John Muir Writings

Studies in the Sierra

by John Muir

JOHN MUIR'S

Studies in the Sierra

WITH AN INTRODUCTION BY WILLIAM E. COLBY
FOREWORD BY JOHN P. BUWALDA
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TO JOHN MUIR AND WILLIAM E. COLBY

No geologist today, nor chemist or physician, would venture to predict any "final" pronouncement about his science; the measure of John Muir's total contribution to geology must therefore remain somewhat obscure—less so, perhaps, for having been gathered together here in printed form. But in a broader sense his supremacy is, and always has been, unchallenged. It is as the great public servant, the pioneer in conservation, that the Sierra Club will best remember and honor him.

Second only to Muir in this great service, and dedicated to it with equal devotion, yet over a longer period of time, is William E. Colby. In the wish to record some measure of appreciation of his half century of devotion, the Sierra Club can find no better expression than in the publication of a book which links the names of its two best-loved members.

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[Forward to Foreword]

Foreword

One is somewhat astounded, on each re-reading of parts of Muir's works, at the remarkable knowledge which he had acquired, mainly through his own observations, of glacial processes and their physiographic effects. Muir studied the Sierra canyons, cirques, and peaks at a time when knowledge regarding the principles of glacial erosion was not wide-spread. Geology, in contrast to such sciences as Physics, Chemistry and Astronomy, is a very young branch of learning; more than half of what we know in the geological sciences has been discovered and acquired in the last 75 years. Muir was conversant with the glaciology of his day, as discussed in geologic texts and other geologic literature, but much that he wrote about was not treated in textbooks but related primarily and uniquely to the Sierra and was derived directly from his own extensive and long-continued field studies. His contribution to glacial erosion the more singular when one realizes that little attention had been give to alpine glaciation in western America by other geologists at the time when he worked in the Sierra and he therefore received little stimulus or inspiration from other students of the same natural phenomena. How far he was ahead of his time is perhaps suggested by the fact that it was nearly a half century before another study comparable in scope of the nature of glacial erosion in the Sierra and its effects was undertaken.

Muir recognized very clearly the evidences of ice work in the Sierra and was able to differentiate those areas which had undergone glacial erosion from those which had not been covered. He thereby developed not only a very broad knowledge of the former extent of the ice over the range but also of the paths which it followed in moving from the high areas of accumulation to the lower levels of ablation. He understood fully, for instance, that the ice stream which came down through Tuolumne Meadows bifurcated, and that one branch rose over the 500-foot divide to glide down through what is now the basin of Lake Tenaya and down Tenaya Canyon to join the Merced Glacier, which was fed mainly from an entirely different drainage basin.

By careful observation, inference, and induction Muir reached the important conclusion that the nature of the joint structure in the Sierra granite largely determined the character of the physiographic features modeled by the ice. This seemed a simple idea after it was announced and fully demonstrated, but that is true for many of the most important generalizations of science: ideas that require years and fortunes to discover or demonstrate can be conveyed to later students in a few moments. Muir showed how curved jointing produced the domes found from the Merced to the Kings, and how plane vertical jointing is responsible for the cleaving off of the northern portion of Half Dome. He well said that "the grain of a rock determines its surface forms" under ice attack.

He also demonstrated beautifully that "all the Yosemites in the Sierra occur at the confluence of two or more glacial canyons" and that the greater the number of confluents and their magnitudes and the steeper their gradients the deeper and wider is the Yosemite below their confluence.

Muir also recognized very fully the insignificance of postglacial erosion, and cites in very logical fashion the very sound evidence on which his conclusion was reached. He found the present rock surfaces or hill slopes very little below the surfaces which he could prove had been cut by the ice. He stated that in the high country the postglacial degradation probably did not average more than 3 inches, and in the middle altitudes not more than a foot. While opinions might differ now concerning such exact figures, glacialists would agree that they are of the right order. Muir of course did not know that postglacial time has been only about 15,000 years.

Even though he overestimated the extent of the ice in the Sierra and the total excavation accomplished by it, he was among the first to realize its huge volume and the sculpturing wrought by it. He believed the ice covered the Sierra from summit to base, but we now know that the western half of the range was scarcely reached by it. But his urging its widespread distribution over the mountains was a valuable contribution. His idea that the ice had removed all of the upper part of the granite batholiths, from the slate roof down to the present land surface, a thickness he estimated at a mile, was likewise too large quantitatively, but his writings opened men's minds with regard to the huge volumes of rock that were removed.

Muir was not aware of multiple glaciation—that the Ice Age consisted of four advances and disappearances of the ice—but he may have recognized some of the evidence for it, for he remarks that the glaciers apparently contracted and expanded constantly and that the moraines differ greatly in their nature and their materials.

Although it was not realized by geologists when Muir wrote about the Sierra glaciers that ice is not a rigid solid but more like a very viscous fluid, and that hence it cannot be pushed uphill for any considerable distance, he contributed very important information and ideas regarding Sierra history and glacier mechanics in demonstrating at numerous localities that the ice had risen up over divides hundreds of feet high. We now know that the motive power for such uphill ice movements resides in a overall downhill slope of the upper surface of the ice upstream from the obstacle or ridge.

Muir's essays regarding glacial sculpture in the Sierra are remarkable both in their scientific reasoning and in their literary style. In the early stages of a science, or in the early stages of the study of a natural phenomenon, the investigational methods are usually largely descriptive and the inferences or conclusions drawn from the limited data are commonly at least partly speculative and not the result of rigorous analysis. Muir's habit of making careful and rather complete observations of such phenomena as jointing in the granite and then reasoning rigorously to a conclusion about its effect on the physiographic forms produced under glacier sculpture was one of the early examples in geology of the use of the inductive method which, stated formally in American scientific literature several decades later by Grove Karl Gilbert, T. C. Chamberlin, William Morris Davis, and others, has become the normal and conscious procedure in scientific research.

The style of Muir's writing was equally unique. It combined scientific precision of expression and rationality of treatment with a grace of statement which afforded much pleasure to the reader. He chose just the right words for each idea, and when the English language did not quite suffice for his purposes he invented such quaint but expressive terms as peaklets, mountainets, and "past flowed rock," meaning a rock past which the glacier had moved. His writings are marked by that simplicity and clarity which is characteristic of men who know a subject very thoroughly and whose minds comprehend the human meaning of the knowledge they have accumulated.

Muir was one of the small group of men of whom America has had far too few, who published scientific knowledge in fascinating but accurate form, not only for the enjoyment and information of the public, but a an inspiration to young men and women who through innate interest might take up careers in more intensive research on problems of Nature to which he had given them such stimulating introductions.

John P. Buwalda

California Institute of Technology
August 18, 1947

Preface

John Muir's "Studies in the Sierra," here brought together for the first time in one volume, originally appeared in 1874 and 1875 as a series of seven articles in the *Overland Monthly,* which were later (1915 to 1921) reprinted in the *Sierra Club Bulletin*.

John Muir was the pioneer in recognizing the importance of glaciation in the origin of Yosemite Valley. He was just 30 years of age when, with his views, he challenged the opinions of eminent geologists who had already advanced other theories for the origin of the valley which completely ignored glaciation. It was not long before scientific men recognized the correctness of most of Muir's conclusions. The importance of glaciation in the formation of Yosemite Valley has since been generally recognized, though there still exist some differences of opinion about the relative amount of stream erosion and glacial erosion which has been involved.

The Sierra Club has reprinted these studies in a single volume with a view to making them more widely known and emphasizing, somewhat belatedly, the important contributions which John Muir made to the problem of the origin of Yosemite Valley. It was unfortunate for his fame that John Muir did not, immediately following the appearance of these articles in the *Overland Monthly,* do this himself. With the passing of years these studies have become increasingly unavailable and, on this account, have not been as widely read as they merit; nor has the full credit that was Muir's due always been given him.

The underlying facts which John Muir so painstakingly gathered and his cogent reasoning based on these observed facts are just as valuable and pertinent today as they were when these studies were first written. This volume will, therefore, prove of present interest to all those who wish to learn more about the origin of Yosemite Valley and its geologic features, as well as to those many who may wish to understand better the extraordinary, many-faceted figure of John Muir himself.

William E. Colby

Berkeley, California
September 25, 1949

John Muir in 1873
From a painting by William (Billy) Simms

Introduction

By William E. Colby

One of John Muir's greatest achievements, in a life filled with remarkable accomplishments, was his early recognition and announcement of the important part played by glaciation in the origin of Yosemite Valley. He first visited the valley in April, 1868, and returned in November, 1869, to live there for the next several years. By the following August he had definitely concluded that a great system of glaciers converging in the Yosemite was responsible for the creation of this mighty gorge with its superb cliffs and falls.

It is not strange that a youth with John Muir's inquiring and scientific mind1 and enthusiasm for the outdoors should have been drawn to the study of this creation problem. To see Yosemite Valley is to wonder how it was made. No one can view the vertical cliffs of El Capitan and Half Dome, with Yosemite and Bridalveil fall plunging out of the sky over other equally sheer walls, with Nevada and Vernal falls leaping down over gigantic steps of solid granite in the Merced River's stately descent to the valley and then wander over that broad expanse of parklike floor without speculating how this exceptional aggregation of impressive scenic features came into existence.

It is true that there have been visitors who were content to attribute this wonder spot of the world to an act of original creation by Providence and to urge that it came into existence "full panoplied," as it were, possessing from "the dawn of creation" all its wondrous glory, and who have insisted that it has remained unchanged to this day. John Muir delighted in telling a story of the occasion when in June of 1879 he was taking a horseback party, including Dr. Joseph Cook, a noted clergyman, up Clouds Rest. The conversation naturally turned to the origin of the scenic wonders spread out before them. Muir had expounded his theory of the part glaciers had played in molding the landscape, and Cook had countered with his view that the valley and its surroundings were not the product of any evolutionary growth, but came into being as they now are, "created out of the hand of God." He favored Whitney's theory, that the bottom of the valley had dropped out, because it fitted in with his own view of creation. The reverend gentleman, who was rather portly, had dismounted and was examining a piece of the glacier-polished granite pavement to which Muir had called his attention, when suddenly his iron-nailed shoes slipped on the glassy surface and he sat down on the solid rock with all his ponderous weight. He was rather dazed by the jolt. Muir rushed over to help him to his feet, but could not refrain from taking advantage of the situation by exclaiming, "Now, Doctor, you see the Good Lord has given you this most convincing proof of the mighty work the glaciers have wrought!"

Concerning the origin of Yosemite Valley much has been written and, in the early days of geologic study, various conflicting theories were advanced.2 Naturally the Sierra Club has, from its organization, been deeply interested in this question. Its first and foremost leader, John Muir, was a major contributor to the ultimate clarification of the problem,3 and to the formulation of modern concepts. The Sierra Club was instrumental in persuading the federal government to undertake, through its Geological Survey, the comprehensive study of the valley by the late François E. Matthes, which in 1930 resulted in publication of the monograph, *The Geologic History of the Yosemite Valley*.4 More recently, the influence of the Sierra Club led to preparation of a nontechnical volume, "The Incomparable Valley: A Geological Interpretation of the Yosemite," by François E. Matthes (in press).

Professor J. D. Whitney,5 California State Geologist (1860-1874), formulated and sponsored the first theory which received widespread acceptance. He and his staff started work in the fall of 1860 and by 1865 the State of California had published Volume I, "Geology," as a result of four years of field work. In this volume Whitney expounds his theory of the valley's origin (421-423). He stated that the conclusions there given were not only his own but those of his staff as well. He attributed the existence of most of the great valleys and canyons of California to stream erosion, but noted that the vertical walls of El Capitan and the other great cliffs of Yosemite cannot be satisfactorily explained in this manner.

He says:

> it appears to us probable that this mighty chasm has been roughly hewn into its present form by the same kind of forces which have raised the crest of the Sierra and moulded the surface of the mountains into something like their present shape. The domes, and such masses as that of Mount Broderick, we conceive to have been formed by the process of upheaval itself, for we can discover nothing about them which looks like the result of ordinary denudation. The Half Dome seems, beyond a doubt, to have been split asunder in the middle, the lost half having gone down in what may truly be said to have been "the wreck of matter and the crush of the worlds."

He added however, that "some of the corps" had objected that there were places in the bottom of the valley which seemed to be of solid granite, whereas, on the theory of engulfment, or dropping down of the great block of granite which originally occupied what is now the valley's void, "there should be an unfathomable chasm, filled now, of course, with fragments, and not occupied by a solid bed of rock." His reply to this was that some of

> the masses which have been engulfed may have been of such enormous size as to give the impression where they are only imperfectly exposed, of perfect continuity and connection with the adjacent cliffs. . . this grand cataclysm may have taken place at a time when the granitic mass was still in a semi-plastic condition below, although, perhaps, quite consolidated at the surface and for some distance down.

Pressure, he said, may have united the yielding material and destroyed all traces of fracture and added:

> If the bottom of the Yosemite did "drop out," to use a homely but expressive phrase, it was not all done in one piece, or with one movement, [but different sized segments] may hake descended to unequal depths.

It is of more than passing interest to note that he credited Clarence King and James T. Gardiner with obtaining

> ample evidence of the former existence of a glacier in the Yosemite Valley, and the canyons of all the streams entering it are also beautifully polished and grooved by glacial action. It does not appear, however, that the mass of ice ever filled the Yosemite to the upper edge of the cliffs; but Mr. King thinks it must have been at least a thousand feet thick.

He mentioned the various glacial moraines which King had traced out in considerable detail on the valley floor and stated that the large terminal moraine, occurring about a quarter of a mile below El Capitan, originally formed a complete barrier across the valley and that it was not unlikely that this may have acted as a dam, thus creating a lake

> now filled up with comminuted materials arising from the grinding of the glaciers above, thus giving it its present nearly level surface.

In other parts of this volume Whitney mentioned the evidence of the existence of great glaciers in Tuolumne Meadows and Canyon and in the Kern, Kings, and San Joaquin river valleys. Some of these glaciers he reported to have been over 1,000 feet and even as much as 1,500 feet thick. These data were largely supplied him by Clarence King, who seems to have been much more impressed by the magnitude of these ancient glaciers and their erosive power than was Whitney.6 Only a few years later Whitney, evidently nettled by criticisms of his fault theory and also by suggestions that glacial action was really responsible for the valley's formation, flatly and expressly denied that there was "ample evidence of the former existence of a glacier in the Yosemite Valley," and of glacial moraines which he had previously reported in considerable detail in his volume on the geology of California, as noted above.

In this later publication (1869) he said:

> Much less can it be supposed that the peculiar form of the Yosemite is due to the erosive action of ice. A more absurd theory was never advanced than that by which it was sought to ascribe to glaciers the sawing out of these vertical walls and the rounding of the domes. Nothing more unlike the real work of ice, as exhibited in the Alps, could be found. Besides, there is no reason to suppose, or at least no proof, that glaciers have ever occupied the Valley, or any portion of it. . . so that this theory, based on entire ignorance of the whole subject, may be dropped without wasting any more time upon it. [The Yosemite Guide-Book, p. 73.]

This is a most astounding repudiation of observable facts by an eminent scientist. The only rational explanation for this complete about-face was Whitney's intense pique that a geologist with his reputation should have been proved wrong on so important a matter as the valley's origin. Whitney's theory, when announced, had been quite generally accepted as providing a plausible and satisfactory explanation. To have it undermined must have been gall and wormwood to his proud nature, unduly sensitive to criticism as he was.

John Muir was mainly responsible for demonstrating Whitney's theory about the formation of Yosemite Valley was in error and untenable. Arriving in California in the early spring of 1868, he lost no time in visiting Yosemite Valley. He had read of its matchless qualities, and, attracted as if by a magnet, traveled on foot down through the Santa Clara Valley over Pacheco Pass, and crossed the San Joaquin Valley, which was still in its pristine glory, then a veritable sea of wildflowers from one side to the other. Several feet of snow still buried the trails leading into Yosemite Valley, but this did not deter Muir from continuing to his goal. He found the valley to be one of those widely heralded discoveries which really "come up to the brag," as Emerson expressed it when he visited the valley in later years. Fascinated by its majesty and incomparable grandeur, Muir decided then and there to spend much time in those breathtaking surroundings. Earning enough money in the foothills near Merced tending sheep and doing farm work, and accompanying a band of sheep into Tuolumne Meadows in the summer of 1869, he returned to the valley in November to spend the next several years.

