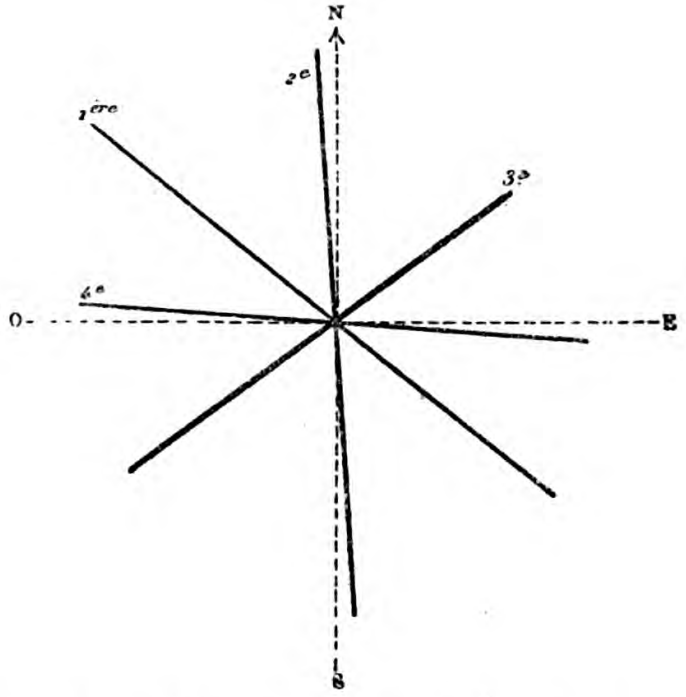


Fig. 106 *bis*.—Direction of the principal Arêtes of the Massif.

inclines of the Aiguille Verte, of les Courtes, and all round the summit of Mont Blanc.

Fig. 106 *bis* denotes these four principal directions. The summits always exhibit themselves at the junction of two, three, and even four of these directions. From the summit of Mont Blanc, the direction No. 1 extends from the right bank of the glacier de la Brenva, south slope (Aiguille de Peuteret), to

the Prarion, north slope ; the direction No. 2, from the Monts de Brouillard, south slope, to the Montagne de la Côte, north slope ; the direction No. 3, from the angle of the séracs du Géant (Envers de Blaitière), north-east slope, to the glacier of the Italian Miage, south-west slope ; the direction No. 4 is only shown by the buttresses which descend into the névés of the glacier de la Brenva, but reappear at the summit of the Monts de la Brenva and at Mont Fréty.

From the summit of the Aiguille Verte likewise start distinct arêtes in the four directions ; the same from les Grandes-Jorasses.

From the direction of these arêtes necessarily results the direction of the glaciers that flowed between them.

Thus it will be remarked that the glacier de l'Argentière, north slope, and the glacier du Mont Dolent, south slope, are in a line with one another, following a middle direction between the first and second arêtes. The same applies to the great glaciers of the Italian Miage. With respect to the Mer de Glace, which has opened a way between several polygons, when it issues from the glacier du Géant it takes a middle direction between the second and third arête, then between the first and second, and after that following the second, ultimately bending round between the first and the fourth.

In issuing from the névés of Leschaux, the glacier which joins the Mer de Glace follows an intermediate line between the first and fourth arête, then between the first and second.

But as these particulars are evident from

the map itself, it is unnecessary to continue them.

The inference therefore would only be that the disorder which strikes us in this immense mountain is merely apparent, and that, in reality, laws have produced these forms, and have determined the great crystalline system; so that the ruin is effected in accordance with certain conditions which are uniformly manifested over every part of the folded and upheaved surface.

Thus were formed the interior valleys, penetrating up to the highest ridges of the massif, and ending in those fine amphitheatres of névés, sheltered by polygonal escarpments—valleys separated by regularly-placed buttresses and crests, which appear to be left for the purpose of providing the glacier currents with affluents intended to nourish them.

But when we think of the time which must have been required for thus *shaping* the mountain—for its disintegration according to certain laws which are incessantly in action, we are struck with awe. When we see by what slow degrees the rocks are rasped and obstacles are borne down by the ice, we ask ourselves how many ages the glacial periods must have required in order to *fashion* the ruins of the elevated parts, to widen the valleys, to erode the declivities, and to obtain uninterrupted courses. And this preliminary work was but a rough-hewing. In their turn, the waters began their work of shaping the great valleys by alluvial deposits. Divided at first into a number of lakes one above another, and swamps separated by moraines or rocky dikes, they gradually rendered these swamps dry by the deposi-

tion of gravels, filled up the lakes, and formed the bed of the streams by an admirably-laid alluvial deposit.

In carrying out this immense work, Nature could remain beautiful and wondrous by her variety, despite the constant uniformity of the same means, and the endless repetition of the same phenomena.

XII.

INFLUENCE OF THE LABOURS OF MAN ON THE DISTRIBUTION OF WATERCOURSES.

THE study of mountain masses should not embrace a merely speculative result, for one of the special characteristics of modern science is the jurisdiction it asserts in the domain of the practical.

Scientific observations no longer yield a merely intellectual satisfaction; while they pave the way for conquests in which the human mind is deeply interested, and while they open new horizons to its gaze, they also enable it to make the study of phenomena subservient to the safety and wellbeing of our race.

But how many centuries have been required to suggest, even to civilized nations, the practical utility of certain branches of knowledge! Who among the scientific men of the last century, to whom we owe so many discoveries, was able to see in those ancient disturbances of the crust of the earth anything but accident and disorder?

Saussure was perhaps the first to examine the mountains according to a scientific method; and though such men as Leonardo da Vinci and Bernard Pallissy had previously gained a glimpse of certain geological phenomena, their ingenious, even delicate, observations did not follow the methodical course of modern science.

Sober and guarded in his deductions, Saussure amassed materials, knew how to investigate, and how to investigate well, which is not so easy as is commonly supposed. His observations are exact, and the leading thought that directs them is the conviction that everything in the order of nature has its rational explanation—that there is no such thing as chance, and that great universal laws regulate and direct everything; and he seeks for this law with that passion which seizes the lovers of truth—a passion without which no valuable discoveries can be made in the natural sciences.

Geology, a study of comparatively recent date, but which has already wonderfully extended the field of human knowledge, had, we might say, to prepare an inventory of the materials that compose the crust of the earth. Having appeared late in the field, this science did not go astray amid the seductive domain of hypothesis; it pursued the course of its observations patiently and methodically; thus it very soon reached the level of its predecessors, and has already found applications whose importance is daily increasing.

It would seem strange that man should have been so long in gaining an exact acquaintance with the ground on which he has to pass his ephemeral existence, if we did not take into account the influence of preconceived opinions among the majority of persons in even civilized nations—opinions which, in the case of some, are inclined towards fatalism, and which, in others, have led them to regard certain simple legends, originating in the obscurity of the past, as truths invested with the highest sanction.

But what is man in presence of the great phenomena which geology reveals? What can he do to utilize or to counteract their consequences?

How can such diminutive beings whose most numerous army would be barely noticed on the slopes of these mountains, in any degree modify the laws which govern the distribution of water-courses, alluvial deposits, denudations, and the accumulation and melting of snows on such vast mountain masses? Is not their impotence manifest?

No; the most terrible and powerful phenomena of nature are only the result of the multiplication of infinitesimal appliances or forces.

The blade of grass or the fibre of moss performs a scarcely appreciable function, but which, when multiplied, conducts to a result of considerable importance. The drop of water which penetrates by degrees into the fissures of the hardest rocks, when crystallized as the result of a lowering of the temperature, ultimately causes mountains to crumble. In nature there are no insignificant appliances, or, rather, the action of nature is only the result of insignificant appliances.

Man therefore can act in his turn, since these small means are not beyond the reach of his influence, and his intelligence enables him to calculate their effects.

Yet owing to his neglect of the study of nature—his parent and great nurturer—and thus ignorant of her procedure, man is suddenly surprised by one of the phases of her incessant work, and sees his crops and habitations swept away by an inundation.

