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Studies in the Sierra. No. IV.-Glacial Denudation.

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GLACIAL denudation is one of the noblest and simplest manifestations of sun-power. Ocean water is lifted in vapor, crystallized into snow, and sown broadcast upon the mountains. Thaw and frost, combined with the pressure of its own weight, change it to ice, which, although in appearance about as hard and inflexible as glass, immediately begins to flow back toward the sea whence it came, and at a rate of motion about equal to that of the hour-hand of a watch.

This arrangement is illustrated in Fig. 1, wherein a wheel, constructed of water, vapor, snow, and ice, and as irregular in shape as in motion, is being sun-whirled against a mountainside with a mechanical wearing action like that of an ordinary grindstone.

In north Greenland, Nova Zembla, the arctic regions of Southeastern Alaska and Norway, the snow supply and general climatic conditions are such that their glaciers discharge di-
directly into the sea, and so perhaps did all first-class glaciers when in their prime; but now the world is so warm, and the snow-crop so scanty, most glaciers melt long before reaching the ocean. Schlagenweit tells us those of Switzerland melt on the average at an elevation of about 7,400 feet above sea-level; the Himalaya glacier, in which the Ganges takes its rise, does not descend below 12,914 feet;* while those of our Sierra melt at an average elevation of about 11,000 feet. In its progress down a mountain-side a glacier follows the directions of greatest declivity, a law subject to very important modifications in its general application. Subordinate ranges many hundred feet in height are frequently overswept smoothly and gracefully without any visible manifestations of power. Thus, the Tenaya outlet of the ancient Tuolumne mer de glace glided over the Merced divide, which is more than 500 feet high, impelled by the force of that portion of the glacier which was descending the higher slopes of Mounts Dana, Gibbs, and others, at a distance of ten miles.

The deeper and broader the glacier, the greater the horizontal distance over which the impelling force may be transmitted. No matter how much the courses of glaciers are obstructed by inequalities of surface, such as ridges and canons, if they are deep enough and wide enough, and the general declivity be sufficient, they will flow smoothly over them all just as calm water-streams flow over the stones and wrinkles of their channels.

PRESENT CONDITION OF THE SIERRA CONSIDERED WITH REFERENCE TO GLACIAL ACTION

The most obvious glacial phenomena presented in the Sierra are: first, polished, striated, scratched, and grooved surfaces, produced by the glaciers slipping over and past the rocks in their pathways. Secondly, moraines, or accumulations of mud, dust, sand, gravel, and blocks of various dimensions, deposited by the glaciers in their progress, in certain specific methods. Thirdly, sculpture in general, as seen in canons, lake-basins, hills, ridges, and separate rocks, whose forms, trends, distribution, etc., are the peculiar offspring of glaciers.

* According to Captain Hodgson.
In order that my readers may have clear conceptions of the distribution and comparative abundance of the above phenomena, I will give here a section of the west flank from summit to base between the Tuolumne and Merced rivers, which, though only a rough approximation, is sufficiently accurate for our purposes. The summit region from D to C (Fig. 2) is composed of metamorphic slates, so also is most of the lower region, B to A. The middle region is granite, with the exception of a few small slate-cappings upon summits of the Merced and Hoffmann spurs. With regard to the general topography of the section, which may be taken as fairly characteristic of the greater portion of the range, the summit forms are sharp and angular, because they have been down-flowed; all the middle and lower regions comprising the bulk of the range have rounded forms, because they have been overflowed. In the summit region all the glacial phenomena mentioned above are found in a fresh condition, simply on account of their youthfulness and the strong, indestructible character of the granite. Scores of small glaciers still exist on the summit peaks where we can watch their actions. But the middle region is the most interesting, because, though older, it contains all the phenomena, on a far grander scale, on account of the superior physical structure of granite for the reception of enduring glacial history.