Muir's scientific and searching turn of mind was powerfully attracted by the problem of determining the origin of such a remarkable manifestation of nature. His subsequent exploration led into every nook of the valley itself; and, finding that the evidence which was there written on the rocks pointed to the higher mountains, he started out on his memorable excursions into the High Sierra. These he has described with such understanding and enthusiasm that his writings have become literary classics. With infinite patience, on hands and knees where the evidence required close and painstaking observation, and with the aid of his magnifying glass and compass, he accumulated a mass of irrefutable facts concerning glacial action in the Yosemite Valley and the High Sierra.

It is questionable whether, on Muir's first hurried visit to the valley in 1868, when he only spent ten days there, he made many detailed observations. He had previously read Whitney's *Geology* and learned of his "bottom-dropping-out" theory. Fortunately, we have in Muir's own diary notes of his first studied observations on the subject.7 These notes were made in the summer of 1869 when he was employed to aid in taking a band of sheep ("hoofed locusts," as he later aptly described them because of their destructive effect on the mountain vegetation) from the Merced foothills up into the Tuolumne Meadows. His first glacial notation was made when they were encamped in July on Tamarack Creek. He at once recognized the large boulders there as glacial erratics resting on "ice-planed" granite "scored and striated in a rigidly parallel way." A few days later, when camped on Indian Creek just above Yosemite Valley, he mentioned "the shining glacier pavement. . . the great smooth domes. . . and brushy moraines." While sketching on North Dome, just above the valley, he remarked on "the ice-burnished pavements and ridges" and "glacier-polished domes." From the slopes of Mount Hoffmann he saw "the billowy glaciated fields of the upper Tuolumne" and looked down on Lake Tenaya,

> The largest of the many glacier lakes in sight [situated in an] ice-sculptured lake-basin [which] seems to have been slowly excavated by the ancient glaciers, a marvellous work requiring countless thousands of years. . . [Beyond the basin were] huge shining domes on the east, over the tops of which the grinding, wasting, molding glacier must have swept as the wind does today.

In August, while camped at the west end of Lake Tenaya, he

> took a walk on the glacier-polished pavements along the north shore, and climbed the magnificent mountain rock at the east end of the lake, now shining in the late afternoon light. Almost every yard of its surface shows the scoring and polishing action of a great glacier that enveloped it and swept heavily over its summit. . . This majestic, ancient ice flood came from the eastward, as the scoring and crushing of the surface shows. Even below the waters of the lake the rock in some places is still grooved and polished; the lapping of the waves and their disintegrating action have not as yet obliterated even the superficial marks of glaciation. In climbing the steepest polished places I had to take off shoes and stockings. A fine region this for study of glacial action in mountain-making.

He called attention to another

> knob. . . of burnished granite, perhaps a thousand feet high [which] probably owes its existence to the superior resistance it offered to the action of the overflowing ice-flood.

He was struck by the gap between Mount Hoffmann and Cathedral Peak,

> which seems to be one of the channels of a broad ancient glacier that came from the mountains on the summit of the range. In crossing this divide the ice-river made an ascent of about five hundred feet from the Tuolumne meadows. This entire region must have been overswept by ice.

Camped three miles east of Lake Tenaya he theorized that,

> Only in those cañons of the larger streams at the foot of declivities, where the down thrust of the glaciers was heaviest, do we find lakes of considerable size and depth.

The foregoing quotations are definite proof that in the summer of 1869, in the few brief days of his acquaintance with the Sierra, John Muir had already recognized the important part that ice had played in the sculpturing of the landscape.

Throughout this "profitable pilgrimage" he was striving in some way to "explain Yosemite grandeur. . . hopeful of some day knowing more, learning the meaning of these divine symbols crowded together on this wondrous page." Perched on North Dome he was "without definite hope of ever learning much" but still was "eager to offer self-denial and renunciation with eternal toil to learn any lesson in the divine manuscript."

It is quite clear that Muir had found the key to the problem that was uppermost in his mind and, in spite of the fact that he had only spent a few days in Yosemite Valley itself, was well on the road toward a clearer understanding of its origin than had previously been reached.

In a letter dated September 8th, 1871, to Mrs. Ezra S. Carr,8 he wrote:

> You know that for the last three years I have been plodding making observations about this Valley and the high mountain region to the East of it, drifting broodingly about and taking in every natural lesson that I was fitted to absorb. In particular the great Valley has always kept a place in my mind. How did the Lord make it? What tools did He use? How did He apply them and when? I considered the sky above it and all of its opening cañons, and studied the forces that came in by every door that I saw standing open, but I could get no light. Then I said, "You are attempting what is not possible for you to accomplish. Yosemite is the *end* of a grand chapter. If you would learn to read it go commence at the beginning." Then I went about to the alphabet valleys of the summits, comparing cañon with cañon with all their varieties of rock structure and cleavage, and the comparative size ant slope of the glaciers and waters which they contained. Also the grand congregation of rock creations were present to me, and I studied their forms and sculpture. I soon had a key to every Yosemite rock and perpendicular and sloping wall. The grandeur of these forces and their glorious results overpower me, and inhabit my whole being. Waking or sleeping I have no rest. In dreams I read blurred sheets of glacial writing or follow lines of cleavage or struggle with the difficulties of some extraordinary rock form. Now it is clear that woe is me if I do not drown this tendency toward nervous prostration by constant labor in working up the details of this whole question.

Later in that year he wrote:9

> Patient observation and constant brooding above the rocks, lying upon them for years as the ice did, is the way to arrive at the truths which are graven so lavishly upon them.

In a letter to Clinton L. Merriam, dated September 24th, 1871,10 he stated:

> You know my views concerning the formation of Yosemite, that the great Valley itself, together with all of its various domes and sculptured walls, were produced and fashioned by the united labors of the grand combination of glaciers which flowed over and through it, their forces having been rigidly governed and directed by the peculiar physical structure of the granite of which this region is made, and, moreover, that all of the rocks and lakes, and meadows of the whole upper Merced basin owe their specific forms and carving to this same glacial agency.

He added11 that he believed in

> the existence in the earlier ages of a Sierra Nevada ice of vast glaciers which flowed to the very foot of the range.

> Already it is clear that all of the upper basins were fined with ice, so deep and universal that but few of the ridges were sufficiently high to separate it into individual glaciers. Vast mountains were flowed over, and rounded or moved away like boulders in a river.
>
> Ice flowed into Yosemite by every one of its cañons, and at a comparatively recent period of its history, its north wall, with perhaps the single exception of the crest of Eagle Cliff, was covered with an unbroken stream of ice, the several glaciers having united before coming to the wall.

On November 16th, 1871,12 he wrote his mother that the valley was not "all exceptional creation," as had been claimed, but that

> Yosemite is one of *many*, one chapter of a great mountain book written by the same pen of ice which the Lord long ago passed over every page of our great Sierra Nevadas. I know how Yosemite and and all the other valleys of these magnificent mountains were made and the next year or two of my life will be occupied chiefly in writing their history in a human book—a glorious subject, which God help me preach aright.

Professor Joseph LeConte, the distinguished geologist, was one of the first men with scientific training to recognize the accuracy of John Muir's observations. Meeting Muir in the valley in August of 1870, he persuaded him to go on to the Tuolumne Meadows with his party. Muir told him of his conviction that the glacier had done the excavating of the valley and of his finding residual glaciers on

Mount Lyell and in the Merced group of peaks. Dr. LeConte’s paper, “Some Ancient Glaciers of the Sierra,” read in September, 1872, credited Muir for these discoveries.

Professor Louis Agassiz, upon reading what Muir had written on the Yosemite glaciers, said enthusiastically, “Here is the first man who has any adequate conception of glacial action. .. Muir is studying to greater purpose and with greater results than anyone else has done.”

In the autumn of 1872 Muir again wrote Mrs. Carr13 that ice was practically the sole denuding agency, that

> Yosemite and Hetch Hetchy are lake basins filled with [glacial material and that] The Yosemite ice in escaping from the Yosemite basin was compelled to flow upward a considerable height on both sides of the bottom walls of the Valley. The cañon below the Valley is very crooked and very narrow, and the Yosemite glacier flowed across all of its crooks and high above its walls without paying any compliance to it. . .
>
> I am surprised to find that *water* has had so little to do with mountain structure here. Whitney says that there is no proof that glaciers ever flowed in this Valley, and yet its walls have not been eroded to the depth of an inch since the ice left it, and glacial action is glaringly apparent many miles below the Valley.

John Erasmus Lester, a visitor to Yosemite in 1872, met Muir and on his return to Rhode Island published and read before the Historical Society there a paper on Yosemite,14 in which he says:

> There is and has been for two years past, living in the Valley, a gentleman of Scottish parentage, by name John Muir, who, Hugh Miller like is studying the rocks in and around the Valley. He told me that he was trying to read the great book spread out before him. He is by himself pursuing a course of geological studies, and is making careful drawings of the different parts of the gorge. No doubt he is more thoroughly acquainted with this valley than any one else. He has been far up the Sierras where glaciers are now in action, ploughing deep depressions in the mountains. He has made a critical examination of the superincumbent rocks, and already has much material upon which to form a correct theory.

Muir characterized Whitney’s theory, as will be noted in his “Studies in the Sierra,” in caustic language (see chapter ii).

Commenting on the part that water may have played in the formation of Sierra valleys, Muir called attention to the fact that in the postglacial epoch the channel of the upper Merced had not been deepened by the river more than three feet. He stated that the average angle which the slope of the Yosemite walls makes with the horizon, if carefully measures with a clinometer, was less than 50 degrees, and added that it was not possible for the bottom to drop out of a valley thus shaped. He emphasized the down-thrusting power of the five Yosemite tributary glaciers where as they entered the valley (see chapter iii) and also noted that after expending this power,

> with which they were endowed by virtue of the declivity of their channels. . . the trunk flowed up out of the valley without yielding compliance to the crooked and comparatively small river canyon extending. . . from the foot of the main valley. In effecting its exit a considerable ascent was made, traces of which are to be seen in the upward slope of the worn, rounded extremities of the valley walls.

He concluded, after contemplating the evidences of the power exerted by the separate glaciers in Yosemite Valley, that, instead of being overwhelmed by the magnitude of the work accomplished, “we ask, *Is this all?* wondering that so mighty a concentration of energy did not find ye, grander expression.” (See chapter iv.)

In answer to the query “What is the quantity of this degradation?’ he emphasizes the crushing power of the currents of moving ice, which

> slid over the highest domes as well as along the deepest cañons, wearing, breaking and degrading every portion of the surface, however resisting. . . 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 as 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 the explanation of the phenomena.

The feeling engendered by John Muir’s drastic criticism of Whitney’s “bottom-dropping-out” theory of Yosemite’s origin ran high. As already noted, Whitney’s intense resentment undoubtedly explains his denial that there was any proof “that glaciers have ever occupied the Valley, or any portion of it,” after having in his earlier geology given in some detail the unmistakable evidences of such glacial occupation of the valley. Of Muir’s attribution of Yosemite’s existence to glaciation he said that “a more absurd theory was never advanced. . .” He referred to Muir as a “sheepherder” and “guide.” On the other hand Muir’s intense feeling is expressed in many letters to his friends and later in his published articles, some of which have been noted above.

It is not surprising that Whitney and Muir felt as they did when all the surrounding circumstances are considered. Whitney was at the peak of his fame, recognized as one of the leading geologists in America, with an exceptional education acquired in America and Europe under the tutelage of outstanding scientists of the world. He had been called to California to undertake a geological survey of the state, which he himself, previous to his appointment by the legislature, had referred to as “the outstanding job of this character in America.” After arriving in California he had been appointed by Governor Low to the “State Commission to manage Yosemite” and after Frederick Law Olmsted’s resignation, had become its chairman. This made it necessary for him to visit the valley frequently. He wrote and published the first guidebooks of the valley and in these fully expounded his theory of its origin. Unquestionably, as chief geologist of a state survey of nation-wide interest, he had given the origin of Yosemite, already world-famous, his best considered thought and was aided by many able assistants. For his mature conclusions to be questioned and even belittled by a mere youth who had no college degree and no greater geological education than could be obtained at the comparatively new university in Wisconsin, was *lese majeste*. Whitney, proud and sensitive by nature, must have been galled beyond expression when, on his Yosemite visits and meetings with the Yosemite State Commission, of which he was chairman he was told, as must frequently have been the case, that this recently arrived and comparatively unknown stripling, was boldly questioning his carefully thought-out explanation. It savored of a David and Goliath contest. Muir's Scotch forthrightness and youth undoubtedly caused him to criticise Whitney's theory more severely than was politic. Muir also was doubtless irked by the fact that Whitney continued to insist on the correctness of his own theory even after its weaknesses had been exposed. Muir told me more than once that he regretted having gone as far as he did in criticising Whitney and that he should have been more deferential, for he really admired Whitney's ability and his geological survey work in California.15

Because of Whitney's doubts and diatribes, John Muir was naturally anxious to fortify his own views. He realized that in Alaska there were large glaciers performing today the same sort of work that had taken place in the Sierra in past geologic times. In his book, *Travels in Alaska*, published posthumously (1915), he tells of his various trips to the northwest coast and we find that these travels were in large part devoted to an intimate and detailed study of the Alaskan glaciers.16 He was a pioneer in these explorations, the first to map portions of this rugged coast, and named many of the hitherto unknown glaciers of Alaska. One of the largest, the Muir glacier, was named by others, in his honor.

Unlike most explorers, who are usually accompanied by a retinue of camp followers and vast quantities of equipage, Muir made these trips into the wild Alaskan fiords accompanied only by Indians and occasionally by the missionary, S. Hall Young. Traveling over the glaciers for days at a time he was invariably alone and, in fact, would have been handicapped had anyone accompanied him, for his skill as a climber and ability to travel light were unexcelled. His intense interest in the glacier problem is demonstrated by the large portion of his Alaska volume which is devoted to these expeditions. He saw with his own eyes "the huge ice tool" with its "mighty flood grinding against the granite walls with tremendous pressure." He found the "facts so fresh and telling and held up so vividly before us, every seeing observer, not to say geologist, must readily apprehend the earth-sculpturing, landscape-making action of flowing ice." In front of one of the glaciers he floundered through "grey mineral mud, a paste made of fine-ground mountain meal. . . swallowing us feet foremost with becoming glacial deliberation." He observed, "the streams that pour from them are busy night and day bringing in sand and mud and stones, at the rate of tons every minute." Muir continues:

> Pushing on next day, I climbed to the top of the glacier by ice-steps and along its side to the grand cataract two miles wide where the whole majestic flood of the glacier pours like a mighty surging river down a steep declivity in its channel. After gazing a long time on the glorious show, I discovered a place beneath the edge of the cataract where it flows over a hard, resisting granite rib, into which I crawled and enjoyed the novel and instructive view of a glacier pouring over my head, showing not only its grinding, polishing action, but how it breaks off large angular boulder-masses—a most telling lesson in earth-sculpture, confirming many I had already learned in the glacier basins of the High Sierra of California.
>
> In general all the rock walls as far as I saw them are more or less Yosemitic in form and color and streaked with cascades.

Again and again he was impressed with the massive granitic domes rocks

> sculptured like those of Yosemite, magnificent valleys like the Yosemite.

> That this whole system of fiords and channels was added to the domain of the sea by glacial action, is to my mind certain.

He found the

> pre-glacial margin of the continent, eroded to varying depths below sea-level, and into which, of course, the ocean waters flowed as the ice was melted out of them.

Up over roping, mossy, bushy, burnished rock-waves we scrambled . . . [to] a fair view of the deep blue waters of the fiord stretching on and on along the feet of the most majestic Yosemite rocks we had yet seen.