Does he proceed to examine the cause of what he calls a cataclysm, but which is only the consequence

of an accumulation of phenomena? No; he attributes it to Providence, restores his dikes, sows his fields, and rebuilds his dwellings; and then .... waits for the disaster—which is a consequence of laws he has neglected to study—to occur again. Is it not thus that things have been taking place for centuries?—while nature, subject to her own laws, is incessantly pursuing her work with an inflexible logical persistency.

The periodical inundations which lay waste vast districts are only a consequence of the action of these laws; it is for us, therefore, to become acquainted with them, and to direct them to our advantage.

We have seen in the preceding investigations that nature had, at the epoch of the great glacial débâcles, contrived reservoirs at successive stages, in which the torrent waters deposited the materials of all dimensions that were brought down—first in the form of drift, whence sifting them, they caused them to descend lower down; the most bulky being deposited first, and the lightest, in the form of silt, being carried as far as the low plains. We have seen that, in filling up most of these reservoirs by the deposit of materials, the torrents tended to make their course more and more sinuous—to lengthen it, and thus to diminish the slopes, and consequently render their flow less rapid. We have seen that in the higher regions the torrents found points of rest—levels prepared by the disintegration of the slopes; and that from these levels they incessantly caused débris to be precipitated, which ultimately formed cones of dejection, often permeable, and at the base of which the waters, retarded in

their course and filtered, spread in rivulets through the valleys.

Not only have men misunderstood the laws of which we mention here only certain salient points, but they have for the most part run counter to them, and have thus been paving the way for the most formidable disasters.

Ascending the valleys, man has endeavoured to make the great laboratories of the mountains subservient to his requirements. To obtain pastures on the slopes, he has destroyed vast forests; to obtain fields suitable for agriculture in the valleys, he has embanked the torrents, or has obliterated their sinuosities, thus precipitating their course towards the lower regions; or, again, bringing the mud-charged waters into the marshes, he has dried up the latter by suppressing a great many accidental reserves.

The mountaineer has had but one object in view—to get rid as quickly as possible of the waters with which he is only too abundantly supplied, without concerning himself with what may happen in the lower grounds.

Soon, however, he becomes himself the first victim of his imprudence or ignorance.

The forests having been destroyed, avalanches have rolled down in enormous masses along the slopes. These periodical avalanches have swept down in their course the humus, produced by large vegetable growths; and in place of the pastures which the mountaineer thought he was providing for his flocks, he has found nothing more than the denuded rock, allowing the water produced by rain or thawing to flow in a few moments down to the lower

parts, which are then rapidly submerged and desolated.

To obtain a few acres by drying up a marsh or a small lake, he has often lost double the space lower down in consequence of the more rapid discharge of pebbles and sand.

As soon as vegetation has attempted to grow on the cones of dejection—the products of avalanches, and which consist entirely of débris—he will send his herds of goats there, which will destroy in a few hours the work of several years.

At the terminal point of the elevated combes—where the winter causes the snows to accumulate—far from encouraging the larger vegetable growths, which would mitigate the destructive effects of the avalanches, he has been in the habit of cutting down the trees, the approach to such points being easy, and the cones of dejection favouring the sliding down of the trunks into the valley.

This destruction of the forests appears to entail consequences vastly more disastrous than are generally supposed. Forests protect forests, and the more the work of destruction advances, the more do they incline to abandon the altitudes in which they once flourished. At the present day, around the massif of Mont Blanc, the larch, which formerly grew vigorously at an elevation of 6000 feet, and marked the limit of the larger vegetable growths, is quitting those heights, leaving isolated witnesses in the shape of venerable trunks which are not replaced by young trees.

This observation may be verified below the Pierre Pointue, Montenvers, and the Col de la Forclaz (Martigny side).

Above the Tête Noir on the upheaved plateau of anthracite carboniferous strata which separates the Val de Barberine from the Val de Trient, on a slope inclined towards the south (at an altitude of from 6000 to 6500 feet) there existed some years ago a beautiful forest of larches. The lower parts of the forest have been cleared. At the present day all the upper parts are dead, and exhibit only barked grey trunks. Old and young trees have perished, and nothing germinates between them. Even grass does not grow on the soil, which is strewed with decayed branches, showing once more the rock moutonné by the ice.

There were formerly in the valley of Andermatt forests of pine and larch of considerable extent at an elevation of 5000 or 6000 feet; of these forests which were devastated at the close of the last century there is no vestige but a small wood above the village of Andermatt, which shelters it from avalanches. But the trees are old, and young growths do not appear. Thus, although the glaciers have been tending to diminish for the last forty years in a somewhat rapid ratio—which would seem to indicate an elevation of the mean temperature, the forests are quitting the heights where they still lingered, to take a lower position. Is there any connexion between these two results? We shall not endeavour to solve the problem. But the facts deserve at least the attention of naturalists. We do not observe, it may be remarked, that forests rise higher in mountainous countries that have no glaciers than in those where they do occur. The contrary would seem to be the case. And in the mountains of Dauphiné, which have few or no glaciers, the forests are not

seen at an elevation greater than 5000 feet. The slopes of these mountains retain their arid character even much lower at many points.

If it were demonstrated that forest growths ascend in proportion to the extent of the glaciers, and descend as these disappear, the fact would be of considerable importance. We would therefore urge the intelligent explorers of mountain regions to collect as many observations as possible on the subject, by whose help we might ascertain whether it is the forests that have an influence on the development of the glaciers, or whether the glaciers are a cause of the more energetic vegetation of the forests.

It cannot be doubted that the glaciers which, as we have seen, attract a considerable part of the moisture of the atmosphere, excite around them a movement of the air that is charged with it; that they cause an abundant evaporation, and thus keep up a variable hygrometric condition in their neighbourhood, but one which may be very favourable to vegetation. At an elevation of 4000 or 5000 feet the larger growths—the pines and larches—are favoured by the neighbourhood of glaciers, and flourish vigorously in such a position, if they are not hindered in their growth by over keen blasts; whereas, at the same altitude, at a distance from glaciers, unless they are surrounded by very favourable conditions in point of shelter and moisture, they are but feeble, and do not reach an advanced age.

In any case it would seem that the efforts of men ought to tend to favour the growth of forests, and not their destruction at the extreme point of

elevation where they are capable of existing. But in this respect the carelessness of the mountaineers is consummate, and for the sake of a few hours' warmth they will even set fire to the butts of trees of centenarian growth, or drive their herds of goats to those limits of sylvan vegetation, where the animals tear up the young scions when they chance to spring up among the denuded rocks. Nature seems to grow weary of this daily contest, and abandons to sterility areas that were once covered with forests. The larches disappear, and even the mosses quit these wildernesses of stone. In passing through Savoy, the Oberland, and the Valois, we observe everywhere, with regret, that the forests are tending to lessen their altitude at the same time that the glaciers are diminishing; that a gloomy solitude prevails beyond an altitude of 6000 feet, and that the winter snows, melting at the first heat of spring, cause ravages of an unceasingly serious character on the slopes, making months of dryness follow suddenly on days of torrential violence; removing the fertile accumulations of dust, bringing down those immense *traversales* of shifting stones which invade the upper valleys, and fill the cavities and basins that offer a lodgment, and spread sterility everywhere. Instead of favouring the higher marshes and lakes, man, with a view of gaining a few square yards of turf that are soon occupied by pebbles, provides outlets for these lakes or marshes. Thus he sends down more rapidly into the lower parts the waters whose outflow nature was economizing. Meantime, his selfish labour does not even profit him; the marshy beds are denuded, and cease to produce anything. The disintegration of the rocks is acce-

lerated; being in contact with varieties of temperature, they scale off, and the débris, carried down by the waters resulting from thawing, hasten to lay waste wide areas in the valleys; the torrent waters reaching the same points in a few moments, overflow and cover the fields and pastures with sand. Then an attempt is made to regulate their course, dikes are raised to embank them, windings are obviated, they are made to flow in a straight line, so that in their rapid course these torrents carry to a distance pebbles and gravel, and form larger and larger sterile cones of dejection. Then fine weather supervenes, the bed is dry, and the pastures are no longer irrigated; in place of the impetuous torrent flows a slender rill lost in heaps of pebbles.

Who can say whether this more and more rapid discharge of the torrent waters does not contribute to the ablation of the glaciers by diminishing the causes of evaporation? How many evils might man avoid if, instead of contravening Nature in her work, he understood her designs, and lent himself to their accomplishment!