Notwithstanding the grandeur of the canions and moraines of this region, with their glorious adornments, stretching in sublime simplicity delicately compliant to glacial law, and the endless variety of picturesque rocks rising in beautiful groups out of the dark forests, by far the most striking of all the ice phenomena presented to the ordinary observer are the polished surfaces, the beauty and mechanical excellence of which no words will describe. They occur in large irregular patches many acres in extent in the summit and upper half of the middle regions, bright and stainless as the un trodden sky. They reflect the sunbeams like glass, and though they have been subjected to the corroding influences of the storms of countless thousands of years, to frosts, rains, dews, yet are they in many places unblurred, undimmed, as if finished but yesterday. The attention of the mountaineer is seldom arrested by moraines however conspicuously regular and artificial in form, or by canions however deep, or rocks however noble, but he stoops and rubs his hand admiringly on these shining surfaces, and tries hard to account for their mysterious smoothness. He has beheld the summit snows descending in booming avalanches, but he concludes that these cannot be the work of snow, because he finds it far beyond the reach of avalanches; neither can water be the agent, he says, for he finds it on the tops of the loftiest domes. Only the winds seem capable of following and flowing in the paths indicated by the scratches and grooves, and some observers have actually ascribed the phenomenon to this cause. Even horses and dogs gaze wonderingly at the strange brightness of the ground, and smell it, and place their feet upon it cautiously; only the wild mountain sheep seems to move wholly at ease upon these glistening pavements.

This polish is produced by glaciers slipping with enormous pressure over hard, close-grained slates or granite. The fine striations, so small as to be scarcely visible, are evidently caused by grains of sand imbedded in the bottom of the ice; the scratches and smaller grooves, by stones with sharp graving edges. Scratches are therefore most abundant and roughest in the region of metamorphic slates, which break up by the force of the overflowing currents into blocks with hard cutting angles, and gradually disappear where these graving tools have been pushed so far as to have had their edges worn off.

The most extensive areas of polished surfaces are found in the upper half of the middle region, where the granite is most solid in structure and contains the greatest quantity of silex. They are always brighter, and extend farther down from the axis of the range, on the north sides of canions that trend in a westerly direction than on the south sides; because, when wetted by corroding rains and snows, they are sooner dried, the north sides receiving sunshine, while the south walls are mostly in shadow and remain longer wet, and of course their gla-
associated surfaces become corroded sooner. The lowest patches are found at elevations of from 3000 to 5000 feet above the sea, and thirty to forty miles below the summits, on the sunniest and most enduring portions of vertical walls, protected from the drip and friction of water and snow by the form of the walls above them, and on hard swelling bosses on the bottom of wide cañons, protected and kept dry by broad boulders with overhanging eaves.

MORAINES

In the summit region we may watch the process of the formation of moraines of every kind among the small glaciers still lingering there. The material of which they are composed has been so recently quarried from the adjacent mountains that they are still plantless, and have a raw, unsettled appearance, as if newly dumped, like the stone and gravel of railroad embankments. The moraines belonging to the ancient glaciers are covered with forests, and extend with a greater or less degree of regularity down across the middle zone, as we have seen in Study No. III. Glacial rock forms occur throughout this region also, in marvelous richness, variety, and magnitude, composing all that is most special in Sierra scenery. So also do cañons, ridges and sculpture phenomena in general, descriptions of whose scenic beauties and separate points of scientific interest would require volumes. In the lower regions the polished surfaces, as far as my observations have reached, are wholly wanting. So also are moraines, though the material which once composed them is found scattered, washed, crumbled, and reformed, over and over again, along river-sides and over every flat, and filled-up lake-basin, but so changed in position, form of deposit, and mechanical condition, that unless we begin with the undisturbed moraines of the summit region and trace them carefully to where they become more and more obscure, we would be inclined to question the glacial character of these ancient deposits.

The cañons themselves, the valleys, ridges, and the large rock masses are the most unalterable and indestructible glacial phenomena under consideration, for their general forms, trends, and geographical position are specifically glacial. Yet even these are so considerably obscured by post-glacial erosion, and by a growth of forests, underbrush, and weeds, that only the patient and educated eye will be able to recognize them beneath so many veils.

The ice-sheet of the glacial period, like an immense sponge, wiped the Sierra bare of all pre-glacial surface inscriptions, and wrote its own history upon the ample page. We may read the letter-pages of friends when written over and over, if we are intimately acquainted with their handwriting, and under the same conditions we may read Nature's writings on the stone pages of the mountains. Glacial history upon the summit of the Sierra page is clear, and the farther we descend, the more we find its inscriptions crossed and recrossed with the records of other agents. Dews have dimmed it, torrents have scrawled it here and there, and the earthquake and avalanche have covered and erased many a delicate line. Groves and meadows, forests and fields, darken and confuse its more enduring characters along the bottom, until only the laborious student can decipher even the most emphasized passages of the original manuscript.