He noted that the fiord was interrupted and

> this novel interruption of the channel is a bar of exceedingly hard resisting granite, over which the great glacier that once occupied it swept, without degrading it to the general level and over which tidewaters now rush in and out with the violence of a mountain torrent.

He found many Yosemite-like "mansions of the icy North." Of one of them he says,

> This is a Yosemite Valley in process of formation, the modeling and sculpture of the walls nearly completed and well planted, but no groves as yet or gardens or meadows on the raw and unfinished bottom. It is as if the explorer, in entering the Merced Yosemite, should find the walls nearly in their present condition, trees and flowers in the warm nooks and along the sunny portions of the moraine-covered brows, but the bottom of the valley still covered with water and beds of gravel and mud, and the grand glacier that formed it slowly receding but still filling the upper half of the valley.

He was profoundly impressed by the

> extraordinary grandeur of [one] wild unfinished Yosemite. Domes swell against the sky in fine lines as lofty and as perfect in form as those of the California valley, and rock-fronts stand forward, as sheer and as nobly sculptured. No ice-work that I have ever seen surpasses this, either in magnitude of the features or effectiveness of composition.

Of one valley in particular he wrote:

> This is in form and origin a typical Yosemite valley, though as yet its floor is covered with ice and water-ice above and beneath, a noble mansion in which to spend a winter and a summer! It is about ten miles long, and from three-quarters of a mile to one mile wide. It contains ten large falls and cascades, the finest one on the left side near the head. . .

> The amount of timber on the walls is about the same as that on the Yosemite walls, but owing to greater moisture, there is more small vegetation,—bushes, ferns, mosses, grasses, etc.; though by far the greater portion of the area of the wall-surface is bare and shining with the polish it received when occupied by the glacier that formed the fiord.

The foregoing quotations from *Travels in Alaska* abundantly demonstrate that these Alaskan explorations gave him telling evidence in support of the theories which he had advanced and which are expounded in his "Studies in the Sierra." He saw the living glaciers of Alaska actually doing the same sort of rock-gouging and rock-plucking work that he was convinced the ancient glaciers of the Sierra had done in their work of fashioning the yosemities of California.

In 1893 he visited Switzerland and the fiords of Norway, searching for—and finding—further confirmation of his views.

In 1913 the interest in the Yosemite problem, both popular and in scientific circles, prompted the United States Geological Survey to undertake a comprehensive geologic investigation of the entire Yosemite region and neighboring High Sierra. To the glacial and geomorphic studies was assigned the distinguished topographer and geologist who had already made the superb topographic map of Yosemite Valley, the late François E. Matthes, an internationally recognized authority on glaciers. He was assisted by Frank C. Calkins, who investigated the rocks of the region. The results of many years of painstaking research by these geologists were published in 1930 as Professional Paper 160, entitled, *Geologic History of the Yosemite Valley*. This monumental work is generally recognized as a classic in geologic literature and one of the finest publications of the United States Geological Survey. The text, unique in that it is written largely in nontechnical language, in order that it may be understood by laymen and scientists alike, is supplemented by many fine illustrations, and by folded topographic and geologic maps.

In this monograph, as well as in various shorter publications, Matthes gives great credit to John Muir, "who first saw clearly that the glaciers themselves had done most of the excavating." However, Matthes's own studies indicated that "Muir. . . went too far in his claims for glacial erosion."

Matthes found that in the Yosemite region, as in most glaciated regions which similarly have been investigated in detail, the glacial record is very complex, indicating that the Glacial Period involved several distinct glaciations. In the interglacial stages between these glaciations, the Yosemite region was ice-free. Accordingly, Yosemite Valley was interpreted by Matthes as the joint product of stream erosion by the Merced River and of ice erosion by the glaciers of the several glacial stages. To answer the critical question "as to how much of the work was done by the streams and how much by the glaciers" Matthes employed the modern techniques of geomorphology (as explained fully in Professional Paper 160) and found that preglacial stream erosion formed a **V**-shaped canyon in the Yosemite granite, so that

> at the lower end of the valley the glacial deepening measures only about 500 feet, but up the valley it increases gradually, reaching a maximum of about 1,500 feet near the head of the valley . . . lateral cutting has been a more important element in the transformation of the Yosemite chasm than downward cutting. At every point the widening accomplished exceeds the deepening. It is, in fact, mainly through lateral cutting that the narrow **V** canyon of preglacial time has been transformed into the broad **U** trough of today.

Matthes recognized that the glacier excavated "an elongated basin" which it "scooped out in the rock floor of the valley," thus creating a shallow "lake Yosemite" whose depth was increased by the terminal moraine dam below E1 Capitan. He did not know the depth of this lake basin, as no borings had ever been made to determine this fact, but estimated "a depth ranging from 100 to not less than 300 feet" for various parts of the valley, with the probability that "the basin was deepest. . . in the upper part of the valley, opposite Yosemite Village." He says, further, that

> the existence of the rock basin is purely inferential. . . until a series of borings along the whole length of the valley shall afford the necessary facts,

and adds that such borings

> would contribute much desired data regarding the still challenged eroding efficiency of glaciers. . .
>
> As to the extent to which the ancient glaciers have remodeled and excavated the valley, nothing, perhaps would go further toward settling this vexed question than a series of direct measurements establishing beyond doubt the depth of former Lake Yosemite.17

The importance of rock structure, particularly jointing, in determining the facility with which the glaciers quarried and ground the rock surfaces over which they moved—a factor first recognized and expounded by Muir—was fully recognized by Matthes also, who developed the relationship in great detail, showing that jointing has played a major role in the control of the varied Sierra landforms.

In recent years another important chapter has been added to study of the depth of the bedrock floor and the rock basin below the existing surface floor of Yosemite Valley. Dr. John P. Buwalda, former head of the Division of Geology of the California Institute of Technology, investigated these problems by geophysical methods, through use of the Institute's seismic reflection equipment. Field work was done in 1934 and 1935, and subsequently the extensive mathematical calculations were made by a colleague, Dr. Beno Guttenberg. The procedures involved drilling holes in the valley to shallow depths, and the explosion of dynamite charges in these holes. The reflection returns of the resulting wave; were accurately timed, thus giving the depth to which the waves traveled before being reflected back from bedrock.

This study indicated that bedrock is deepest between the Government Administration Building and Camp Curry, where it is 1,800 to 2,000 feet below the present surface. Three miles downstream, opposite El Capitan, bedrock is 1,000 feet higher; and two and one-half miles farther downstream, at the lower end of the valley, bedrock is only 200 feet below the present surface. Upstream from Camp Curry, the depth decreases gradually and a short distance up on Tenaya Creek and on the Merced River near Happy Isles it steps up suddenly, the bedrock being actually exposed a mile or so still farther upstream.

This study, then, indicated that the glaciers scooped out a great spoon-shaped depression in the bedrock beneath what is now Yosemite Valley. The depression is 1,800 to 2,000 feet deep in the upper part of the valley, and 200 feet deep at its lower end. Where the depression is deepest; as in front of Camp Curry, bedrock is some 5,000 feet below Glacier Point—65 to 70 per cent of the total depth of the valley previously estimated at this point.18

Many geologists feel, as did Matthes, that the last word concerning the depth of bedrock below the floor of Yosemite must await a series of borings along the length of the valley. However, the geophysical studies, which have since been confirmed by an entirely independent series of tests, indicating as they do a maximum depth far greater than previously estimated, give new emphasis to John Muir's remarkable acumen in early discerning the great importance of glacial action in the formation of Yosemite and the other great canyons of the Sierra.

On the occasion of a program broadcast on April 17, 1938 in observance of the centennial of John Muir's birth, François Matthes paid this tribute to the pioneer student of the Yosemite:

> To one thoroughly at home in the geologic problems of the Yosemite region it is now certain, upon reading Muir's letters and other writings, that he was more intimately familiar with the facts on the ground and was more nearly right in their interpretation, than any professional geologist of his time. . . Muir was probably as nearly right in his glacial theory of the Yosemite as any scientist in the early seventies could have been.19

Thus Muir's "Studies in the Sierra" still stand, after seventy-five years, as a splendid introduction to the fundamental workings of Nature that have created the Yosemite Valley as we know it today.

Glacier Writings of John Muir

Books

Mountains of California. (Chapters on Glacier Meadows of the Sierra and Mountain Lakes of California.)

Travels in Alaska. (Much of this volume is devoted to the glaciers of Alaska.)

Articles in Books and Magazines

"Glaciers and Snow-banners." *Contemporary Biography of California's Representative Men*. San Francisco. Bancroft, 1882. Vol. 2, pp. 104-112.

"Notes on the Pacific Coast Glaciers." (Harriman Alaska Expedition.) 1901, Vol. 1, pp. 119-135.

"The Glaciation of the Arctic and Sub-Arctic Regions Visited by the U. S. Steamer "Corwin" (1881). U. S. Senate documents, 48th Congress, 1st Session, 8:204, pp. 135-147.

"Peaks and Glaciers of the High Sierra." *Picturesque California* (1882).

"Studies in the Formation of Mountains in the Sierra Nevada, California." American Association for the Advancement of Science. (1824) Vol. 23, Part 2, pp. 49-64.

"Alaska" *American Geologist* (1893), 2:287-299.

"Alaska Trip," *Century,* Aug. 1897, Vol. 54, pp. 513-526.

"Ancient Glaciers of the Sierra," *Californian,* Dec. 1880, Vol. 2, pp. 550-551.

"Discovery of Glacier Bay," *Century,* June 1895, Vol. 50, pp. 234-247.

"Living Glaciers of California," *Overland,* Dec. 1872, Vol. 9, pp. 547-549.

"Studies in the Sierra," *Overland,* 1874; Vol. 12, pp. 393-403, 489-500; Vol. 13, pp. 67-79, 174-184, 393-401, 530-540; Vol. 14, pp. 64-73.

"Mountain Sculpture," *American Journal of Science,* 1874, Vol. 7, pp. 515-516.

NEWSPAPER ARTICLES

New York Tribune, "Yosemite Glaciers," Dec. 5, 1871.

San Francisco Bulletin, "Notes of a Naturalist, Alaska Glaciers," Sept. 23, 1879, Sept. 27, 1879; "Sum Dum Bay," Aug. 1880, Oct. 7, 1880; "An Alaska Yosemite," Oct. 16, 1880; "Among the Glaciers and Bergs of Sum Dum Bay," Oct. 23, 1880; "Taku Fiords and Glaciers," Nov. 13, 1880.

See also *The Life and Letters of John Muir* (2 Volumes, 1923-1924), by William Frederic Badè, and *Son of the Wilderness, A Life of John Muir* (1945), by Linnie Marsh Wolfe, for detailed accounts of this glacial controversy and the leading part that John Muir had in it.

Notes

1. John Muir, as a youth on his father's farm, easily excelled all the help in whatever he undertook. He kept his axes sharper and knew how to use them to great effect. He early demonstrated his ability as an inventor. His wooden clocks, barometer, thermometer, bed-tipping apparatus (to insure early rising), revolving desk (bringing each book before him at the appointed study hour), and his great success in inventing labor-saving devices in the factory where he was employed after leaving the University in Wisconsin, all attest to this. His grasp of geological problems and his intimate knowledge of botany are proof of the fact that both Emerson and Agassiz were justified in urging him to lecture at Harvard on these subjects, an invitation which had little appeal to such a lover of outdoor freedom. His explorations in Alaska and other parts of the world made him eligible to be called an explorer. His great success as a grower of grapes and fruit, when he netted more than $10,000 a year for ten consecutive years and then decided that he had laid away money enough for all worldly purposes, illustrates the success that he made of everything he put his hand to. But above an else he excelled as a writer and teacher of the gospel of the outdoors that he loved so well. Few have approached him in his rare ability to interpret nature and translate her moods in language that has such universal appeal.

The events in his full life are so ably narrated in *Son of the Wilderness, the Life of John Muir,* by Linnie Marsh Wolfe (1945), that the reader is referred for all such incidents to this Pulitzer Prize biography. Also see Dr. William Frederic Badè's *Life and Letters of John Muir* (1923), and John Muir's *Story of My Boyhood and Youth* (1913), as well as *Reader's Digest,* September, 1949.

2. These are set forth and discussed in *Geologic History of Yosemite Valley* (1930), by François E. Matthes , U. S. Geological Survey Professional Paper 160 (pp. 4-6, 94-95). Also see *The Life and Letters of John Muir* (1923), by William Frederic Badè, chapter ix, "Persons and Problems" (pp. 275-278, 282-287, 308-309, 352-353, 356-359); and *Son of the Wilderness* (pp. 130-135, 186-187).

E. C. Andrews, the noted geologist of Australia, in 1910 wrote a monograph entitled "An Excursion to the Yosemite" (Roy. Soc. New South Wales Journal, vol. 44, pp. 262-315), in which he emphasizes the importance of "glacial stairways" in the process of glacial erosion. Later, in a letter to me he stated that he had for the first time read Muir's "Studies in the Sierra," just being published in the *Sierra Club Bulletin,* and added that "John Muir's note on glacial action is very fine indeed. In Muir you had a man in America long ago who explained the action of ice rivers. . . ."

Andrew C. Lawson, a long-time member of the Sierra Club, and former head of the Department of Geology of the University of California, has expressed his views on this subject in an article entitled "Geology of Yosemite National Park," which appeared in Anson Hall's *Handbook of Yosemite National Park* (1921, pp. 99-122).

3. An article by John Muir entitled "Yosemite Glaciers" appeared in the *New York Tribune,* December 5, 1871. In the December 1872 *Overland Monthly* appeared another article by him entitled "Living Glaciers of California." The fun and detailed presentation of his theory followed in 1874 and 1875 in the series of seven articles "Studies in the Sierra."

4. The demand for this publication was so great that the original edition of 1930 was exhausted, and a reprint became necessary, first in May, 1939, and again in May, 1946. It may still be purchased from the Superintendent of Public Documents, Government Printing Office, Washington, D.C., for $3.25.

I have a copy of this paper which contains the following inscription:

> "To Wm. E. Colby, who, as Secretary of the Sierra Club, took the first steps toward bringing about the reinvestigation of the Yosemite Valley of which the results are here set forth.—François E. Matthes."

In recognition of Matthes' splendid work the Sierra Club elected him an Honorary Vice-President. Matthes died in June, 1948, shortly after retirement from the Geological Survey. It is hoped that his remaining Sierra studies will be brought to completion and published posthumously.

5. Josiah Dwight Whitney, 1819-1896, a distinguished American geologist who, prior to his becoming the Chief Geologist of the California Geological Survey, was connected with official geological surveys in the states of New Hampshire, Wisconsin, and Illinois. He headed the California Survey from 1860 to 1874 and not only prepared a large volume on geology of California published by the state in 1865, but also wrote and published various guide books to Yosemite Valley, 1869-1874. He was Professor of Geology at Harvard University, 1865-1896. Whitney doubtless aided in the passage of the Act of Congress which, on June 30, 1864, granted to the State of California "the cleft or gorge . . . in the Sierra Nevada Mountains, known as Yosemite Valley"—for this language reflects his theory of the valley's origin. Whitney refers to the Yosemite Valley as "the Gosh a'Mighty" in a letter to his brother dated June 19, 1861. (Brewster's *Life and Letters, Josiah Dwight Whitney* (1909), p. 202.)