But let us proceed to consider practical means of amelioration. The mischief must be counteracted at its origin—not when it has acquired such power that the efforts of man become futile.

The torrents originate in the glaciers, or in temporary or permanent reservoirs of snow.

One of the functions of the glaciers is, as we have seen, to regulate the discharge of the watercourses, and they are never the cause of sudden, disastrous inundations. The same cannot be said of the permanent or temporary snows; whether they melt in part or completely at the beginning of the warm

season, they produce avalanches or partial débâcles on the slopes of the mountains.

We will consider the avalanches first.

These are always produced on steeply inclined planes below an upper reservoir; a trough or

Fig. 107.—Upper cones of dejection.

amphitheatre more or less spacious—the bed of an ancient glacier, Fig. 107. In winter the snow accumulates at A. When the first warm rains occur, the waters find a passage beneath the bed of snow, and thoroughly drench it, so that the mass, sliding down

by its own weight, is precipitated through the opening B on the cone of dejection formed by a long series of disintegrations of the summits and successive falls.

Avalanches always follow the same channel or *couloir*, or nearly so, and, precipitating débris along it every year, make it a long train of stones of no great size, easily shifted, and to which vegetation cannot attach itself.

Nevertheless the forests of resinous trees like such stony heaps; their roots require air, so that they catch hold of the débris and envelope them. Of a shifting soil they soon make a firm and solid slope, where *humus* is arrested, and causes mosses and lichens to grow, which attach together large and small stones.

What then too often happens? The woodcutters chiefly attack the trees that border the couloirs of avalanches, because these channels afford them a ready path for transporting the logs. The trunks that have been cut down, falling on these declivities, slide down them into the valley, where they are collected. In their passage they break the young shoots that endeavour to grow between the stones; and even roll these down, so that the following spring the avalanche, instead of finding only a narrow channel, and trees at the side to break and scatter it, has before it a wide smooth path quite prepared to facilitate its fall. This fall is only the more terrible, so that the avalanche which, at starting, found no obstacles tending to divide it, rolls down in vast masses with increasing rapidity, and sweeps away everything in its course before reaching its destination. Sometimes even

it bounds from point to point, and spreads far in the valley.

The severest regulations should be adopted with a view to prevent the cutting down of the woods along the couloirs; and such regulations should be strictly enforced—which is still more difficult than the devising of the code itself.[1]

While in the upper trough-like hollows there are permanent snows, a torrent of no great volume is flowing all the year through, in the channel, or at the meeting of the cone with the slopes, or with a neighbouring cone. In this case another intermediate cone of dejection, C, is formed, and avalanches from D to C (Fig. 107).

Instead of clearing the woods away from the couloirs, it would be possible to plant them; some attempts have been made in the Oberland and in the valley of the Rhone, and with good results. To effect this, at the upper point, B, of the couloir, long iron spikes have been planted, quincunx fashion. These iron spikes arrest the avalanche, and compel it to melt there; or if its weight is too considerable to allow the stakes to stop it, they divide it in its fall, so that instead of falling in a mass, it rolls down in fragments and dust till the trees arrest it. To plant the couloirs, wattle-work of pine branches, fastened by wooden stakes driven into the gravel, is placed at intervals of some yards, say, one above another. During the summer this wattle-work arrests the earth and sand carried down by the rain, and the

[1] In August, 1875, we observed that woods had been cut down in the upper Val du Bonhomme, so as to threaten a dangerous result; i.e. along the couloirs and on points where the avalanches are already destructive.

dead branches and detritus. Thus landing-places are formed in which pine seeds are sown. The young trees, which are much exposed, are swept away; but some always remain, and the sacrifice of the victims is not altogether useless. Débris still persist, which endeavour to recover their ground; their resistance, however feeble, has contributed to scatter the avalanche.

But at the upper orifice B of the couloirs it is not always possible to fix iron spikes. The soil there is often nothing more than the rocky bed of the glacier in which the fixing of the spikes would be a very long and expensive undertaking.

Then, at the extremity of the avalanche beds, above the outlet B, it is possible with the aid of stones, which are abundant on these beds, to form a series of barriers perpendicular to the direction of the inclines. These cairns of rocks and broken stones, Fig. 108 (see A) which do not greatly project, arrest the snows, prevent them from sliding down in large sheets, and oblige them to melt on the spot or to divide before discharging themselves. Such barriers, which are frequently adopted, and to which the mountaineers of Savoy give the name of *tournes*, are only placed by them in the valleys at the extreme verge of the fall of the avalanches, to protect their habitations. It is, however, not at the limit of the course of the avalanches that they should be erected, but where they begin to accumulate to descend in formidable masses into the couloirs. The snows are precipitated into these couloirs only because there exists above them the moutonné smoothed bed of an ancient glacier—a bed free from asperities. Generally a few trifling obstacles are sufficient to stop them in

their course at the moment when they are beginning to move.

These *tournes*, Fig. 109, shown in horizontal projection A, and in section, B on *a b*, need in most cases be only two or three yards high at the salient, above the line of the slope, and their upper surface

Fig. 108.—Avalanches.

should be more or less declivitous in proportion to this incline.

They cannot stay an avalanche in the middle of its course, but they oppose its sliding at the commencement far better than in its terminal impetus at the

end of its course, which can never be exactly known.

However, the points where they should be fixed, in the wide funnels which surmount the cones of dejection, require to be marked by a good observer. Their preservation and preventive effect depend on the choice of these points.

In keeping the snows on the summits, two grave perils are avoided, viz. 1st, the fall of the avalanches; 2nd, the suppression of the small torrents

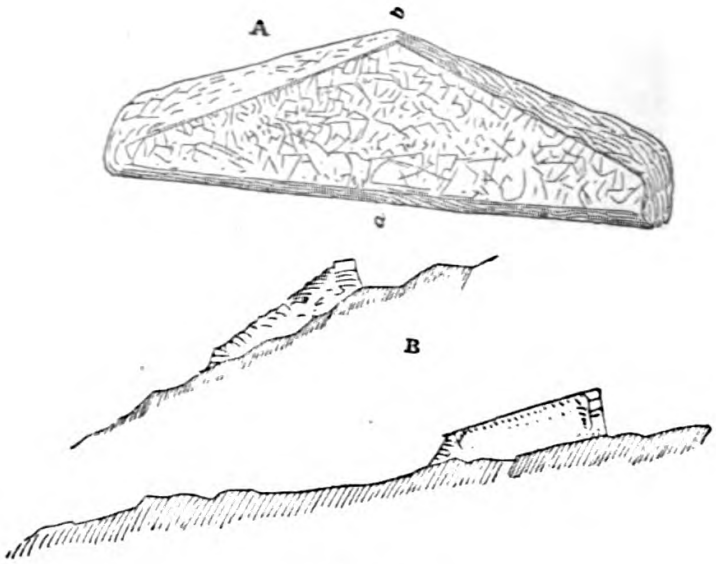


Fig. 109.—Tournes.

which are so necessary to the irrigation of the low grounds.

If the time given by the shepherds to the preservation of the higher pastures and the distribution of the waters, so as to make them flow away rapidly, was employed in these works of general advantage, disasters would be obviated, while they would not be deprived of the advantage of the upper pastures. But no one takes the trouble to make them under-

stand the general laws which regulate the course of nature in these districts, or to show them that their interests are bound up with those of the dwellers in the valley. Yet is it not the same persons who in winter move down into the vales, and in summer ascend the higher steeps with their cattle? Have not the mountaineers, who from June to September send their herds to such elevated points, pasture-grounds in the valleys which they mow, to accumulate a provision for the winter?—Thus their ignorance leads them to destroy by an unintelligent treatment of the upper pasturages, those which they possess below, while moreover they contribute to the laying waste of extensive districts.

Above the point A, the outlets of the snow basins, Fig. 107, there is always an accumulation of humus, sometimes even a marsh. There, if the elevation allows, forest growths readily shoot forth, being sheltered and watered, and finding a thick vegetable soil. But it is there especially that the mountaineers are eager to cut down the pines to send them down the couloirs; and if the couloirs have been partly covered by vegetation, the woodcutter clears away these obstacles, so as to enable the trunks to slide freely to the bottom of the cone.