METHODS OF GLACIAL DENUDATION

All geologists recognize the fact that glaciers wear away the rocks over which they move, but great vagueness prevails as to the size of the fragments, their abundance, and the way in which the glacial energy expends itself in detaching and carrying them away. And, if possible, still greater vagueness prevails as to the forms of the rocks and valleys resulting from erosion. This is not to be wondered at when we consider how recently glacial history has been studied, and how profound the silence and darkness under which glaciers prosecute their works.

In this article I can do little more for my readers than indicate methods of study, and results which may be obtained by those who desire to study the phenomena for themselves. In the first place, we may go to the glaciers themselves and learn what we can of their weight, motions, and general activities*—

*Here I would refer my readers to the excellent elementary works of Agassiz, Tyndall and Forbes.
how they detach, transport, and accumulate rocks from various sources. Secondly, we may follow in the tracks of the ancient glaciers, and study their denuding power from the forms of their channels, and from the fragments composing the moraines, and the condition of the surfaces from which they were derived, and whether these fragments were rubbed off, split off, or broken off.

The waters which rush out from beneath all glaciers are turbid, and if we follow them to their resting-places in pools we shall find them depositing fine mud, which, when rubbed between the thumb and finger, is smooth as flour. This mud is ground off from the bed of the glacier by a smooth, slipping motion accompanied with immense pressure, giving rise to the polished surfaces we have already noticed. These mud particles are the smallest chips which glaciers make in the degradation of mountains.

Toward the end of the summer, when the winter snows are melted, particles of dust and sand are seen scattered over the surfaces of the Sierra glaciers in considerable quantities, together with angular masses of rock derived from the shattered storm-beaten cliffs that tower above their heads. The separation of these masses, which vary greatly in size, is due only in part to the action of the glacier, although they all are borne down like drift on the surface of a river and deposited together in moraines. The winds scatter down most of the sand and dust. Some of the larger fragments are set free by the action of frost, rains, and general weathering agencies; while considerable quantities are borne down in avalanches of snow, and hurled down by the shocks of earthquakes. Yet the glacier performs an important part in the production of these superficial effects, by undermining the cliffs whence the fragments fall. During my Sierra explorations in the summers of 1872 and 1873, almost every glacier I visited offered illustrations of the special action of earthquakes in this connection, the earthquake of March, 1872, having just finished shaking the region with considerable violence, leaving the rocks which it hurled upon the ice fresh and nearly unchanged in position.

But in all moraines we find stones, which, from their shape and composition, and the finish of their surfaces, we know were not thus derived from the summit peaks overtopping the glaciers, but from the rocks past which and over which they flowed. I have seen the north Mount Ritter Glacier and many of the glaciers of Alaska in the act of grinding the side of their channels, and breaking off fragments and rounding their angles by crushing and rolling them between the wall and ice. In all the pathways of the ancient glaciers, also, there remain noble illustrations of the power of ice, not only in wearing away the sides of their channels in the form of mud, but in breaking them up into huge blocks. Explorers into the upper portion of the middle granite region will frequently come upon blocks of great size and regularity of form, possessing some character of color or composition which enables them to follow back on their trail and discover the rock or mountain-side from which they were torn. The size of the blocks, their abundance along the line of dispersal, and the probable rate of motion of the glacier which quarried and transported them, form data by which some approximation to the rate of this sort of denudation may be
reached. Fig. 3 is a rock about two miles west of Lake Tenaya, with a train of boulders derived from it. The boulders are scattered along a level ridge, where they have not been disturbed in any appreciable degree since they came to rest toward the close of the glacial period. An examination of the rock proves conclusively that not only were these blocks—many of which are twelve feet in diameter—derived from it, but that they were torn off its side by the direct mechanical action of the glacier that swept over and past it. For had they simply fallen upon the surface of the glacier from above, then the rock would present a crumbling, ruinous condition—which it does not—and a talus of similar blocks would have accumulated at its base after there was no glacier to remove them as they fell; but no such talus exists, the rock remaining compact, as if it had scarcely felt the touch of a single storm. Yet, what countless seasons of weathering, combined with earthquake violence, could not accomplish, was done by the Tenaya Glacier, as it swept past on its way to Yosemite.