6. It is extraordinary that a man of Whitney's ability should have failed to be impressed by the evidences of glacial action in the Sierra, which he himself had seen and noted. In a letter, dated July 10, 1863, to his friend Professor G. J. Brush, he writes of the view from Mount Dana and of the Tuolumne Meadows region as follows:

> . . . we are in the midst of what was once a great *glacier region* (italics Whitney's) the valleys all about being most superbly polished and grooved by glaciers, which once existed here on a stupendous scale, having a thickness in the Tuolumne Valley, of a thousand feet, and having left splendid moraines—medial, lateral, and terminal. The beauty of the polish on the rocks, covering hundreds of square miles of surface, is something which must be seen to be appreciated. *[Life and Letters, Josiah Dwight Whitney, pp. 230-231.]*

Clarence King, leader of early geological surveys in the western United States and later a director of the U. S. Geological Survey, was, apparently, more interested in glacial action than any of his collaborators, as shown by the fact that Whitney credits him with most of the reported data on the subject contained in the California Survey publications. Had he not been under the dominating influence of a scientist as positive as Whitney, he might have originated the "glacial theory" of the origin of Yosemite which some have erroneously credited to him. That he did not endorse that theory, in spite of his many observations indicating that the ancient glaciers had been very widely distributed in the High Sierra and had occupied Yosemite Valley, is demonstrated by his complete acceptance of Whitney's theory in his "Mountaineering in the Sierra Nevada."

7. *My First Summer in the Sierra, by* John Muir (1911).

8. *The Life and Letters of John Muir,* vol. i, pp. 293-95.

9. *Ibid.,* p. 300.

10. *Ibid.,* p. 303.

11. *Ibid.,* pp. 307-308.

12. *Ibid.,* pp.314-315.

13. *Ibid.,* pp. 354-356.

14. *Ibid.,* p. 360.

15. See *Son of the Wilderness,* pp. 130-133. Professor Whitney was made an honorary member of the Sierra Club in December, 1892. Though John Muir was not present at that meeting he doubtless had been consulted and had given his approval to this action. If my memory serves me aright (the official minutes having been destroyed in the 1906 San Francisco Fire) at John Muir's suggestion, Whitney's sister was substituted in her brother's place to receive Sierra Club publications after his death in 1896.

16. Tarr and Martin in *Alaskan Glacier Studies* (1914), sponsored by the National Geographic Society, credit Muir as the pioneer in publishing accounts of Alaskan glacier studies. (Muir's first trip to Alaska was in 1879.) In this excellent presentation of their detailed studies, the authors confirm many of the conclusions earlier reached by Muir as to the tremendous erosive power of the Alaskan glaciers. See pp. 219, 224, 226, 228-230, 341, 357-358, 367-368.

17. "Little Studies in the Yosemite Valley," by François E. Matthes, *Sierra Club Bulletin,* 9:15.

18. I am indebted to Dr. Buwalda for permission to use these data, which are taken from his illuminating article, "Form and Depth of the Bedrock Trough of Yosemite Valley," *Yosemite Nature Notes,* 20 (October, 1941): 89-93.

Dr. Buwalda writes as of August 10, 1949:

> "Many of the 85 points in the Valley at which we determined the depth of the fill have been re-shot subsequently by another geophysical crew with entirely different equipment and the results check."

If we accept Dr. Buwalda's findings, now corroborated by entirely independent tests, the Yosemite glacier excavated upwards of a cubic mile of granite rock and transported it out of this spoon-shaped lake depression. The removal of this material cannot be attributed to water erosion for it was all originally situated in place back of and below the elevation of the now existing downstream lip of the lake. This recently discovered evidence of the enormous excavating power of the glacier lends confirmation to Muir's main thesis that glaciers were largely instrumental in carving out much of what is now the Valley void, observable to an visitors. Geologists will still differ about the relative amount of this excavation and erosion that was done by water and later by ice, but from now on a heavier burden win rest on the advocates of water erosion.

19. "John Muir and the Glacial Theory of Yosemite," by François E. Matthes, *Sierra Club Bulletin,* 23:2 (April, 1938), pp. 9-10.

STUDIES IN THE SIERRA

I

Mountain Sculpture

In the beginning of the long glacial winter, the lofty Sierra seems to have consisted of one vast undulated wave, in which a thousand separate mountains, with their domes and spires, their innumerable cañons and lake basins, lay concealed. In the development of these, the Master Builder chose for a tool, not the earthquake nor lightning to rend and split asunder, not the stormy torrent nor eroding rain, but the tender snow-flowers, noiselessly falling through unnumbered seasons, the offspring of the sun and sea. If we should attempt to restore the range to its pre-glacial unsculptured condition, its network of profound cañons would have to be filled up, together with all its lake and meadow basins; and every rock and peak, however lofty, would have to be buried again beneath the fragments which the glaciers have broken off and carried away. Careful study of the phenomena presented warrants the belief that the unglaciated condition of the range was comparatively simple; yet the double summits about the head of Kern River and Lake Tahoe, and the outlying spurs of Hoffmann and Merced, would appear to indicate the primary existence of considerable depressions and elevations. Even these great features, however, may be otherwise accounted for.

All classes of glacial phenomena are displayed in the Sierra on the grandest scale, furnishing unmistakable proof of the universality of the ice-sheet beneath whose heavy folds all her sublime landscapes were molded. Her ice-winter is now nearly ended, and her flanks are clothed with warm forests; but in high latitudes, north and south, and in many lofty mountains, it still prevails with variable severity. Greenland and the lands near the south pole are undergoing glaciation of the most comprehensive kind, and present noble illustrations of the physical and climatic conditions under which the Sierra lay when all the sublime pages of her history were sealed up. The lofty Himalaya, the Alps, and the mountains of Norway are more open, their glacial covering having separated into distinct glaciers that flow down their valleys like rivers, illustrating a similar glacial condition in the Sierra, when all her valleys and cañons formed channels for separate ice-rivers. These have but recently vanished, and when we trace their retiring footsteps back to their fountains among the high summits, we discover small residual glaciers in considerable numbers, lingering beneath cool shadows, silently completing the sculpture of the summit peaks.

The transition from one to the other of these different glacial conditions was gradual and shadow-like. When the great cycle of icy years was nearly accomplished, the glacial mantle began to shrink along the bottom; domes and crests rose like islets above its white surface, long dividing ridges began to appear, and distinct glacier rivers flowed between. These gradually became feeble and torpid. Frost-enduring carices and hardy pines pushed upward along every moraine and sun-warmed slope, closing steadily upon the retreating glaciers, which, like shreds of summer clouds, at length disappeared from the young and sunny landscapes.

We can easily understand that an ice-sheet hundreds or thousands of feet in thickness, slipping heavily down the flanks of a mountain chain, will wear its surface unequally, according to the varying hardness and compactness of its rocks; but these are not the only elements productive of inequalities. Glaciers do not only *wear* and grind rocks by slipping over them, as a tool wears the stone upon which it is whetted; they also *crush* and *break*, carrying away vast quantities of rock, not only in the form of mud and sand, but of splinters and blocks, from a few inches to forty or fifty feet in diameter.

The whole mass of the Sierra, as far as our observation has reached, is built up of brick-like blocks, whose forms and dimensions are determined chiefly by the degree of development of elected *planes of cleavage,* which individualize them, and make them separable from one another while yet forming undisturbed parts of the mountain. The force which binds these blocks together is not everywhere equal; therefore, when they are subjected to the strain of glaciers, they are torn apart in an irregular and indeterminate manner, giving rise to endless variety of rock forms.

The granite in some portions of the range is crumbling like meal by the decomposition of its feldspar throughout the mass, but the greater portion has suffered scarcely any disintegration since the close of the glacial period. These harder areas display three series of cleavage or separating planes, two nearly vertical, the other horizontal, which, when fully developed, divide the rock into nearly regular parallelepipeds. The effects of this separable structure upon the glacial erodibility of rocks will be at once appreciated. In order that we may know how mountain chains are taken apart, it is important that we first learn how they are put together; and now that we have ascertained the fact that the Sierra, instead of being a huge wrinkle of the earth’s crust without any determinate structure, is built up of regularly formed stones like a work of art, we have made a great advance in our mountain studies; we may now understand the Scripture: “He bath *builded* the mountains,” as not merely a figurative but a literal expression.

In order that we may obtain some adequate estimate of the geologic value of this cleavage factor in the production of cañons, rock forms, and separate mountains, with their varied sculpture, we must endeavor to find out its range, variations, and what forces are favorable to its development; what are the effects of its suppression in one place, and development in another; what are the effects of the unequal development of the several series. In the prosecution of these inquiries, we soon discover that the middle region of the west flank is most favorable for our purposes, because the lower is covered to a great extent with soil, and the upper, consisting of sharp peaks, is so shattered, or rather has *all* the various planes so fully developed, we are unable to study them in their simple, uncombined conditions. But the middle region, while it has all its cleavage phenomena on the largest scale both of magnitude and specialization, is also simple and less obscured by forests and surface weathering, and affords the deepest. as well as widest naked sections, the former in Yosemite cañons, the latter in flat basins like those of Yosemite Creek, Lake Tenaya, and upper Tuolumne Valley, wherein broad areas of glacier-polished granite are spread out, as clean and unblurred as new maps.

I should have stated that the three series of cutting planes mentioned above are not the only ones existing in these rocks, but we will consider them first, because they are most marked in their modes of development, and have come most prominently into play in the formation of those unrivaled cañons and rocks which have made the Sierra famous. In studying their direction and range, we find that they extend along the west flank from latitude 36° to 40° at least, and from the summit to the soil-covered foot-hills, and in all probability further observation would show that *they are co-extensive with the length and breadth of the chain*. We measured the direction of the strike of hundreds, belonging to the two vertical series, many of which run unbrokenly for miles in a tolerably uniform course, the better developed ones nearly at right angles to the axis of range, the other parallel with it. Cañon sections show that they cleave the granite nearly vertically to a depth of 5,000 feet without betraying any tendency to give out. The horizontal series appear also to be universal. In some places these divisional planes are extended within a few inches of each other, while in others only one conspicuous seam is visible in a breadth of bare rock half a mile in extent. Again, many large domes occur that exhibit none of these planes, and appear to be as entirely homogeneous in structure as leaden balls.

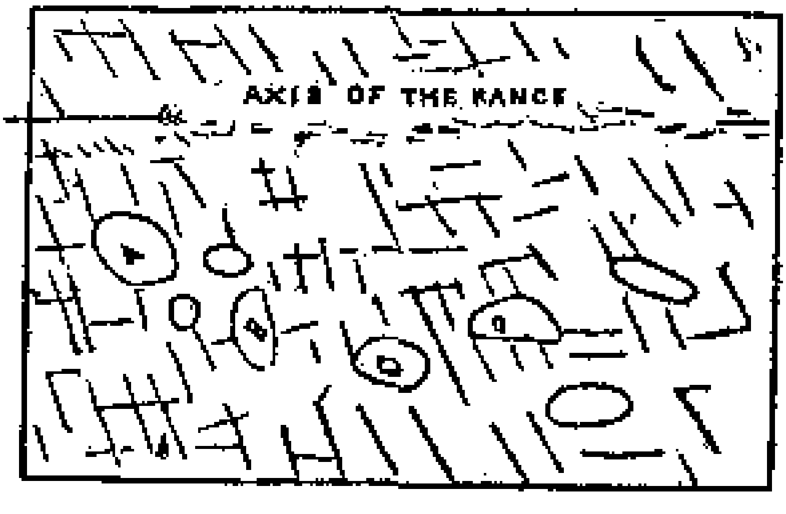


Fig. 1

Thus, let Fig. 1 represent a horizontal section of the range; A, B, C, D, cones and conoides where none of the cleavage planes appear. The question here arises, are these domed portions cleavageless, or do they possess the same cleavage as the surrounding rock, in an undeveloped or latent condition? Careful observation proves the latter proposition to be the true one, for on the warm and moist surfaces of some of the older domes we detect the appearance of incipient planes running parallel with the others, and in general wherever any rock apparently homogeneous in structure is acted upon by the spray of a water-fall, its cleavage planes will appear. We may conclude, therefore, that however numerous the areas may be which seem solid and equal in structure, they are still traversed in definite directions by invisible cutting planes, which render them separable when the conditions required for their development have been supplied.

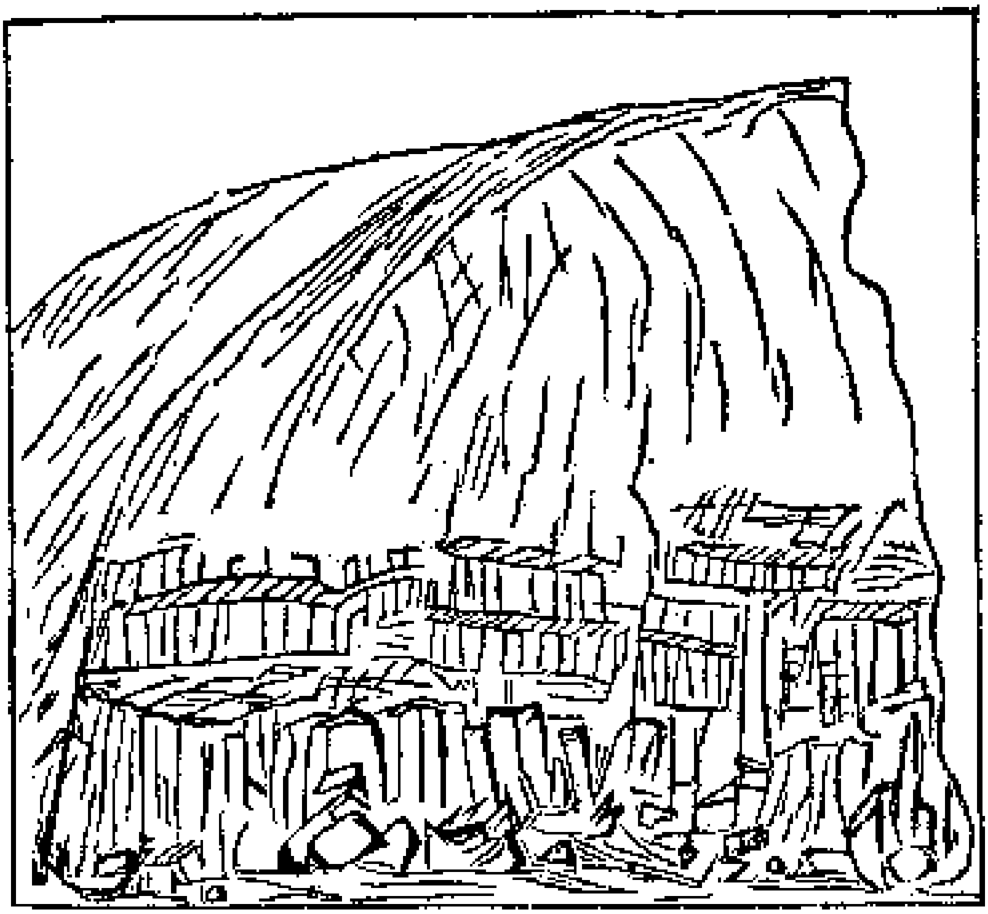


Fig. 2

Fig. 2 represents the side of a dome at the head of Yosemite Fall, with parallelopipedal blocks developed along its base. The development of the brick structure is probably due to spray blown back from the brow of the fall in storms. It is to the development of these brick-making planes by long-continued atmospheric action, that the picturesque ruins so frequently met with on lofty summits are due. Where only one of the cutting vertical series has been developed in a granitic region otherwise strong in its physical structure, and a sufficient amount of glacial force exerted in a favorable direction has been concentrated upon it, its rocks have been broken up in flakes and slabs, and those majestic mural precipices produced which constitute so sublime a part of the Yosemitic scenery of the Sierra.

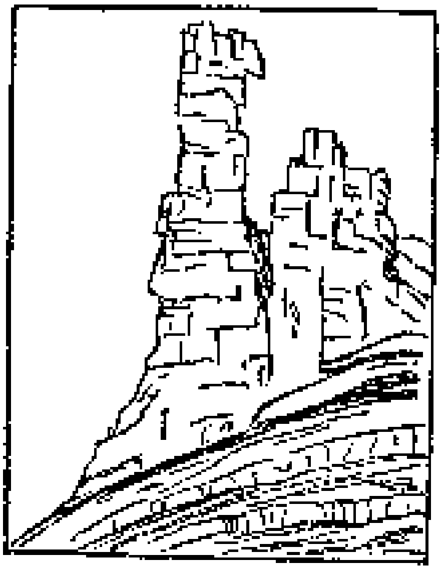


Fig. 3

Fig. 3 represents a granite tower on the crest of Mount Hoffman composed of jointed blocks.