Next year a formidable avalanche is formed, the couloir is enlarged, the pines that border it are thrown down, and sterility once more takes possession of the surface of the cone of dejection. The snows descend in masses from the heights in the spring, and the few patches that remain sheltered at the base of the arêtes of the summit are entirely melted in July. Thenceforward there are no more torrents, nor water in the upper pasturages for the

use of the cattle, or to irrigate the soil. The region becomes a desert, the heaps of stone and dust cover the turf, and only a few marmots find sustenance in these desolate wastes.

Nevertheless the mountaineer is not unintelligent to such an extent as not to be able to comprehend the simple laws whose effects he duly observes.

But who will take the trouble to enlighten him, and make him understand that if he spends an hour a day in moving a few pebbles—which in fact he does in his meadows below—when he is sojourning on the heights, he may change the unfortunate conditions to which his carelessness exposes him?

At the base of every summit, of every rock, is there not on a small scale an arrangement analogous to that given in our Fig. 107? Those large trough-like excavations whose outlets are indicated at A are repeated in infinitely various phases, even to that of basins of a few yards in area. Let man begin by controlling the smaller reservoirs, and he will be able to become master of the larger ones. For this problem of avalanches and snow-meltings is only one of multiplication. If man is powerless in presence of enormous numbers, he may yet act on the units without undertaking a labour that is above his strength and means. Not only do the sudden falls of avalanches devastate considerable areas in the valleys; but, falling from an altitude of 6000 to 3000 feet, the snows melt much more rapidly, accidentally increase the streams, and then, when the melting is completed, there is no longer a provision for the warm season. It would therefore be very desirable to maintain the snows near summits on the ancient beds of the glaciers, which nature has

prepared for them as so many halting-places where they may accumulate and melt slowly, in proportion to the height, the recesses, and the shade of the summits.

Having frequently entered into conversation with mountaineers on those elevated plateaux, I have taken occasion to explain to them these simple problems, to point out to them the foresight of nature and the improvidence of man, and to show how by trifling efforts it was easy to restore a small lake, to render a stream less rapid, and to stop the fall of materials in those terrible couloirs. They would listen attentively, and the next day would anticipate me in remarking, "Here is a good place to make a reservoir. By moving a few large stones here, an avalanche might be arrested."

The herdsmen are the enemies of the forests; what they want is pasturage. As far as they can, therefore, they destroy the forests, without suspecting that their destruction is sure to entail that of the greater part of the pastures.

We saw in the last chapter that the lowering of the limit of the woods appears to be directly proportioned to the diminution of the glaciers—in fact, that the smaller the volume of the glaciers, the more do the forests approach the lower regions. We have found stumps of enormous larches on the beds of the ancient glaciers that surmounted la Flégère, beneath the Aiguilles Pourries and the Aiguilles Rouges, i. e. more than three hundred feet above the level of the modern Châlet de la Flégère, whereas at present the last trees are some yards below this hotel, and maintain but a feeble existence. These deserts are now covered only with

stone débris, rhododendrons, and scanty pasturage. Even in summer, water is absent at many points, so that to supply their cattle the herdsmen of la Flégère have been obliged to conduct the waters of the Lacs Blancs into reservoirs by means of a small dike which follows the slopes of the ancient moraines. Yet the bottoms of the trough-shaped hollows are sheltered, and contain a thick layer of humus, so that it would appear easy, in spite of the altitude (6600 feet), to raise larches there. But the larch is favoured by the neighbourhood of snows or ice. And on this plateau, whose summits reach an average of 8500 feet, scarcely a few patches of snow are now to be seen in August.

Formerly these ancient glacier beds were dotted with small tarns, which have been drained off for the most part by the herdsmen themselves, who hoped thus to gain a few square yards of pasture. Such tarns, frozen from October to May, preserve the snow and form small glaciers, while their number caused these solitudes to preserve permanent névés, which, covering the rocky beds, retarded their disintegration. It was then also that the larches, whose stumps still remain, covered the hollows and sheltered parts of the combes. The area of pasturage was evidently limited; but the pasturage itself was good, well watered, and could not be encroached upon. Now both tarns and névés have disappeared, and larches likewise, while we see inroads constantly made on the meadows by stony débris and sand.

If care be not taken, the valley from Nant-Borant to Bonhomme, which still enjoys such fine pastures, protected by some remains of forests, will be invaded by débris; for these forests are already being cleared

in consequence of a complete misunderstanding of the conditions imposed by the nature of the locality.

Conifers would seem to have been created with a view to the purpose they serve on the slopes of the mountains. Their branches, which exhibit a constant verdure, arrest the snows, and are strongly enough attached to their trunk to enable them to support the load they have to carry. In winter we may see layers of snow eight inches or a foot thick on the palmated branches of the firs, yet which scarcely make them bend. Thus every fir is a shelf which receives the snow and hinders it from accumulating as a compact mass on the slopes. Under these conditions avalanches are impossible. When the thaws come, these small separate stores crumble successively into powder. The trunk of the conifer clings to the rocks by the help of its roots, which, like wide-spread talons, go far to seek their nourishment, binding together among them all the rolling stones. In fact, the conifer prefers a rock, settles on it, and envelopes it with its strong roots as with a net, which, stretching far and wide, go in search of neighbouring stones and attach them to the first as if to prevent all chance of their slipping down. In the interstices débris of leaves and branches accumulate, and a humus is formed which retains the waters and promotes the growth of herbaceous vegetation.

It is wonderful to see how, in a few years, slopes, composed of materials of all shapes, without any appearance of vegetation, become covered with thick and vigorous fir plantations; i.e. if the goats do not tear up the young shoots, and if a little rest is left to the heaps on which they grow. Then the sterile ground is

clothed, and, if an avalanche occurs, it may prostrate some of the young trees and make itself a passage, but vegetation is eager to repair the damage. Does man ever aid in this work? No; he is its most dangerous enemy. Among these young conifers he sends his herds of goats, which in a few days make sad havoc, tear off the shoots, or hinder them from growing; moreover, he will cut down the slender trunks for firewood, whereas the great neighbouring forest would furnish him, in the shape of dead wood and fallen branches, with abundance of fuel.

We have observed this struggle between man and vegetation for several years in succession. Sometimes, but rarely, the rising forest gains the victory, and, having reached a certain development, can defend itself. But most frequently it is atrophied, and presents a mass of stunted trunks, which an avalanche crushes and buries in a few moments.

While on the cones of dejection the destruction of the forests is a grave danger, there, at any rate, the materials are ranged in proportion to their weight and volume, and these denuded cones can only widen their base a little.

It is not the same with the moraines. On these glacier deposits the materials are confounded, for they have been deposited gently, small and large together, as the glacier threw them off, and sometimes left between them considerable voids. The conifers especially prefer these deposits, consisting of fine sand and stones of all dimensions, with air cavities, all mingled together; they grow there with especial energy and rapidity, and give great firmness to the steep slopes. But if the moraine is stripped of this protecting mantle, the rains and

melted snows disintegrate it the more rapidly as the conditions of stability in the materials are abnormal. Then, if floods occur, we see whole sections of these masses drenched and borne down so as to cover vast cultivated areas in the valleys.

Five years ago a road fit for vehicles was made along the great ancient moraine of the right bank of the Glacier des Bois, in the vale of Chamonix, below Lavancher. Each year since its construction the denuded part of the moraine above the road has been crumbling down on this highway, and it has been necessary to clear it and restore the shoring every summer. Gradually the disorder has increased; great blocks, loosed from their position, have been rolling to the bottom, breaking the firs, and bringing down with them large masses of vegetable mould. There is always danger in meddling with moraines or clearing the woods from them; for it is their débris which, carried down by the waters, cause the greatest devastation in the valleys.

While the crumbling down and drenching of the moraines occasion disastrous consequences in the valleys, it is much worse when these moraines exist at great heights, and borne down by sudden thaws or storm-rains, descend through very steeply-inclined ravines, and spread over the lower grounds.