A still more striking and instructive example of side-rock erosion may be found about a mile north of Lake Tenaya. Here the glaciated pavements are more perfectly preserved than elsewhere in the Merced basin. Upon them I found a train of granite blocks, which attracted my attention from their isolated position, and the uniformity of their mechanical characters. Their angles were unworn, indicating that their source could not be far off. It proved to be on the side of one of the lofty elongated ridges stretching toward the Big Tuolumne Meadows. They had been quarried from the base of the ridge, which is ice-polished and undecayed to the summit. The reason that only this particular portion of the ridge afforded blocks of this kind, and so abundantly as to be readily traceable, is that the cleavage planes here separated the rock into parallelepipsds which sloped forward obliquely into the side of the glacier, which was thus enabled to grasp them and strip them off, just as the spikelets of an ear of wheat are stripped off by running the fingers down from the top toward the base. An instance where the structure has an exactly opposite effect upon the erodibility of the side of a rock is given in Fig. 4, where the cleavage planes separate it into slabs which overlap each other with reference to the direction of the glacier's motion, like the shingles of a roof. Portions of the sides of rocks or cañon walls whose structure is of the latter character always project, because of the greater resistance they have been able to offer to the action of the past-flowing glacier, while those portions whose structure is similar to that of the former example always recede.

Fig. 5 is a profile view of a past-flowed glacier rock, about 1500 feet high, forming part of the north wall of Little Yosemite Valley near the head. Its grooved, polished, and fractured surface bears witness in unmistakable terms to the enormous pressure it has sustained from that portion of the great South Lyell Glacier which forced its way down through the valley, and to the quantity, and size, and kind of fragments which have been removed from it as a necessary result of this action. The dotted lines give an approximate reconstruction of the rock as far as to the outside layer at A. Between A and B the broken ends of concentric layers, of which the whole rock seems to be built, give some idea of the immense size of
some of the chips. The reason for the greater steepness of the front from A to B than from B to C will be perceived at a glance; and, since the cleavage planes and other controlling elements in its structure are evidently the same throughout the greater portion of its mass as those which determined its present condition, if the glacial winter had continued longer its more characteristic features would probably have remained essentially the same until the rock was nearly destroyed.

The section given in Fig. 6 is also taken from the north side of the same valley. It is inclined at an angle of about twenty-two degrees, and therefore has been more flowed over than flowed past. The whole surface, excepting the vertical portion at A, which is forty feet high, is polished and striated. The arrows indicate the direction of the striae. At A a few incipient cleavage planes are beginning to appear, which show the sizes of some of the chips which the glacier would have broken or split off had it continued longer at work. The whole of the missing layer which covered the rock at B, was evidently detached and carried off in this way. The abrupt transition from the polished surface to the split angular front at A shows in a most unequivocal manner that glaciers erode rocks in at least two very different modes—first, by grinding them into mud; second, by breaking and splitting them into blocks, whose sizes are measured by the divisional planes they possess and the intensity and direction of application of the force brought to bear upon them. That these methods prevail in the denudation of overflowed as well as past-flowed rocks, is shown by the condition of every cañon of the region. For if mud particles only were detached, then all the bottoms would be smooth grooves, interrupted only by flowing undulations; but, instead of this condition, we find that every cañon bottom abounds in steps sheer-fronted and angular, and some of them hundreds of feet in height, though ordinarily from one to ten or twelve feet. These step-fronts in most cases measure the size of the chips of erosion as to depth. Many of these interesting ice-chips may be seen in their tracks removed to great distances or only a few feet, when the melting of the glaciers at the close of the period put a stop to their farther progress, leaving them as lessons of the simplest kind.

Fig. 7, taken from the Hoffmann fork of Yosemite Creek basin, shows the character of some of these steps. This one is fifteen feet high at the highest place, and the surface, both at top and bottom, is ice-polished, indicating that no disturbing force has interfered with the phenomena since the termination of the glacial period.

Fig. 8 is a dome on the upper San Joaquin, the top of which is about 7700 feet above sea-level. The arrow indicates the direction of application of the ice-force, which is seen to coincide with the position of remaining fragments of layers, the complements of which have been eroded away. Similar fragments occur on the stricken side of all domes whose structure and position were favorable for their formation and preservation.