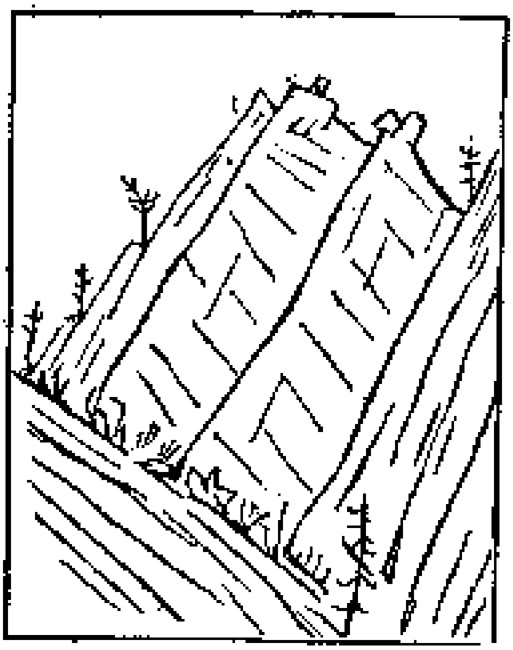


Fig. 4

Another series of cutting planes which pass diagonally through the we have been considering, give rise to pyramidal and roof-shaped forms. This diagonal cleavage is found in its fullest development in the metamorphic slate of the summit, producing the sharp-pointed peaks for which the summit region is noted. To it is also due the huge gables which a found in Yosemite and Tuolumne cañons, such as the Three Brothers, and the pointed rock adjoining the Royal Arches. Fig. 4 represents the highest of the big Three Brothers, Yosemite Valley, illustrating *diagonal cleavage in Granite;* and

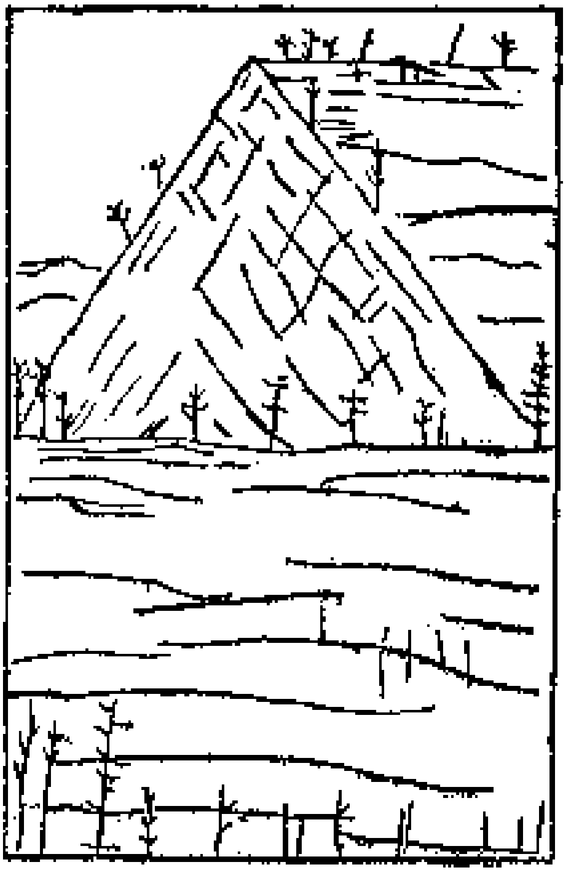


Fig. 5

Fig. 5 is a gable on the south wall of the Tuolumne Cañon.

Fig. 6

It will be at once perceived that the forms contained in Fig. 6 (a rock situated near the small side-cañon which separates El Capitan and the Three Brothers, in Yosemite Valley), have resulted from the partial development of both diagonal and rectangular cleavage joints. At *a, b, c, d,* incipient diagonal planes are beginning to appear on the otherwise solid front. Some of the planes which have separated the two summit blocks, *e* and *f,* may be seen at *g*.

The greatest check to the free play and controlling power of these divisional planes is the occurrence, in immense numbers and size, of domes, cones, and round wave-ridges, together with an innumerable brood of modified forms and combinations. The curved cleavage which measures and determines these rounded forms, may be designated *the dome cleavage,* inasmuch as the dome is apparently the most perfect typical form of the group.

Domes of close-grained silicious granite are admirably calculated to withstand the action of atmospheric and mechanical forces. No other rock form can compare with it in strength; no other offered so unflinching a resistance to the tremendous pressure of the glaciers. A dam of noble domes extends across the head of Yosemite Valley, from Mount Starr King to North Dome, which was effectually broken through by the combined force of the Hoffmann and Tenaya glaciers; but the great south Lyell glacier, which entered the valley between Starr King and Half Dome, was unable to force the mighty barrier, and the approach of the long summer which terminated the glacial epoch, found it still mazing and swedging compliantly among the strong unflinching bosses, just as the winds are compelled to do at the present time.

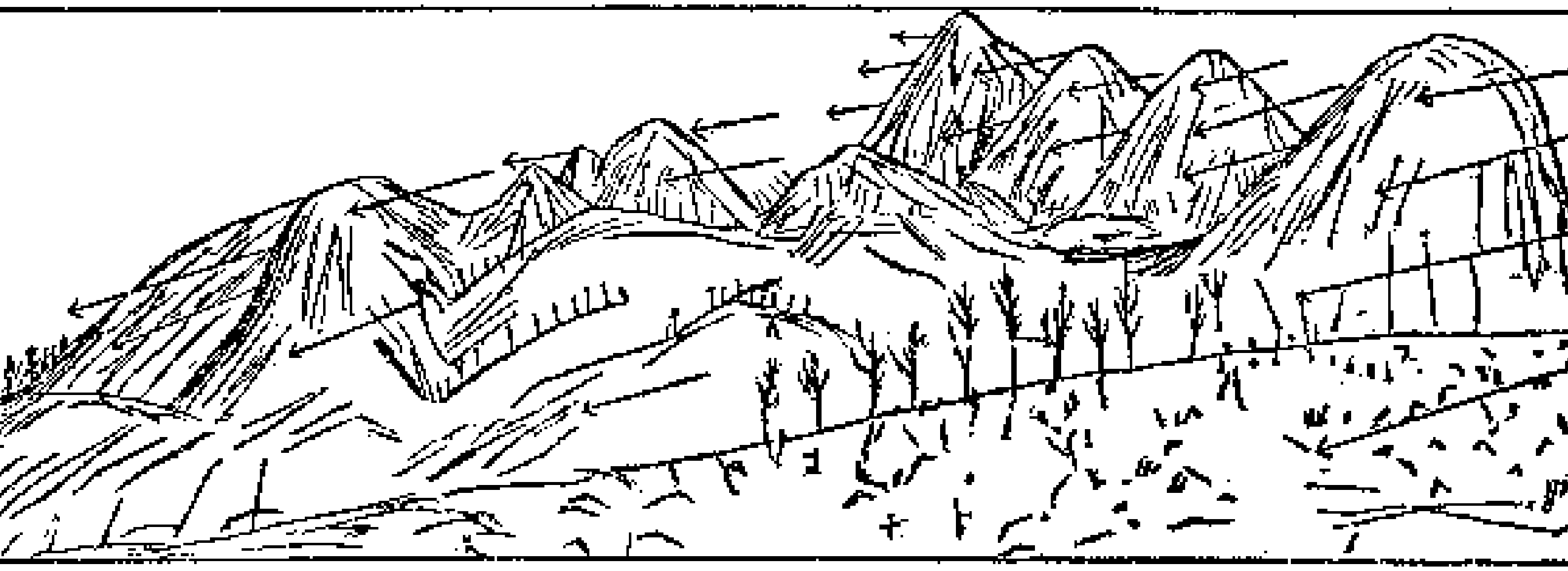


Fig. 7

The Starr King group of domes (Fig. 7) is perhaps the most interesting of the Merced basin. The beautiful conoid, Starr King, the loftiest and most perfect of the group, was one of the first to emerge from the glacial sea, and ere its new-born brightness was marred by storms, dispersed light like a crystal island over the snowy expanse in which it stood alone. The moraine at the base is planted with a very equal growth of manzanita.

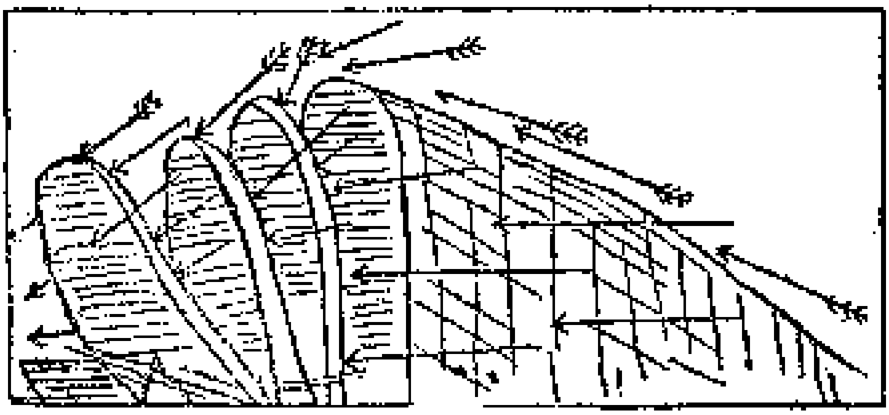


Fig. 8

There appear to be no positive limits to the extent of dome struture in the granites of the Sierra, when considered in all its numerous modifications. Rudimentary domes exist everywhere, waiting their development, to as great a depth as observation can reach. The western flank was formerly covered with slates, which have evidently been carried off by glacial denudation from the middle and upper regions; small patches existing the summits and spurs of the Hoffmann and Merced mountains are all are now left. When a depth of two or three thousand feet below the hot of the slates is reached, the dome structure prevails almost to the exclusion of others. As we proceed southward or northward along the chain from the region adjacent to Yosemite Valley, dome forms gradually become less perfect. Wherever a broad sheet of glacier ice has flowed over a region of domes, the superior strength of their concentric structure has prevented them from being so extensively denuded as the weaker forms in which they lie imbedded; but after thus obtaining a considerable elevation above the general level, unless their cleavage planes were wholly latent they were liable to give way on the lower side, producing forms like Fig. 8, in every stage of destruction. In the case of rocks wherein no cleavages of any kind were developed, forms have resulted which express the greatest strength considered with reference to the weight and direction of the glacier that overflowed them. Their most common form is given in Fig. 9.

Fig. 9

Some of their cross-sections are approximately given in Fig. 10.

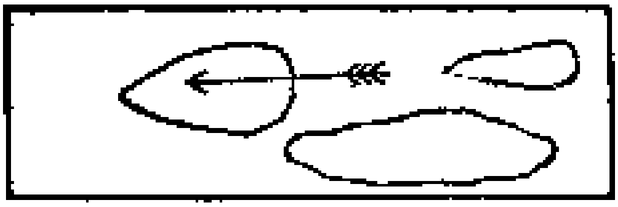


Fig. 10

But few examples are to be found where cleavage and irregularity of hardness do not come in to complicate the problem, in the production of that variety of which nature is so fond.

We have already seen that domes offer no absolute barrier to the passage of vertical and horizontal cleavage planes; but it is also true that domes cut one another.

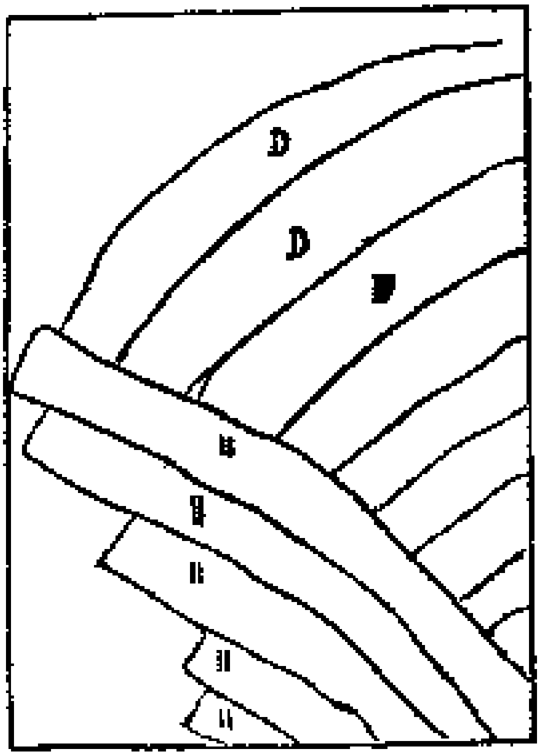


Fig. 11

Fig. 11 is a section obtained near the head of a remarkably deep and crooked gorge in the Tenaya Cañon, four miles above Mirror Lake. The broken edges of the concentric layers of a dome, marked thus ´´, present themselves on the overleaping wall of the gorge, and upon the buried dome whose section thus appears another dome is resting, furnishing evidence that a series of concentric shells which form a dome may be cut by another series of the same kind, giving rise to domes *within* domes and domes *upon* domes.

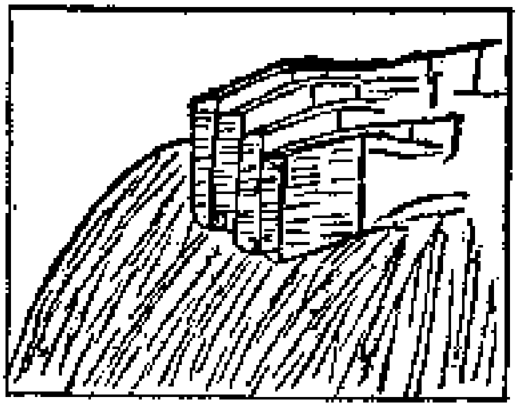


Fig. 12

Fig. 12 represents bricks, thirty or forty feet in height, placed directly upon a smooth, well-curved dome, which dome, in turn, is borne upon or rather stands out from a yet larger dome-curved surface forming a portion of the east side of El Capitan rock, near the top.

The Tuolumne middle region presents a sublime assemblage of glacier-born rocks, of which a general view may be obtained from the summit of Mount Hoffmann. These were overswept by the wide outlets of the great Tuolumne *mer de glare*. The Tuolumne Cañon outlet flowed across the edges of the best developed or north 35° east vertical cleavage planes, which gave rise to an extraordinary number of rocks, like Fig. 8, with their split and fractured faces invariably turned down stream, and round abraded sides up against the ice-current.

This glaciated landscape is unrivaled in general effect, combining as it does so many elements of sublimity. The summit mountains, majestic monuments of glacial force, rise grandly along the azure sky. The brown Tuolumne meadow, level as a floor, is spread in front, and on either side a broad swath of sombre pines, interrupted with many small meadow openings, around the edges of which the forest presses in smooth close lines. On the level bottom of the *mer de glace,* mountains once stood, which have been broken and swept away during the ice-winter like loose stones from a pavement. Where the deep glacial flood began to break down into the region of domes, a vast number of rock forms are seen on which their glacial history is written in lines of noble simplicity.

No attribute of this glacial landscape is more remarkable than the map-like distinctness of its varied features. The directions and magnitudes of the main ice-currents, with their numerous subordinate streams, together with the history of their fluctuations and final death, are eloquently expressed in the specific rocks, hills, meadows, and valleys over which they flowed. No commercial highway of the sea, edged with buoys and lamps, or of the land, with fences and guide-boards, is so unmistakably marked as these long-abandoned highways of the dead glaciers.