Those upper moraines still possess their glaciers, or have been deprived of them at a more or less recent epoch. If the glaciers have melted, these moraines, at an altitude of 6600 feet, are habitually covered with rhododendrons, mosses, and a little grass; then they keep their ground, and are not swept down; but if the glaciers still exist, these moraines, disturbed by the ice, remain absolutely

devoid of vegetation; and if an abundant melting occurs after considerable storm-rains, the moraine heap, forming a dam, is ruptured at a certain point; the torrent sweeps down into its bed a mass of mud, mingled with enormous blocks, which is precipitated like an avalanche and spreads over the valley, covering it with débris over a more or less extensive surface. The pastures and other fields are then buried beneath a thick layer of gravel, which the unfortunate cultivators are obliged to remove to recover the buried humus and bring it back to the surface—a wearisome labour; one, indeed, which is so disheartening that such fields are often abandoned. Thus in the vale of Chamonix the torrent de Greppon periodically covers with gravel and tumbled rocks all the pastures situated between the point where it reaches the alluvial soil and the Arve—containing about seventy-four acres of the best land. Yet the torrent de Blaitière, its next neighbour, and which flows under exactly the same conditions, does not discharge into the valley any débris from the upper moraine. Why? Because the torrent de Blaitière reaches the soil of the valley only by a series of falls —of cascades—with intervening levels; while the torrent de Greppon flows in a straight line, along a crevice in the crystalline schists, without any cascade in its course. The bed of the latter torrent is a perfect gully, which, in a few moments, will bring masses of mud and moraine blocks into the vale. Yet the banks of this gully are formed, especially in the lower part of its bed, of sand, in which are embedded enormous blocks of protogine considerably more than a hundred cubic yards in volume.

It would be very easy to roll these blocks into the bed, and thus wedging them together, form a succession of levels, so as to arrest the falling rubbish, which would itself contribute to their completion.

We should thus produce a series of cascades, of no great elevation, it is true, but sufficient to retard the impetus of the mud avalanches. If the poor mountaineers who have been employed whole seasons in recovering their buried vegetable soil, and in endeavouring to raise dikes which are as constantly broken through, had devoted a quarter of this time to improving the course of the Greppon, they would be in security; whereas now, after every storm, those who have succeeded in regaining their fields tremble lest they should see them covered again.

But, more than this, we have assured ourselves, on the spot, that the masses of material brought down by the terrible and destructive moraine of the glacier des Nantillons might be arrested even before reaching the upper part of the torrent at the point where the latter descends obliquely, after having abandoned the bed of the ancient glacier.

At this bend, with a little labour, a barrier might be constructed sufficiently solid to arrest the débris before it has acquired the impetus which the steepness of the torrent below this point gives it. The materials brought down would of themselves complete the barrier, and would form a level through which the waters would be able to filter, and would no longer be precipitated into a mass of mud. We have cited this example among a hundred others, because there the phenomenon is reproduced at short intervals, and it is easy to ascertain exactly the remedy that must be applied to the mischief; for

the materials are not wanting, and are of such a nature as, by their weight, to be capable of resisting a sweeping pressure, while they may be easily precipitated into the bed of the torrent by undermining the gravels that support them.

In the natural arrangement of the torrents, we often see that the least obstacle—in the case of a flood—rapidly modifies the outflow, or induces a deviation or erosion. The water, always seeking the shortest path, loses neither time nor force in overcoming an obstacle if it can with less effort pass along by the side of it. Attentive observation, therefore, will enable man to exercise an influence on the course of the torrent-waters; and sometimes a few stones or the trunk of a tree, judiciously placed, would be able to prevent disastrous results.

But it is only when the movement has acquired an irresistible force that man begins to think about arresting its effects. Vain efforts! His most costly and tedious labours are swept away like chaff!

It is the source of the torrents to which attention should chiefly be directed, whereas it is there that everything is left to chance, or man interferes in a spirit of selfish stupidity with the provident arrangements of nature. A dozen small weirs, which three or four workmen might construct in a week or two, would in many cases suffice to hinder the waters of rivulets proceeding from different sources from uniting at a single point at a given moment, and thus forming, when floods occur, a torrent loaded with débris, sweeping down everything in its course, ruining the banks, and covering fertile fields with sand and pebbles. Materials are never wanting for the construction of such weirs, which, if intelligently

placed, would in a short time form levels. The beds and sides of torrents, and the stones dislodged from the rocks, abundantly supply materials.

It very rarely happens that the upper torrents flow in a straight line. The very character of the rocks which form their bed compels their course to

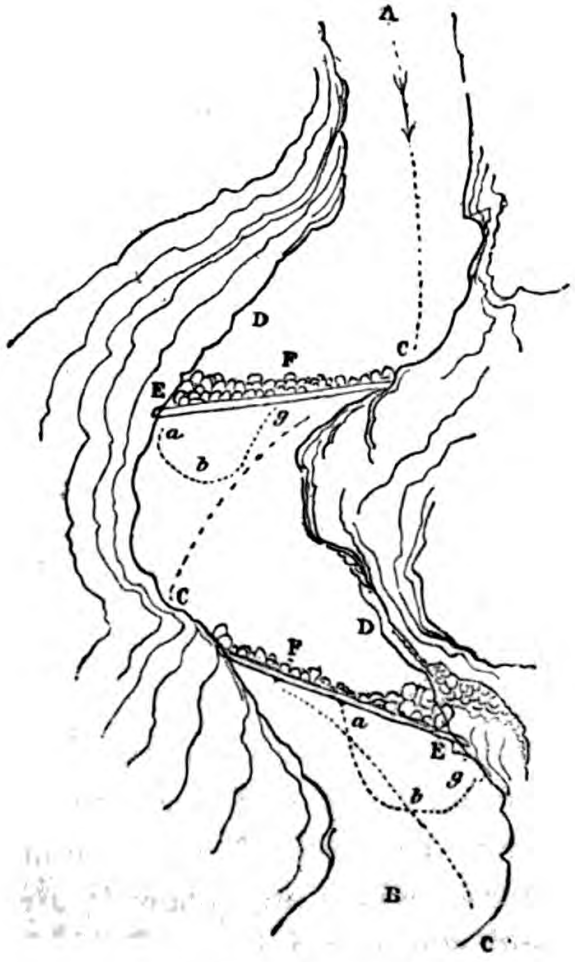


Fig. 110.—Barriers in upper torrents.

follow zigzag lines (Fig. 110). If A B represent the course of a torrent, the chief force of its current will be directed on C; at D there will be relative repose or slackening of speed. It is, in fact, at C that the undermining effects take place, and the rocks are

worn away. The trunk of a tree or stones ranged from C to E will soon produce at D an embankment of pebbles and sand—a level; and a fall is produced along the breadth F C. It is then that it will be desirable to load the level D, chiefly from F to C, with large stones, so as to cause the fall to take place between F and E. Thus if we increase the length of the axis of the torrent, and proportionally diminish its inclination, we provide levels that slacken the speed of the current, and even an undermining process *a b g* at the base of each fall, forming so many reservoirs that incessantly throw up the pebbles on to the level and consolidate it. It is by aiding the processes employed by nature, and not by seeking to counteract them, that we are able to modify an undesirable state of things.

We have tried these weirs on a small scale, for some days, in a torrent which, at every fall of rain, brought down a quantity of gravel, and succeeded in obtaining a regular course of greatly slackened speed and limpid water.

The most destructive torrents are not those which flow between rocky and very durable banks, but such as are precipitated into ravines of argillaceous schists—which are generally straight in their course, and whose disintegrated banks break down in considerable masses into the current, hinder its flow, and being diluted into the form of thick mud, accidentally form slightly coherent dams, which the waters ultimately sweep down in formidable avalanches, irresistible in their course, and carry along trees and enormous rocks, to spread them in cones of dejection in the valleys. To arrest

these mud currents in their course is an impossibility.

Sometimes they present a mass so compact, and of such tenacious character, that they roll but very slowly. The water accumulates above them, and in its impatience hollows out in a few moments one of these disintegrated banks, to spread beyond the bed, and covers the pastures with débris or deeply furrows them, carrying away the fertile soil to a distance.

The only remedy for such an occurrence is the formation of upper reservoirs to retain the waters resulting from melting or from rain for some time, and to hinder them from being precipitated all at once into the same ravine.