Fig. 9 is a fragmentary dome situated on the south side of the Mono trail, near the base of Mount Hoffmann. Remnants of concentric shells of granite from five to ten feet thick are seen on the up-stream side at A, where it received the thrust of the Hoffmann Glacier, when on its way to join the Tenaya, above Mirror Lake. The edges of unremoved layers are visible at B and C. This rock is an admirable illustra-
tion of the manner in which a broad deep glacier clasps and denudes a dome. When we narrowly inspect it, and trace the striae, we perceive that it has been eroded at once in front, back and sides, and none of the fragments thus removed are to be found around its base. Here I would direct special attention to the fact that it is on the upper side of this rock at A, just where the pressure was greatest, that the erosion has been least, because there the layers were pressed against one another, instead of away from one another, as on the sides and back, and could not, therefore, be so easily broken up.

**QUANTITY OF GLACIAL DENUDATION**

These simple observations we have been making plainly indicate that the Sierra, from summit to base, was covered by a sheet of crawling ice, as it is now covered by the atmosphere. Its crushing currents slid over the highest domes, as well as along the deepest canyons, wearing, breaking, and degrading every portion of the surface, however resisting. The question, therefore, arises, What is the quantity of this degradation? As far as its limit is concerned it is clear that, inasmuch as glaciers cannot move without in some way and at some rate lowering the surfaces they are in contact with, a mountain range may be denuded until the declivity becomes so slight that the glaciers come to rest, or are melted, as was the case with those concerned in the degradation of the Sierra. However slow the rate of wear, given a sufficient length of time, and any thickness of rock, whether a foot or hundreds of thousands of feet, will be removed. No student pretends to give an arithmetical expression to the glacial epoch, though it is universally admitted that it extended through thousands or millions of years. Nevertheless, geologists are found who can neither give Nature time enough for her larger operations, or for the erosion of a mere cañon furrow, without resorting to sensational cataclysms for an explanation of the phenomena.

If the Sierra were built of one kind of rock, homogeneous in structure throughout its sections, then perhaps we would be unable to produce any plain evidence relative to the amount of denudation effected; but, fortunately for the geologist, this is not the case. The summits of the range in the section under special consideration are capped with slates; so are several peaks of outlying spurs, as those of the Merced and Hoffmann, and all the base is slate-covered. The circumstances connected with their occurrence in these localities and absence in others, furnish proof little short of demonstration that they once covered all the range, and, from their known thickness in the places where they occur, we may approximate to the quantity removed where they are less abundant or wanting. Moreover, we have seen in Study No. III that the physical structure of granite is such that we may know whether or not its forms are broken. The opposite sides of valley walls exhibiting similar fragmentary sections often demonstrate that the valleys were formed by the removal of an amount of rock equal in depth to that of the valleys.

Fig. 10 is an ideal section across the range from base to summit. That slates covered the whole granitic region between B and D is shown by the fact that slates cap the summits of spurs in the denuded gap where they are sufficiently high, as at C. Also,
where the granite comes in contact with the slates, and for a considerable depth beneath the line of contact, it partakes, in a greater or less degree, of the physical structure of slates, enabling us to determine the fact that in many places slates have covered the granite where none are now visible for miles, and also furnishing data by which to approximate the depth at which these surfaces lie beneath the original summit of the granite. Phenomena relating to this portion of the argument abound in the upper basins of the tributary streams of the Tuolumne and Merced; for their presentation, however, in detail, we have no space in these brief outlines.

If, therefore, we would restore this section of the range to its unglaciated condition, we would have, first, to fill up all the valleys and canyons. Secondly, all the granite domes and peaks would have to be buried until the surface reached the level of the line of contact with the slates. Thirdly, in the yet grander restoration of the missing portions of both granite and slates up the line between the summit slates and those of the base, as indicated in Fig. 10 by the dotted line, the maximum thickness of the restored rocks in the middle region would not be less than a mile and a half, and average a mile. But, because the summit peaks are only sharp residual fragments, and the foothills rounded residual fragments, when all the intervening region is restored up to the dotted line in the figure, we still have only partially reconstructed the range, for the summits may have towered many thousands of feet above their present heights. And when we consider that residual glaciers are still engaged in lowering the summits which are already worn to mere blades and pinnacles, it will not seem improbable that the whole quantity of glacial denudation in the middle region of the western flank of the Sierra considerably exceeds a mile in average depth. So great was the amount of chipping required to bring out the present architecture of the Sierra. — Ed.}

Reprinted from the Overland Monthly of August, 1874. This is the fourth of a series of seven studies in which Mr. Muir developed his theories of the geology of the Sierra.—Ed.