If, from some outlook still more comprehensive, the attentive observer contemplates the wide flank of the Sierra, furrowed with cañons, dimpled with lake basins, and waved with ridges and domes, he will quickly perceive that its present architectural surface is not the one upon which the first snows of the glacial winter fell, because, with the simple exceptions of the jagged summit-peaks from whose *névé* fountains the glaciers descended, there exists over all the broad flank of the range *not one weak rock form*. All that remain to roughen and undulate the surface are strong domes, or ridge-waves, or crests, with pavement-like levels or solid-walled cañons between. All the rest have been broken up and swept away by the glaciers. Some apparent exceptions to this general truth will present themselves, but these will gradually disappear in the light of patient investigation. The observer will learn that near the summit ice-fountains there are absolutely no exceptions, even in appearance, and that it is only when he follows down in the paths of the glaciers, and thus comes among rocks which were longer left bare by them in their gradual recession, that he begins to find instances of rocks at once weak in structure and strong in form.

The regular transition from strong to weak rocks will indicate that the greater weakness of those farther removed from the summits, is due to some force or forces which acted upon them subsequently to the time they were sustaining the wear and tear of the glaciers. The causes of this after-weakness are various. First we may note the most apparent—the slow decomposition of the mass of the rock by the atmosphere, under favorable conditions of heat and moisture. Some varieties of granite crumbled rapidly by the decomposition of their feldspar throughout the mass. Rocks traversed by feldspathic veins, that are otherwise strong, fall apart on the decomposition of the veins, into a heap of loose blocks. Frost also, combined with moisture, produces a wasted, shattered appearance. But by far the most general and influential cause of the feeble condition of old rocks, which formerly withstood the terrible ordeal of glacial action, is the subsequent development of one or several of their cleavage planes.

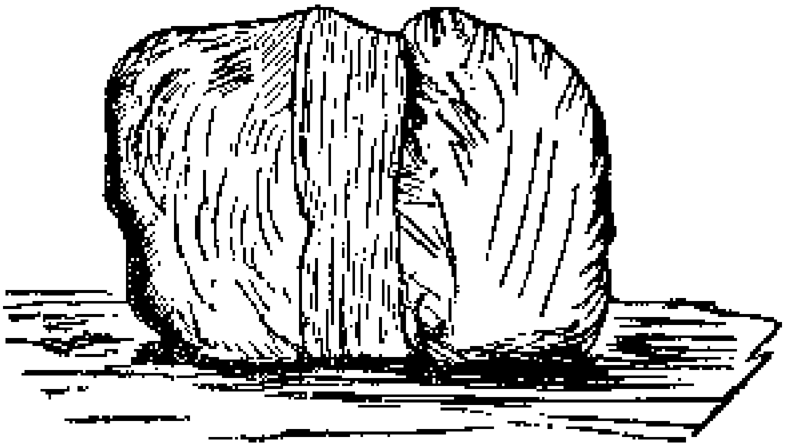


Fig. 13

For example, here is (Fig. 13) a boulder of hard metamorphic slate, which, after withstanding many a crush and blow in its winter history, until its angles were worn and battered, at length, on the recession of the glacier to which it belonged, came to rest on a smooth hard pavement, so level that it could not have rolled or fallen to its present position. Yet it is now split in two, having fallen apart by its own weight, on the ripening of one of its cleavage planes, just as the valves of seeds ripen, open, and fall.

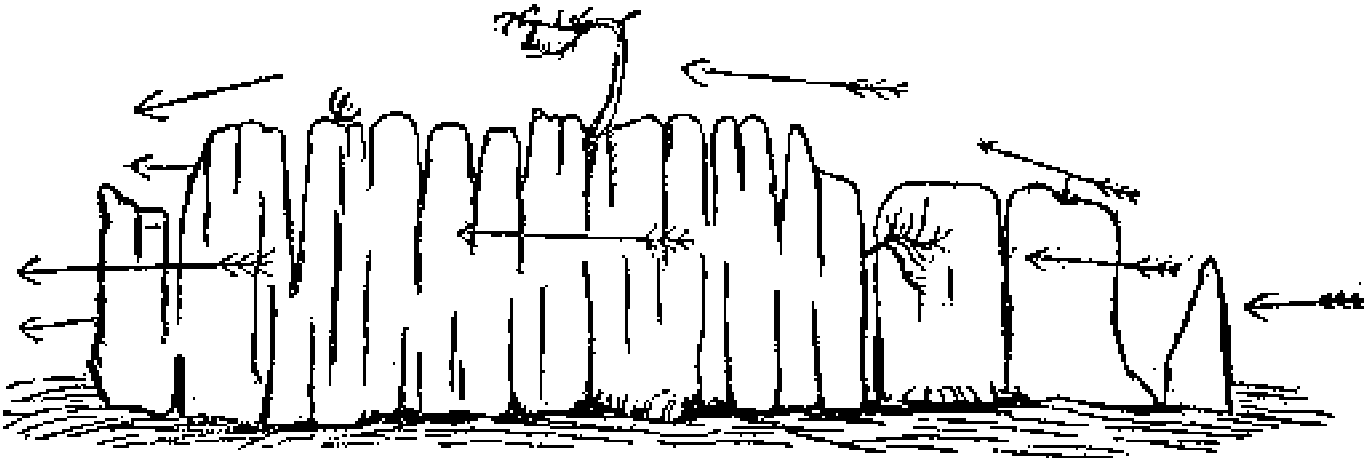


Fig. 14

Fig. 14 is a profile view of a rock 200 yards from the head of the Yosemite Fall, which is now weak and ready to fall apart by the development of the vertical north 35° east cleavage planes, the edges of which are seen in front; yet it is certain that this rock was once subjected to the strain of the oversweeping Yosemite basin glacier, when on its way to join the main trunk Yosemite glacier in the valley.

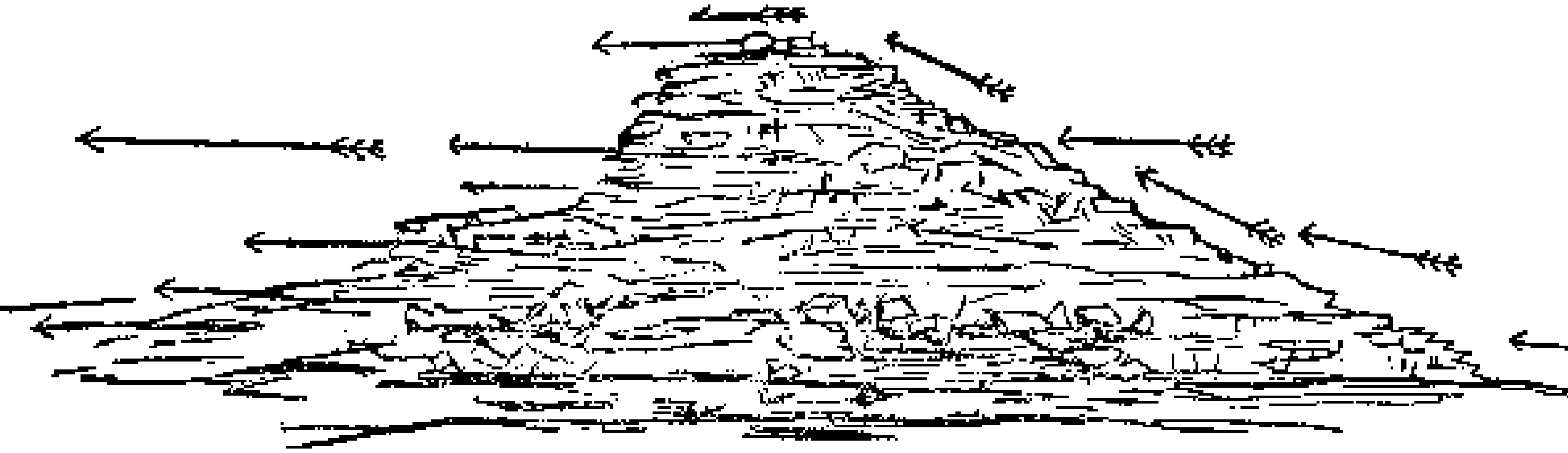


Fig. 15

Fig. 15 is a ruinous dome-top on the divide between Yosemite Creek basin and cascade. The beginner in such studies would not perceive that it had been overswept; yet hard portions near the base show clear evidence of glacial action, and, though ruinous and crumbling, it will at once appear to the educated eye that its longer diameter is exactly in the direction of the oversweeping ice-current, as indicated in the figure by the arrows. Rock masses, hundreds or even thousands of feet in height, abound in the channels of the ancient glaciers, which illustrate this argument by presenting examples in every stage of decay, the most decayed always occurring just where they have been longest exposed to disintegrating and general weathering agents. The record of ice phenomena, as sculptured, scratched, and worn upon the mountain surfaces, is like any other writing, faint and blurred according to the length of time and hard usage to which it has been exposed. It is plain, therefore, that the present sculptured condition of the Sierra is due to the action of ice and the variously developed cleavage planes and concentric seams which its rocks contain. The architect may build his structures out of any kind of stone, without their forms betraying the physical characters of the stone employed; but in Sierra architecture, *the style always proclaims the nature of the rock*.

In walking the sublime cañon streets of the Sierra, when we see an arch spanning the pine groves, we know that there is the section of a glacier-broken dome; where a gable presents itself, we recognize the split end of a ridge, with diagonal cleavage planes developed atop, and these again cut by a vertical plane in front. Does a sheer precipice spring from the level turf thousands of feet into the sky, there we know the rock is very hard, and has but one of its vertical cutting planes developed. If domes and cones appear, there we know the concentric structure predominates. No matter how abundant the glacial force, *a vertical precipice can not be produced unless its cleavage be vertical,* nor a dome without dome structure in the rock acted upon. Therefore, when we say that the glacial ice-sheet and separate glaciers *molded* the mountains, we must remember that their molding power upon *hard granite possessing a strong physical structure is* comparatively slight. In such hard, strongly built granite regions, *glaciers do not so much mold and shape,* as *disinter forms already conceived and ripe*. The harder the rock, and the better its specialized cleavage planes are developed, the greater will be the degree of controlling power possessed by it over its own forms, as compared with that of the disinterring glacier; and the softer the rock and more generally developed its cleavage planes, the less able will it be to resist ice action and maintain its own forms. In general, the *grain of a rock determines its surface forms;* yet it would matter but little what the grain might be-straight, curved, or knotty—if the excavating and sculpturing tool were sharp, because in that case it would cut without reference to the grain. Every carpenter knows that only a dull tool will follow the grain of wood. Such a tool is the glacier, gliding with tremendous pressure past splitting precipices and smooth swelling domes, flexible as the wind, yet hard-tempered as steel. Mighty as its effects appear to us, it has only developed the predestined forms of mountain beauty which were ready and waiting to receive the baptism of light.

II

Mountain Sculpture

Origin of Yosemite Valleys

All the valleys and cañons of the western flank of the Sierra, between 36° and 39° north latitude, naturally classify themselves under two genera, each containing two species. One genus comprehends all the slate valleys, the other all that are built of granite. The latter is far the more important, both on account of the greater extent of its geographical range and the grandeur and simplicity of its phenomena. All the valleys of both genera are valleys of erosion. Their chief distinguishing characteristic may be seen in the following descriptions:

Slate Valleys

1. Cross-sections, **V**-shaped, or somewhat rounded at bottom, walls *irregular in structure*, shattered and weak in appearance, because of the development of slaty cleavage planes and joints, which also prevent the formation of plane-faced precipice. Bottom showing the naked bed-rock, or covered by rocky debris, and sloping in the direction of the trend. Nearly all of the foothill valleys belong to this species. Some of the older specimens are smoothly covered with soil, but *meadows and lakes are always wanting*.

2. More or less widened, *branching at the head*. Bottom, with meadows, or groves or lakelets, or all together. Sections and wads about as in No. 1. Fine examples of this species occur on the head-waters of the San Joaquin.

Granite Valleys

1. Cross-sections narrowly or widely **V**-shaped. Walls seldom interrupted by side cañons, magnificently simple in structure and general surface character, and presenting plane precipices in great abundance. Bottom sloping in the direction of the trend, mostly bare, or covered with unstratified glacial and avalanche bowlders. Groves and meadows wanting.

2. *Branching at head, with beveled and heavily abraded lips at foot*. Bottom *level* meadowed, laked, or groved. Walls usually very high, often interrupted by side cañons. Sections as in No. 1. To this species belongs the far-famed *Yosemite* who origin we will now discuss.

We will henceforth make use of the word Yosemite both as a specific and geographical term.

Yosemite Valley is on the main Merced, in the middle region of the range. It is about seven miles long from east to west, with an average width at bottom of a little more than half a mile, and at the top of a mile and a half. The elevation of the bottom above sea level is about 4,000 feet. The average height of the walls is about 3,000 feet, made up of a series of sublime rock forms, varying greatly in size and structure, partially separated from one another by small side cañons. These immense wall-rocks, ranged picturesquely together, do not stand in line. Some advance their sublime fronts far out into the open valley, others recede. A few are nearly vertical, but far the greater number are inclined at angles ranging from twenty to seventy degrees. The meadows and sandy flats outspread between support a luxuriant growth of sedges and ferns, interrupted with thickets of azalea, willow and briar-rose. The warmer sloping ground along the base of the walls is planted with noble pines and oaks, while countless alpine flowers fringe the deep and dark side cañons, through which glad streams descend in falls and cascades, on their way from the high fountains to join the river. The life-giving Merced flows down the valley with a slow, stately current, curving hither and thither through garden and grove, bright and pure as the snow of its fountains. Such is Yosemite, the noblest of Sierra temples, everywhere expressing the working of Divine harmonious law, yet so little understood that it has been regarded as "an exceptional creation," or rather *exceptional destruction* accomplished by violent and mysterious forces. The argument advanced to support this view is substantially as follows: It is too wide for a water-eroded valley, too irregular for a fissure valley, and too angular and local for a primary valley originating in a fold of the mountain surface during the process of upheaval; therefore, a portion of the mountain bottom must have suddenly fallen out, letting the super-incumbent domes and peaks fall rumbling into the abyss, like coal into the bunker of a ship. This violent hypothesis, which furnishes a kind of Tophet for the reception of bad mountains, commends itself to the favor of many, by seeming to account for the remarkable sheerness and angularity of the walls, and by its marvelousness and obscurity, calling for no investigation, but rather discouraging it. Because we can not observe the bed-rock to ascertain whether or not it is fractured, this engulfment hypothesis seems to rest safely under cover of darkness, yet a film of lake gravel and a meadow blanket are its only concealments, and, by comparison with exposed sections in other Yosemites where the sheer walls unite with the solid, unfissured bottom, even these are in effect removed. It becomes manifest, by a slight attention to facts, that the hypothetical subsidence must have been limited to the valley proper, because both at the head and foot we find the solid bed-rock.

The breaking down of only one small portion of the mountain floor, leaving all adjacent to it undisturbed, would necessarily give rise to a very strongly marked line of demarcation, but no such line appears; on the contrary, the unchanged walls are continued indefinitely, up and down the river cañon, and lose their distinguishing characteristics in a gradual manner easily accounted for by changes in the structure of the rocks and lack of concentration of the glacial energy expended upon them. That there is comparatively so small a quantity of debris at the foot of Yosemite walls is advanced as an argument in favor of subsidence, on the grounds that the valley is very old, and that a vast quantity of debris must, therefore, have fallen from the walls by atmospheric agencies, and that the hypothetical "abyss" was exactly required to furnish storage for it. But the Yosemite Valley is not very old. It is very young, and no vast quantity of debris has ever fallen from its walls. Therefore, no abyss was required for its accommodation.

If, in accordance with the hypothesis, Yosemite is the only valley furnished with an abyss for the reception of debris, then we might expect to find all abyssless valleys choked up with the great quantity assumed to have fallen; but, on the contrary, we find their debris in the same condition as in Yosemite, and not more abundant. Indeed, in some portions of valleys as deep and sheer as Yosemite there is absolutely no talus, and that there never has been any is proved by both walls and bottom being *solid and ice-polished*. Many examples illustrative of this truth may be seen in the great Tuolumne and Kings River valleys.