Usually these ravines, which are deeply hollowed out by the waters in the argillaceous schists, begin with a trough of greater or less width (see Fig. 79), and more or less precipitous, but at whose orifice the ravine, which is at first narrow and of no great depth, is enlarged, and becomes deeper as it descends the slopes.

These troughs are always hollowed out in a part that has sunk down or is already greatly depressed by the passage of the ice in ancient times; sometimes they attain considerable dimensions, for example, the combes which we see on the right in ascending the Italian Val Ferret. But, large or small, the troughs or combes unite the waters resulting from melting or from storms in a few moments, and carry them down in great quantity into the valleys through these single direct ravines whose incline is regular and generally very rapid. It is in the troughs or combes that reservoirs ought to be provided by means of dams in the gorge. The herds-

men of Mont Joli and le Prarion are accustomed to form them to get watering-places for the flocks. For on these schistose slopes, surmounted by rounded summits, it may happen that the desolating torrent, within two hours after the storm, would scarcely furnish a bucketful of water. What the workmen do with the help of clods of turf or stones to secure a few cubic yards of water might be very easily done at each trough, and often at the gorge of the combes, by a

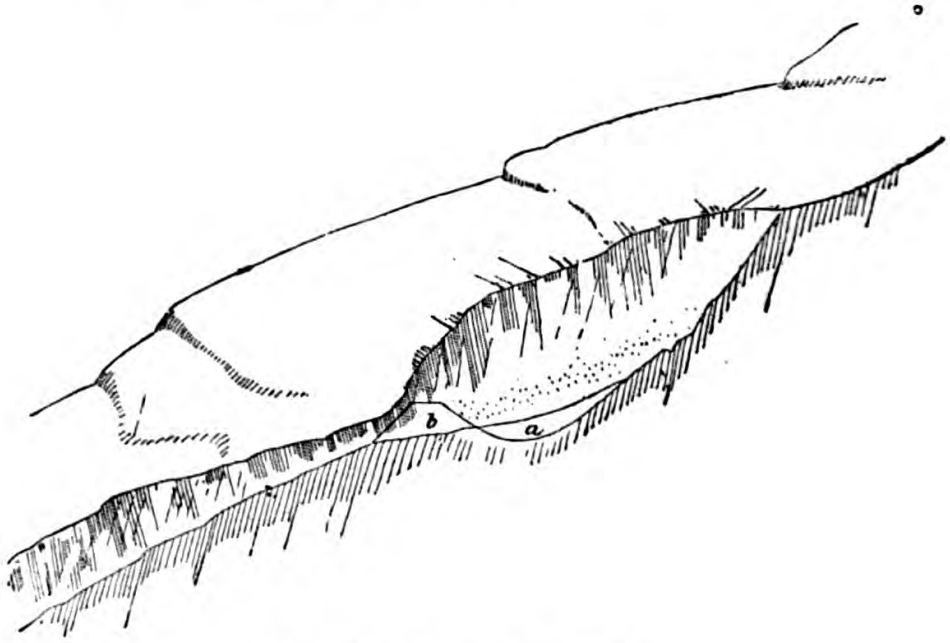


Fig. 111.—Barriers in Combes.

few days' labour; for the bottom of these amphitheatres is always filled with movable materials, which might be shifted so as to form the dam, as seen in the longitudinal section of a schistose trough (Fig. 111)—at *a*, excavations, at *b*, embankment. Though relatively small, these reservoirs tend to delay the course of the torrent at its commencement by a few minutes, and these few minutes are sufficient to obviate the danger.

We have seen, not once merely, but several times, the Petit-Nant which comes down above the hospice of Nant-Borant, and whose source is about 5000 feet from this hospice, in one of those very deep schistose troughs, swell so considerably, after half-an-hour's storm-rain, that it swept down in black mud, blocks of rock of four or five cubic yards in bulk, and the uprooted trunks of firs, and carried away in a few moments enormous masses from the banks so as to undermine the timbers of the bridge, which went some twenty feet beyond those banks —threatening to destroy the bridge itself, which is the only approach to the col du Bonhomme. Scarcely had the rain ceased when the torrent resumed its harmless flow. All this was an affair of a quarter of an hour.

We shall not enter into all the details respecting the plans to be adopted with regard to the upper torrents; the circumstances are infinitely varied; but what cannot be too much insisted on is that man could, without great effort, obviate the disasters to which he is subjected, by dealing with the evil at its commencement.

But engineers with rare exceptions seldom visit these heights, or at least study them but very superficially, and limit themselves to planning or executing works in the valleys or plains—works which can only oppose a feeble barrier against the effect of the waters, when they have acquired by their volume an invincible momentum.[2]

[2] We do not stand alone in directing attention to this neglect or indifference, and on this question we think it worth while to cite here a passage from the *Notice sur l'amélioration du régime des eaux d'après les principes appliqués en Suisse*, by M. A. de

Set ten men to attack a hundred, one after another, and you will easily beat them; but if you

Salis, chief inspector of public works to the Swiss Confederation:—

"It is a common notion that the task of the engineer does not extend beyond keeping in order the river waters of the plains and valleys.

"As regards the higher districts, the idea prevails that they should be left to that empirical treatment devoid of all method which attempts to cure every imperfection of nature by means of a single recipe.

"The requirements of the case are very different from what is here supposed.

"It is precisely in the elevated districts that the work of the engineer should begin. This work takes every variety of form. Nowhere is the ability to perceive the most suitable remedies in view of the object to be attained, and the means of execution, of greater consequence than it is up there. But to judge with certainty, in every case that presents itself, requires more than the routine of an empiric—it requires the science and experience of the engineer.

"It is plain that a task of such magnitude as the restoration and conservation of a desirable state of things in our mountain districts needs for its accomplishment the united efforts of the forester and the engineer, and that these two different professions should aid and supplement each other's work.

"The existence of the forests moderates the flow of the rain water, which, spreading over the surface of the ground, can no longer be concentrated in the couloirs and ravines.

"On the other hand, the roots give cohesion to the soil, and hinder the furrowing effects of torrents.

"Consequently, when once the equilibrium is disturbed,—when once the active force of the water overcomes the resistance of the ground, it is first of all necessary to restore the firmness of the latter by human labour, in order that, having partly regained its stability, the re-wooding may come to complete the work of cure.

"But it is evident that these two functions must necessarily be mingled—that they should, more or less, overstep and enter into each other's domain.

". . . We must, in fact, not disguise from ourselves that there

wait until the hundred men unite to resist the ten, it is plain that you will be beaten.

are obstacles against which measures otherwise the most efficacious are of no avail.

"We will not even take account, among the difficulties to be overcome, of selfish cupidity and ignorance—those inveterate enemies of our forests.

"We rely for overcoming these on the sense of duty to future generations, not less than on the enlightenment arising from more widely-diffused education among our mountain population.

"We shall lay stress rather on the climate and the nature of the soil in certain regions, as the chief obstacles to the efforts made by man for replanting our mountain districts.

"In support of these considerations we may observe that nearly half the basin in which the principal streams originate is above the region of forests. The bearing of this fact will be better understood if we remember that floods do not occur while it only rains in the lower districts, and that the vapours of the atmosphere are precipitated on the summits in the form of snow. As the water does not immediately flow from these heights, the danger of inundation is counteracted by the snow; this is a fact of observation well known to all who are acquainted with the climate of our mountains. . ." M. de Salis follows up these intelligent observations by some brief remarks relating to the insuperable difficulties which, in his opinion, stand in the way of even the partial regulation of the water discharge at altitudes higher than the forests. Our opinion, as previously explained, is that, while these difficulties are great, they are not insurmountable, and that in many cases they might be encountered without undertaking any very expensive work.

It suffices, in fact, in many cases, to simply aid Nature, or not to contravene what she is doing. But it should be mentioned that in his remarkable Report, drawn up for the *Exposition Géographique de Paris*, in 1875, M. de Salis has only approached one part of the question—that referring to the regulating of water-courses in the valleys—and has only incidentally referred to the upper torrents and reservoirs above the forests. We think it worth while to cite another passage from this Report, emanating

Thus, besides the enormous loss of property caused by the unrestrained state of the waters in the higher

as it does from such high authority, and presenting the results of such a lengthened experience:—

"After having reviewed the obstacles which limit the range of man's efforts in his struggle against the devastations of torrents, we will once more ask ourselves this question, '*May we, in despite of every discouraging consideration, enter upon such an enterprise with some hope of success?*'

"Before replying, let us first remember that the question of primary importance is to put a stop to the destruction of the forests. We would further remark that it would be in itself a great gain if we no longer impeded Nature in her restorative action, as is now done only too detrimentally by the excessive extension of the grazing-lands, especially for those for sheep and goats.

"The mischief will be more speedily remedied when the efforts of man are combined with those of Nature for the consolidation of the ground, and are not directed to its disintegration.

"But the considerations we are about to urge appear to us of primary importance.

"First, let it be understood that the formation of water-worn materials offers less danger to the plain the higher their source. In fact, most of the materials brought down by a torrent are deposited either at the foot of the ravine (what we call upper cones of dejection), or further on in the parts of the bed presenting a relatively gentle incline. Hence only those materials reach the plain which have been reduced by trituration to the condition of sand or fine gravel.

"Attentive consideration of the basin of every Alpine stream shows that the sources of the most disastrous drifts are also those which are nearest to the plains—that is, those which exist in the lower regions of the mountains. Such, e. g., are the ancient lower frontal moraines or deposits of glacial mud.

"This is also in accordance with the fact that the greater part of the rounded pebbles are not supplied by rock débris of recent formation, but either by deposits of gravel dating from the glacial epoch or by very ancient dislodgments.

"Of course these vast deposits do not occur in the higher

and middle parts, on all the lower parts vast sums are uselessly squandered in contending against periodical disasters, even if—as sometimes happens—the works undertaken are not of a nature to increase still further the extent of the mischief.

But it will not suffice merely to investigate the evil at its source; it will be necessary to take still further precautions.

It is very fortunate that the upper valley of the Rhone is terminated by the Lake of Geneva, and that Nature has contrived this immense reservoir

regions of the Alps; and therefore it is that they have been covered with forests and have thus been enabled to resist the action of torrents. But no sooner are the woods cut down than these slopes are so much the more rapidly devastated. Once attacked, the immense stores of these water-worn materials have been able to supply drift material in volume sufficiently considerable to explain the rapidity with which the mischievous consequences of clearing the woods have been manifested. The superficial detritus annually furnished by atmospheric agencies would never have been able to produce drifts so voluminous and destructive.

"Hence it will be understood that it is not in the higher regions beyond the range of human enterprise that we must go in order to grapple with those sources of danger most to be dreaded by the plains, but rather—and it is fortunate that this is the case—to heights where man may still be aided in his work by the incessantly renewed force of vegetable life."

Most assuredly! but in order that this vegetable life may be developed it is absolutely necessary, as we have shown, to hinder, e. g., the effect of avalanches formed above those forests, to put a check to the furrowing action of certain torrents, to retain the water resulting from rain and rapid thaws as long as possible in those numberless upper reservoirs which Nature had contrived, and which the herdsmen too frequently destroy, &c. In fact, the attentive study of the engineer should not be limited to the forest altitudes.

to collect the waters issuing from that valley, to store them, and to regulate the course of that river in its lower part; for works undertaken in the upper valley of the Rhone would be calculated to occasion the most terrible inundations further down. As such a lake exists, there is no necessity for criticizing these works of the Upper Rhone. In ridding itself as rapidly as possible of the water and the gravel, the population of the valley is working for its own advantage, without having to concern itself much about what will take place below, since the lake is there, and will not soon be filled. But the misfortune is that the same thing is being done in valleys opening, not into a large reservoir, but into fertile plains. We must, therefore, offer a few remarks on this subject.

We have seen (Figs. 90, 91, and 92) that when torrents reach the alluvial beds of wide valleys, they tend gradually to take a more winding course, uniting in a single trunk; and that between these windings there remain marshes—low parts—in which the swollen waters spread tranquilly until they can flow on slowly. Nature has arranged things thus, and she has acted wisely. Sometimes even intermediate reservoirs collected the superabundant waters of floods, and by slowly discharging them maintained an equal current in the plains during dry seasons.

Man was desirous of possessing these alluvial and level-bottomed vales, so well adapted for culture. He wished continually to increase the extent of the cultivated districts by draining these intermediate lakes, when their inconsiderable depth enabled him to do so. By this means he gained fresh arable

lands or good meadows. And as these marshes left by the subsiding waters, producing nothing but sedges, were of no use to him, he endeavoured to fill them up by inducing alluvial deposits over their surface, which the earth-laden floods furnished without expense.

But in times of flood the sinuosities of the current still inundated the raised land between the elbows. He therefore embanked the shores; but soon observed that his embankments had the effect of raising the bed of the main stream, and that the torrent sometimes overflowing the dikes flooded the land with greater violence in proportion as the bed and the dikes were more elevated; and that it then set to work to hollow out a new bed, quitting that which had been embanked with so much trouble. Then man resolved to rectify the course of the winding stream, i. e. to cut the bends by a channel. He thus obtained a more rapid flow, hindered the filling up of the bed by this very rapidity of the current, and secured a quicker escape for the water.

But then it happened that these waters reached their point of outflow too swiftly, and that, if they emptied themselves into a lake, they sensibly augmented their delta or terminal cone of dejection; if they emptied themselves on a plain, they suddenly discharged there a much greater volume of water.

This system, which, as we said just now, may have no other disadvantage when the stream issues into a lake than that of more rapidly filling it up, is productive of great danger when the stream spreads at the opening of valleys or plains; for in that case it discharges in a few hours, or even in a few minutes, the volume of water which it would have discharged

in the space of several days while the course was a sinuous one with superposed levels.

But this is not all. In its course, a main torrent, like the Rhone above the Lake of Geneva, receives numerous affluents descending from the lateral valleys. All these currents, having a rapid fall, form, at their outflow into the wide valley, a cone of dejection produced by the materials and boulders which they have driven thus far in virtue of their incline, but which they deposit in the main bed. These cones, chiefly consisting of gravel and pebbles, are barren, and the streams which form them spread capriciously over their surface, continually changing their bed, and consequently their point of influx into the main torrent, and leave marshes above, retained by the conical projection.

These natural barriers again tend to retard the general flow, and even to form small new intermediate lakes exactly in proportion as the older lakes are filled up.

This did not suit the convenience of the inhabitants of the valleys, who some fine morning would find a vast pool in the place occupied by their field the evening before.

They therefore determined to rid themselves quickly of the waters whose behaviour towards them was so capricious, and to control their course definitely. From the outlet of the torrent into the valley, therefore, they made a straight channel on the cone itself, abutting at right angles on the main current (Fig. 112). Let A B represent the main current; a torrent D C, issuing at C into the valley, has deposited the great cone marked by the dotted curves, and on this cone has spread in several

branches, falling as rivulets into the main stream. From the point C, at its outlets, it was continually depositing gravel and pebbles, and this accumulation had forced the torrent A B to hug the steep bank E. Desiring to appropriate the cone