Where the granite of Yosemite walls is intersected with feldspathic veins, as in the lowest of the Three Brothers and rocks near Cathedral Spires, large masses are loosened, from time to time, by the action of the atmosphere, and hurled to the bottom with such violence as to shake the whole valley; but the aggregate quantity which has been thus weathered off, so far from being sufficient to fill any great abyss, *forms but a small part of the debris slopes actually found on the surface,* all the larger angular taluses having been formed simultaneously by severe earthquake shocks that occurred three or four hundred years ago, as shown by their forms and the trees growing upon them. The attentive observer will perceive that *wherever a large talus occurs, the wall immediately above it presents a scarred and shattered surface* whose area is always proportional to the size of the talus, but *where there is no talus the wall is invariably moutonée or striated*, showing that it is young and has suffered little change since it came to light at the close of the glacial period. On the 23rd of March, 1872, I was so fortunate as to witness the sudden formation of one of these interesting taluses by the precipitation of the Yosemite Eagle Rock by the first heavy shock of the Inyo earthquake, whereby their local character and simultaneity of formation was fully accounted for. This *new earthquake* gave rise to the formation of many *new taluses* throughout the adjacent valleys, corresponding in every particular with the older and larger ones whose history we have been considering.

As to the important question, What part may water have played in the formation of Sierra valleys? we observe that, as far as Yosemite is concerned, the five large streams which flow through it are universally engaged in the work of *filling it up*. The granite of the region under consideration is but slightly susceptible of water denudation. Throughout the greater portion of the main upper Merced Valley the river has not eroded its channel to a depth exceeding three feet since it first began to flow at the close of the glacial epoch, although acting under every advantage of concentration and quick descent. The highest flood-mark the young river has yet recorded upon the clean glacial tablets of its banks is only seven or eight feet above the present level, at ordinary stages. Nevertheless, the aggregate annual quantity that formerly passed down these cañon valleys was undoubtedly far greater than passes at the present time, because on the gradual recession of the glaciers at the dose of the period, the supply would necessarily be more constant, from their melting all through the seasons. The evidence, however, is incontestable, which shows that the highest floods of Sierra rivers in the upper and middle regions of the range never much exceeded those of the present time.

Five immense glaciers from five to fifteen hundred feet in depth poured their icy floods into Yosemite, uniting to form one huge trunk, moved down through the valley with irresistible and never-ceasing energy, crushing and breaking up its strongest rocks, and scattering them in moraines far and near. Many, while admitting the possibility of ice having been the great agent in the production of Yosemite valleys, conjecture that earthquake fissures, or cracks from cooling or upheaval of the earth's crust, were required to enable the glaciers to make a beginning and to guide them in the work. We have already shown [in the earlier chapter about mountain sculpture] that cleavage planes and joints exist in a latent or developed condition in all the granite of the region, and that these exert immense influence on its glacial erodibility. During five years' observation in the Sierra, I have failed to discover a single fissure of any kind, although extensive areas of clean-swept glacial pavements afford ample opportunity for their detection, did they exist. Deep slots, with regular walls, appearing as if sawed, or mortised, frequently occur. These are formed by the disintegration of soft seams a few inches or feet in thickness, contained between walls of stronger granite. Such is the character of the so-called fissure said to exist in a hard portion of the south wall of Yosemite, opposite the Three Brothers, so frequently quoted in speculations upon the valley's origin.

The greatest effects of earthquakes on the valley we have already noticed in avalanche taluses, which were formed by the precipitation of weak headlands, that fell like ripe fruit. The greatest obstacle in the way of reading the history of Yosemite valleys is not its complexity or obscurity, but simply the *magnitude of the characters* in which it is written. It would require years of enthusiastic study to master the English alphabet if it were carved upon the flank of the Sierra in letters sixty or seventy miles long, their bases set in the foothills, their tops leaning back among the glaciers and shattered peaks of the summit, often veiled with forests and thickets, and their continuity often broken by cross-gorges and hills. So also the sculptured alphabet cañons of the Sierra are magnificently simple, yet demand years of laborious research for their apprehension. A thousand blurred fragments must be conned and brooded over with studious care, and kept vital and formative on the edges, ready to knit like broken living bones, while a final judgment is being bravely withheld until the entire series of phenomena has been weighed and referred to an allunifying, all-explaining law. To one who can leisurely contemplate Yosemite from some commanding outlook, it offers, as a whole, a far more natural combination of features than is at all apparent in partial views obtained from the bottom. Its stupendous domes and battlements blend together and manifest delicate compliance to law, for the mind is then in some measure emancipated from the repressive and enslaving effects of their separate magnitudes, and gradually rises to a comprehension of their unity and of the poised harmony of their general relations.

Nature is not so poor as to possess only one of anything, nor throughout her varied realms has she ever been known to offer an exceptional creation whether of mountain or valley. When, therefore, we explore the adjacent Sierra, we are not astonished to find that there are many Yosemite valleys identical in general characters, each presenting on a varying scale the same species of mural precipices, level meadows, and lofty waterfalls. The laws which preside over their distribution are as constant and apparent as those governing the distribution of forest trees. They occur only in the middle region of the chain, where the declivity is considerable and where the granite is Yosemitic in its internal structure. The position of each valley upon the Yosemitic zone indicates a marked and inseparable relation to the ancient glaciers, which, when fully deciphered, amounts to cause and effect. So constant and obvious is this connection between the various Yosemites and the *névé* amphitheatres which fountained the ancient ice-rivers, that an observer, inexperienced in these phenomena, might easily anticipate the position and size of any Yosemite by a study of the glacial fountains above it, or the position and size of the fountains by a study of their complementary Yosemite. *All Yosemites occur at the junction of two or more glacial cañons*. Thus the greater and lesser Yosemites of the Merced, Hetch Hetchy, and those of the upper Tuolumne, those of Kings River, and the San Joaquin, all occur immeditely below the confluence of their ancient glaciers. If, in following down the cañon channel of the Merced Glacier, from its origin in the *névé* amphitheatres of the Lyell group, we should find that its sudden expansion and deepening at Yosemite occurs without a corresponding union of glacial tributary cañons and without any similar expansion elsewhere, then we might well be driven to the doctrine of special marvels. But this emphatic deepening and widening becomes harmonious when we observe smaller Yosemites occurring at intervals all the way down, across the Yosemitic zone, *wherever a tributary cañon unites with the trunk,* until, on reaching Yosemite where the enlargement is greatest, we find the number of confluent glacier-cañons is also greatest, as may be observed by reference to Fig. 1.

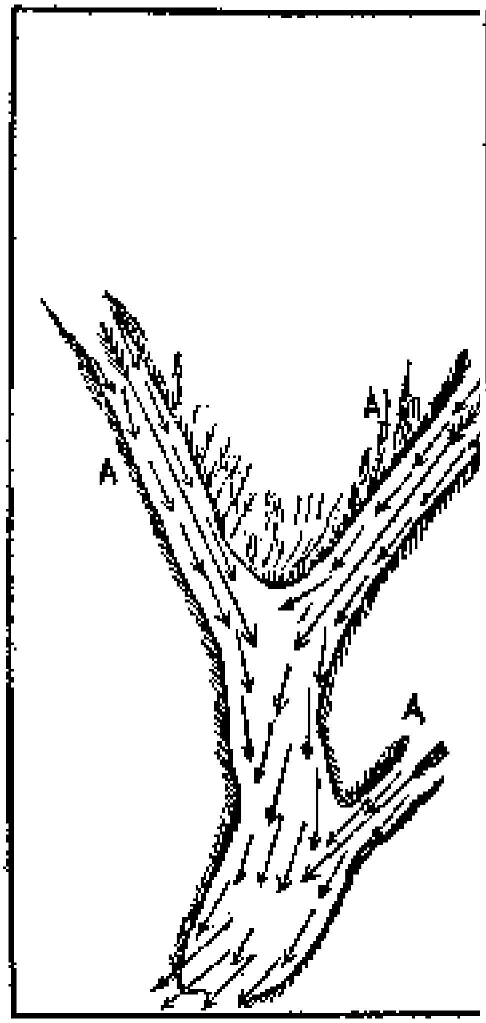


Fig. 1—Tuolumne Yosemite.
(A A A, Glaciers.)

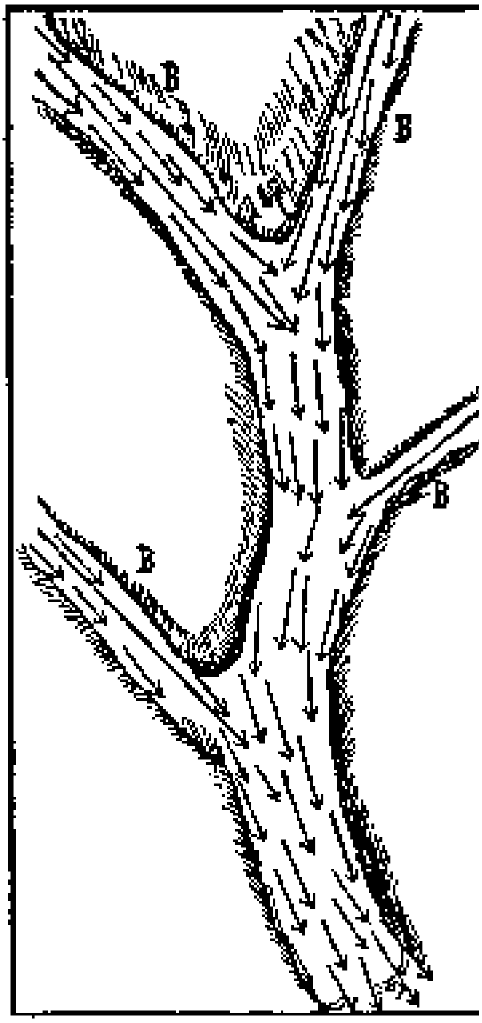


Fig. 2.—Kings River Yosemite.
(B B B B, Glaciers.)

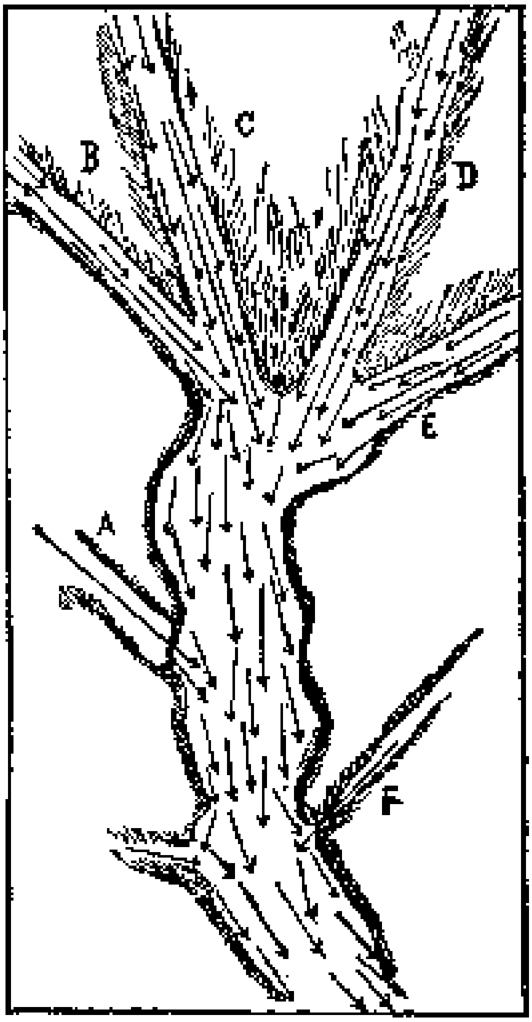


Fig. 3.—Merced Yosemite glaciers.
(A, Yosemite Creek; B, Hoffman;
C, Tenaya; D, South Lyell;
E, Illilouette; F, Pohono.)

Still further, the aggregate areas of their cross-sections is approximately equal to the area of the cross-sections of the several resulting Yosemites just as the cross-section of a tree trunk is about equal to the sum of the sections of its branches. *Furthermore, the trend of Yosemite valleys is always a direct resultant of the sizes, directions, and declivities of their confluent cañons*, modified by peculiarities of structure in their rocks. Now all the cañons mentioned above are the abandoned channels of glaciers, therefore, these Yosemites and their glaciers are inseparably related. Instead of being local in character, or formed by obscure and lawless forces, *these valleys are the only great sculpture phenomena whose existence and exact positions we may confidently anticipate.*

Depth of Yosemite

Much stress has been laid on the mere uncompared arithmetical depth of Yosemite, but this is a character of no consequence to the consideration of its origin. The greatest Merced Yosemite is 3,000 feet deep; the Tuolumne, 2,000; another, 1,000; but what geologist would be so unphilosophical as to decide against the identity of their origin from difference in depth only. One pine tree is 100 feet high, lean and crooked, from repressing winds and the poverty of the soil which nourished it; while another, more fortunate in the conditions of its life, is 200 feet high, erect and vigorous. So, also, one Yosemite is 3,000 feet deep because of the favorable structure of its rocks and the depth and number of ice-rivers that excavated it; another is half as deep, because of the strength of its rocks, or the scantiness of the glacial force exerted upon it. What would be thought of a botanist who should announce that our gigantic *Sequoia* was not a tree at all, offering as a reason that it was too large for a tree, and, in describing it, should confine himself to some particularly knotty portion of the trunk? In Yosemite there is an evergreen oak double the size of ordinary oaks of the region, whose trunk is craggy and angular as the valley itself, and colored like the granite bowlders on which it is growing. At a little distance this trunk would scarcely be recognized as part of a tree, until viewed in relation to its branches, leaves and fruit. It is an admirable type of the craggy Merced cañon-tree, whose angular Yosemite does not appear as a natural portion thereof until viewed in its relation to its wide-spreading branches, with their fruit and foliage of meadow and lake.

We present a ground-plan of three Yosemite valleys, showing the positions of their principal glaciers, and the relation of their trends and areas to them. The large arrows in Figs. 1, 2, 3 show the positions and directions of movement of the main confluent glaciers concerned in the erosion of three Yosemites. With regard to the number of their main glaciers, the Tuolumne Yosemite may be called a Yosemite of the *third* power; the Kings River Yosemite, of the fourth power; and the Merced Yosemite, of the fifth power. The granite in which each of these three Yosemites is excavated is of the same general quality; therefore, the differences of width, depth, and trend observed, are due almost entirely to the number, magnitude, declivity and mode of combination of the glacial system of each. The similarity of their ground-plans is obvious from a single glance at the figures; their cross-sections are no less similar. One of the most characteristic from each of the valleys under consideration is shown in Figs. 4, 5 and 6, drawn on the same scale.

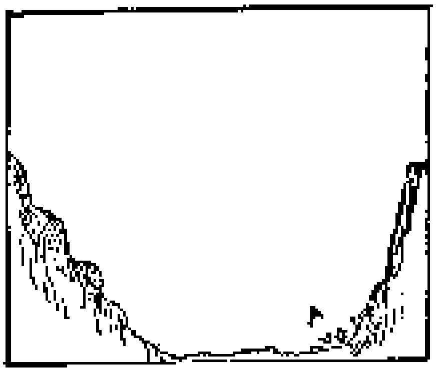


Fig. 4.—Section across the Hetch Hetchy Valley, or lower Tuolumne Yosemite

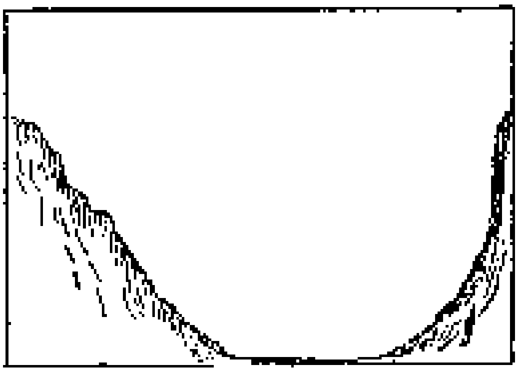


Fig. 5.—Section across the Kings River Yosemite

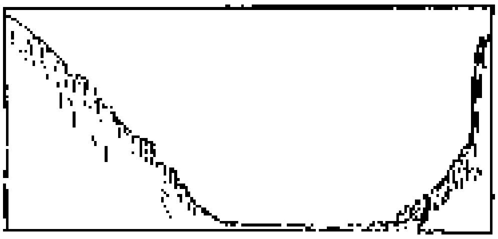


Fig. 6.—Section across Merced Yosemite

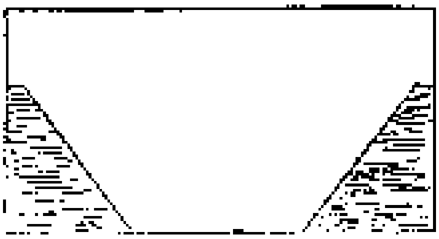


Fig. 7.—Idealized section across Merced Yosemite

The perpendicularity of Yosemite walls is apt to be greatly over-estimated. If the slopes of the Merced Yosemite walls were to be carefully measured with a clinometer at intervals of say 100 yards, it would be found that the average angle they make with the horizon is less than 50°, as shown in Fig. 7. It is not possible that the bottom could drop out of a valley thus shaped, no matter how great the upheaval or down-heaval, or side-heaval.