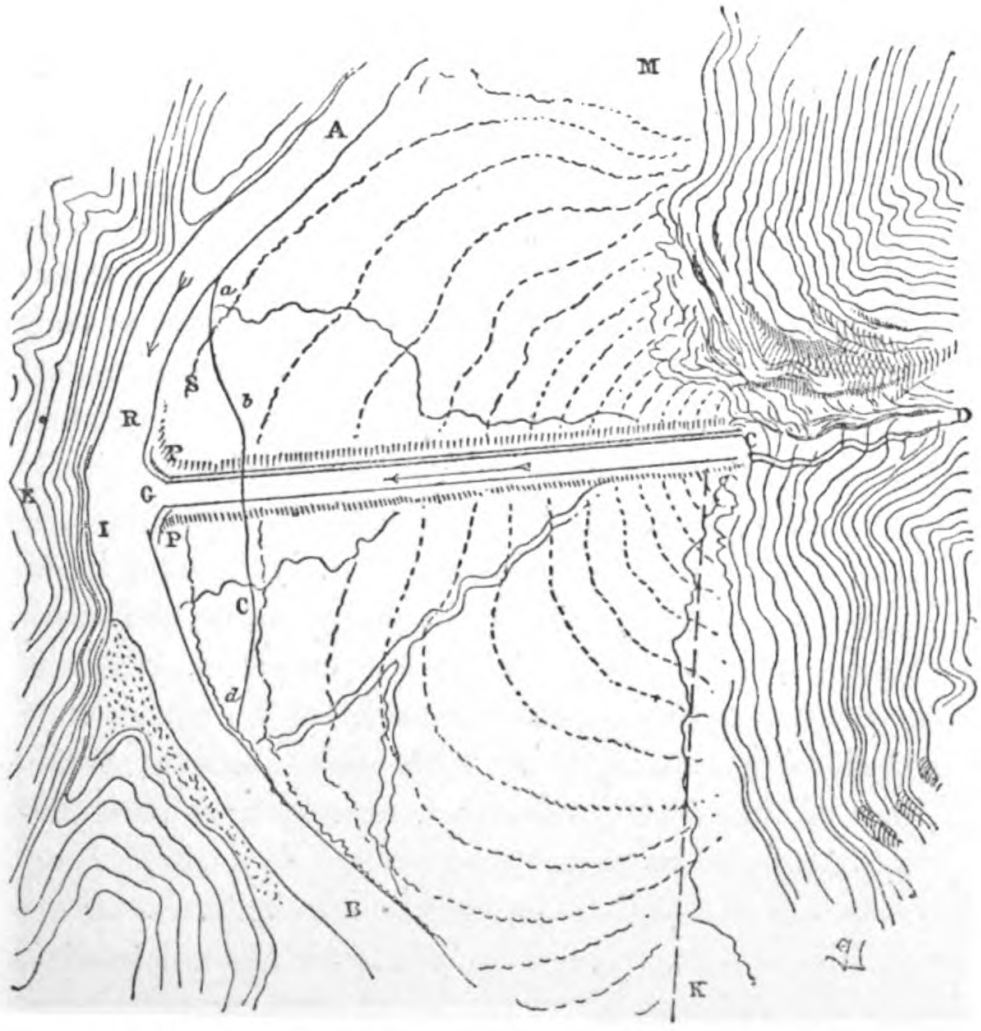


Fig. 112.—Alteration of torrent courses on the cones of dejection.

of dejection and to get rid of the marsh M, caused by the drift of the cone, they made the direct channel C G down the incline of the cone, terminating at G in the main torrent.

In times of flood, the torrent D C rushes in with

violence at G, bars the torrent A B, and causes a reflux of its waters upwards. But at the same time the torrent D C carries down with it in its channel all the débris which it formerly spread over the surface of the cone. In consequence of the liquid obstruction produced at G, and the eddying upwards, the gravel and pebbles are deposited partly at R, and encumber the bed. The upstream flood, however, which can no longer discharge itself, destroys the bank at S, carries away the channel heads P, and produces a sudden heaping up from R to I; the result of which is that after the flood the main current follows the course *a*, *b*, *c*, *d*, continually carrying away the base of the cone, encumbering the principal bed with materials, and often causing below such disturbances that, in a few hours, more ground is lost than had been gained by a year's work, and a considerable outlay.

All endeavours to regulate a main stream in a valley should tend, not to the doing away with the windings, and straightening the currents, but, on the contrary, to the encouragement of the turns, and lengthening the inclines, with the adoption sometimes of direct channels, or wears, with sluices, for the purpose of causing the gravel to be deposited on the points where it tends to raise the beds.

While in a narrow valley it is desirable not to disturb the natural distribution of streams of minor importance, this is still more imperative in the case of a wide river receiving numerous and considerable affluents, and flowing through a plain.

The devastations resulting from such disturbances are then of terrific extent, as we witnessed during the late inundations of the Garonne.

In the valley of the Rhone, above the Lake of

Geneva, the procedure indicated in Fig. 112 has for some time been adopted; and those lateral torrents have to cross over the entire width of the valley to discharge themselves into the river, since they have produced cones of dejection that have pushed the bed of the river against the opposite slope. In these transverse channels the waters rush with violence, and necessarily carry with them into the main bed the materials which they had been depositing on their cone of dejection.

Already the fact to which we here call attention has occurred in several places; ends of channels have been carried away. The remedy is therefore here worse than the evil. It is indeed rather in the direction C K, or even, when the levels allow it, in the direction C A, that these channels should be made; that is in the direction which the torrents, left to themselves, most frequently take over the cones of dejection which have acquired a great extension at the base.

But even this plan does not permit the deposit of the gravel before the discharge into the main torrent. We must therefore resolve prudently to adopt the measures employed by Nature, viz. relays or reservoirs; and the ground thus lost will be largely compensated for by the indefinite adjournment of disasters.

Reservoirs in steps at successive heights are the only means for preventing the destructive effects of floods, for regulating the streams, and supplying the plains during the dry seasons. If, when Nature is left to herself, she gradually fills up those she had formed, she is incessantly forming fresh ones; but here man interferes and prevents the work. He is

the first to suffer from his ignorance and cupidity; and what he considers his right to the possession of the soil is too often the cause of injury to his neighbours and to himself.

Civilized nations are aware that in the towns they build it is necessary to institute sanitary regulations, that is, regulations for the public welfare, which are a restriction imposed on the absolute rights of property. These civilized nations have also established analogous regulations respecting highways, the water-courses in the plains, the chase and fishing; but they have scarcely troubled themselves about mountain districts, which are the sources of all the wealth of the country; for where there are no mountains there are no rivers, consequently no cultivated lands; nothing but *steppes*, furnishing, at best, pasturage for a few cattle distributed over immense areas.

On the pretext that mountain regions are difficult of access, those among us who are entrusted by destiny, ambition, or ability, with the management of the national interests, find it easier to concern themselves with the plains than with the heights.

We allow that in those elevated solitudes Nature is inclement, and is stronger than we are; but it so happens that an inconsiderable number of shepherds and poor ignorant mountaineers are free to do in those altitudes what their immediate interests suggest to them. What do those good people care about that which happens in the plains? They have timber for which the saw-mill is ready, and they fell it where the transport to that saw-mill is least laborious. Is not the incline of the couloir formed expressly for sliding the trunks directly to the mill?

They have water in too great abundance, and they get rid of it as fast as they can. They have young fir-plants, of which the goats are fond, and to make a cheese which they sell for fifty centimes they destroy a hundred francs' worth of timber, thereby exposing the slopes to be denuded of soil, and their own fields to be destroyed. They have infertile marshes, and they drain them by digging a ditch requiring two days' work. These marshes were filled with accumulations of peat, which, like a sponge, retained a considerable quantity of water at the time of the melting of the snows. They dry up the turf for fuel, and the rock, being denuded, sends in a few minutes into the torrents the water which that turf held in reserve for several weeks.

Now and then an observer raises a cry of alarm and calls attention to the reckless waste of territorial wealth.

Who listens to what he says? Who reads what he writes?

Rigorously faithful to her laws, Nature does not carry up again the pebble which a traveller's foot has rolled down the slope—does not replant the forest which your thoughtless hands have cut down, when the naked rock appears, and the soil has been carried away by the melted snows and the rains—does not restore the meadow to the disappearance of whose soil our want of precaution has contributed. Far from comprehending the marvellous logic of these laws, you contravene their beneficent control, or at least impede their action. So much the worse for you, poor mortal!

Do not, however, complain if your lowlands are devastated, and your habitations swept away; and do

not vainly impute these disasters to a vengeance or a warning on the part of Providence. For these disasters are mainly owing to your ignorance, your prejudices, and your cupidity.

If these pages should help to awaken the attention of the public to questions, which are far more important than most of those which engage its interest—if they should encourage among engineers an attentive and practical study of the regulation of mountain streams—if they should convince those who are capable of making the necessary arrangements that it is not at their desks, but on the ground that we must endeavour to resolve these problems—we shall consider ourselves amply compensated for our labours, difficulties, and sacrifices.

But in any case we are assured of always finding, in the observation of the grand phenomena of Nature, the most complete and certain of rewards, for Nature has infinite enjoyments in store for those who investigate her laws.

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