Having shown that Yosemite, so-called, is not unique in its ground-plan or cross-sections, we will now consider some of the most remarkable of its rock forms. The beautiful San Joaquin Dome in the cañon of the San Joaquin, near the confluence of the south fork, looking south (Fig. 9), shows remarkable resemblance to the Yosemite Half Dome, as seen from Tenaya Cañon (Fig. 8).

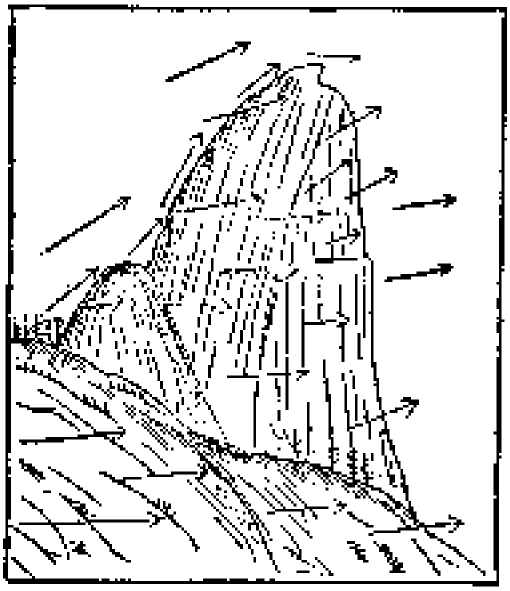


Fig. 8

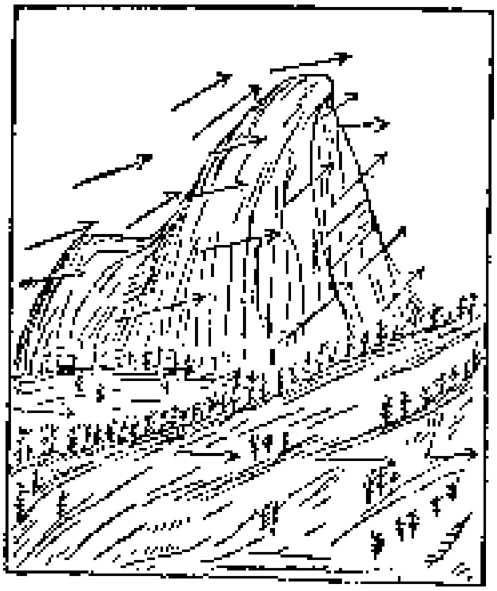


Fig. 9

They are similarly situated with reference to the glaciers that denuded them, Half Dome having been assailed by the combined Tenaya and Hoffman glaciers on the one side, and by the South Lyell or Merced Glacier on the other; the San Joaquin Dome, by the combined glaciers of the middle and north forks, on one side, and by the glaciers of the south fork on the other. The split dome of Kings River Yosemite is a worthy counterpart of the great Half Dome of the Merced Yosemite. They occur at about the same elevation, and are similarly situated with reference to the ancient glacial currents, which first overswept them and then glided heavily by on either side, breaking them up in chips and slabs, until fashioned and sculptured to their present condition. The Half Dome is usually regarded as being the most mysterious and unique rock form in the valley, or, indeed, in the world, yet when closely approached and studied, its history becomes plain.

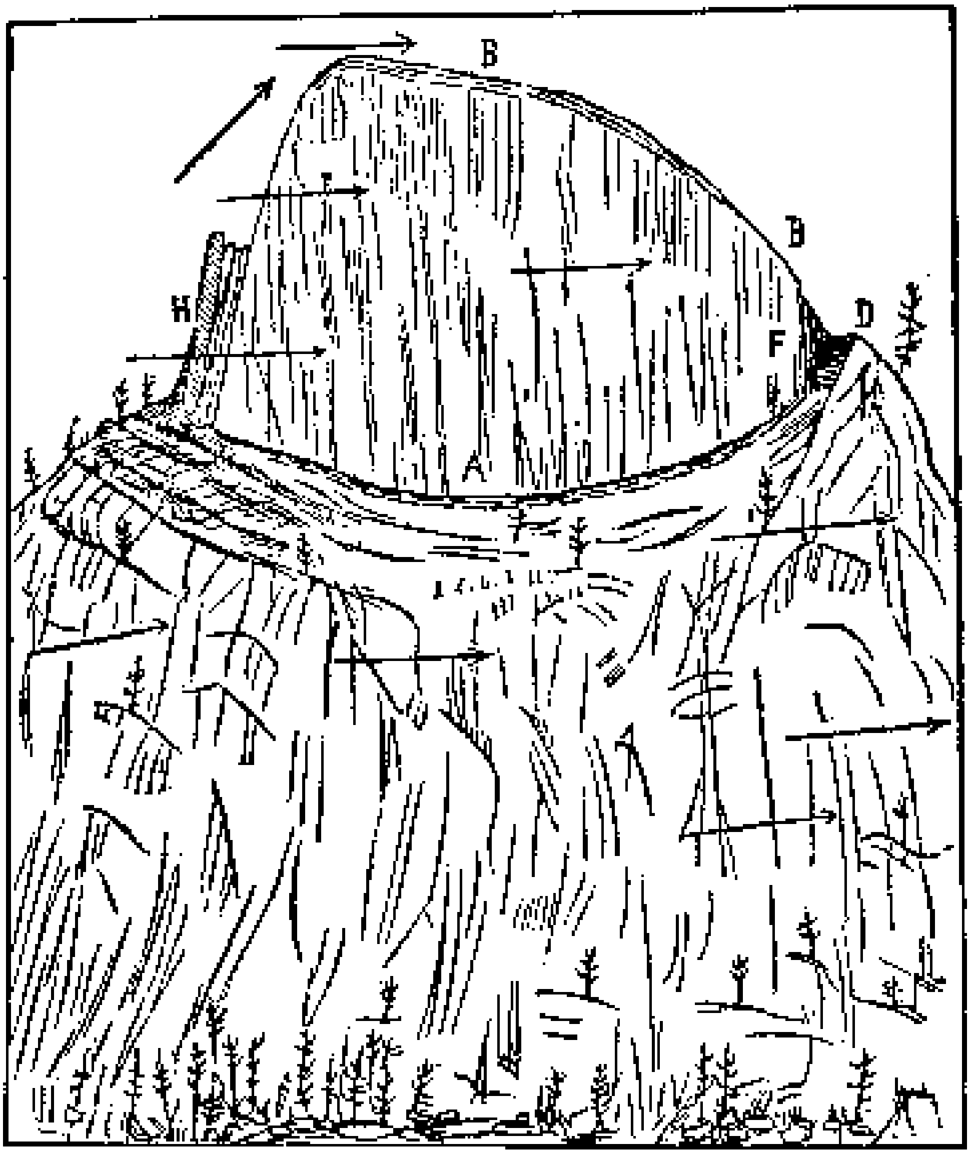


Fig. 10.—North Face of Half Dome,
Yosemite Valley

From A to B, Fig. 10, the height is about 1,800 feet; from A to the base, 3,000. The upper portion is almost absolutely plain and vertical, the lower is inclined at an angle with the horizon of about 37°. The observer may ascend from the south side to the shoulder of the dome at D, and descend along the face toward A H. In the notch at F a section of the dome may be seen, showing that it is there made up of immense slabs set on edge. These evidently have been produced by the development of cleavage planes, which, cutting the dome perpendicularly, have determined the plane of its face, which is the most striking characteristic of the rock. Along the front toward A H may be seen the stumps of slabs which have been successively split off the face. At H may be seen the edges of residual fragments of the same slabs. At the summit we perceive the cut edges of the concentric layers which have given the curved dome outline, B B. At D, a small gable appears, which has been produced by the development of diagonal cleavage planes which have been cut in front by vertical planes. After the passage of the main Tenaya Glacier in the direction of the arrows, small glacierets seem to have flowed down in front, eroding shallow groove channels in the direction of greatest declivity; and even before the total recession of the main glacier a wing-shaped ice-slope probably leaned back in the shadow, and with slow action eroded the upper portion of the dome. All the rocks forming the south walls of deep Yosemite cañons exhibit more or less of this light after-sculpture, effected in the shade after the north sun-beaten rocks were finished.

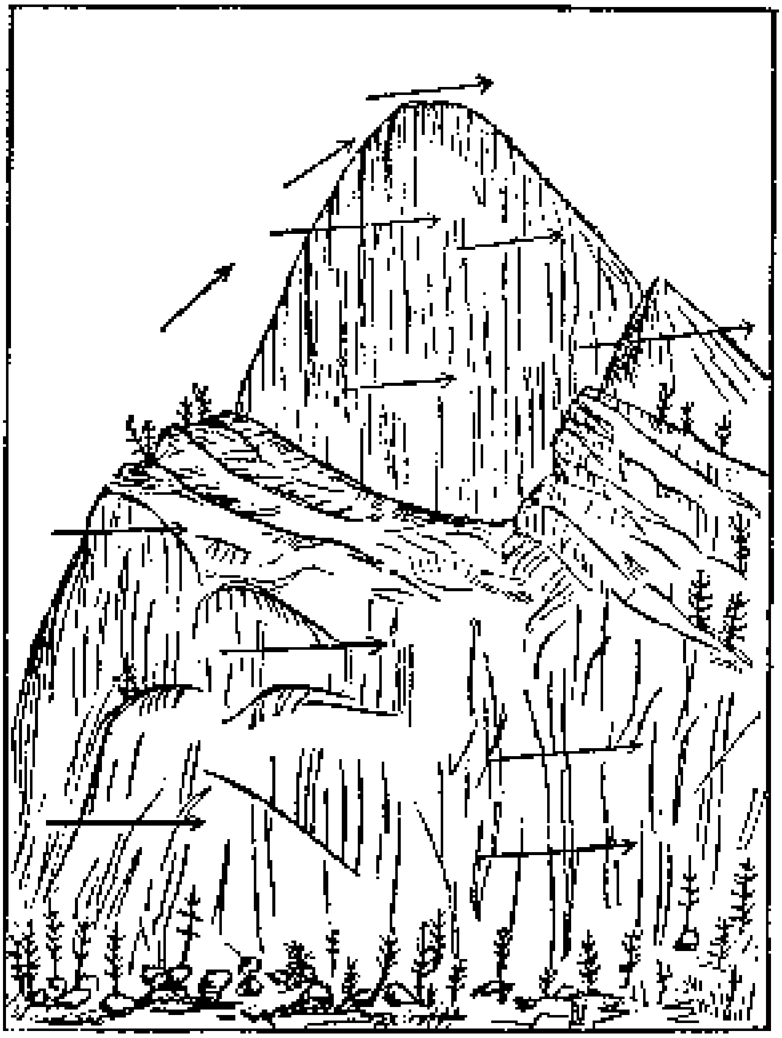


Fig. 11.—North Face of Half Dome
of Kings River Yosemite Valley

The south side of the dome has been heavily *moutonée* by the Lyell Glacier, but is, nevertheless, nearly as vertical as the north split side. The main body of the rock corresponds in form and attitude with every other rock similarly situated with reference to ice-rivers, and to elevation above sea level, the special split dome-top being, as we have seen, a result of special structure in the granite out of which it was formed. Numerous examples of this interesting species of rock may be culled from the various Yosemites, illustrating every essential character on a gradually changing scale.

Fig. 12 is a view of the back or south side of Half Dome, Yosemite, showing its *moutonée* condition; Fig. 13 represents El Capitan of Yosemite, situated on the north side of the valley; Fig. 14, El Capitan of Big Tuolumne Cañon, near the middle, situated on the north side; Fig. 15, El Capitan of Big Tuolumne Cañon, near the head, situated on the north side.

Fig. 12

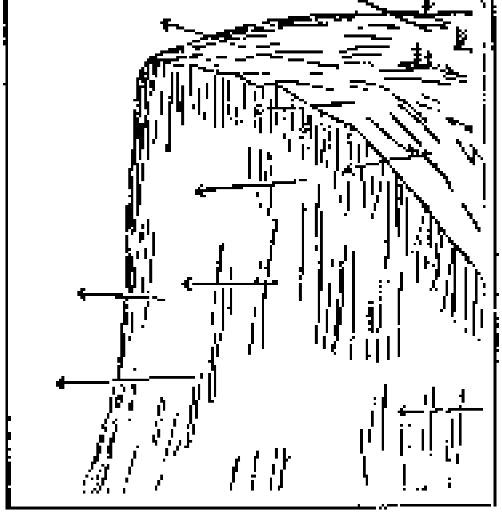


Fig. 13

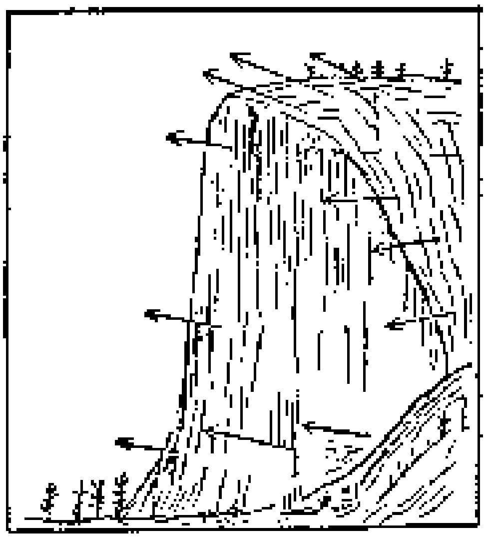


Fig. 14

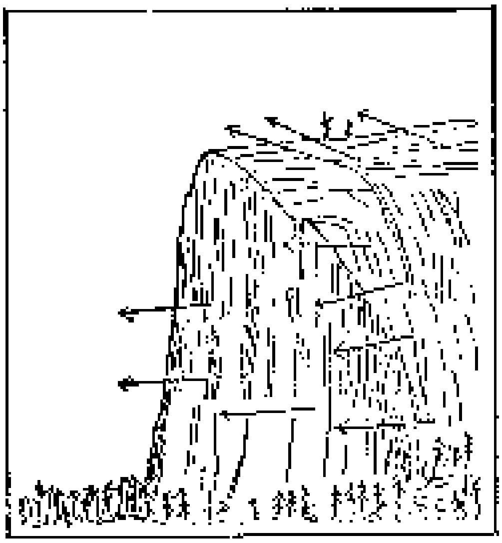


Fig. 15

The far-famed El Capitan rock presents a sheer cleaved front, over three thousand feet high, and is scarcely less impressive than the great dome. We have collected fine specimens of this clearly defined rock form from all the principal Yosemites of the region. Nevertheless, it also has been considered exceptional. Their origin is easily explained. They are simply *split ends of ridges which have been broken through by glaciers*.

For their perfect development the granite must be strong, and have some of its vertical cleavage planes well developed, nearly to the exclusion of all the others, especially of those belonging to the diagonal and horizontal series. A powerful trunk glacier must sweep past in front nearly in the direction of its cutting planes, with small glaciers, tributary to the first, one on each side of the ridge out of which the Capitan is to be made.

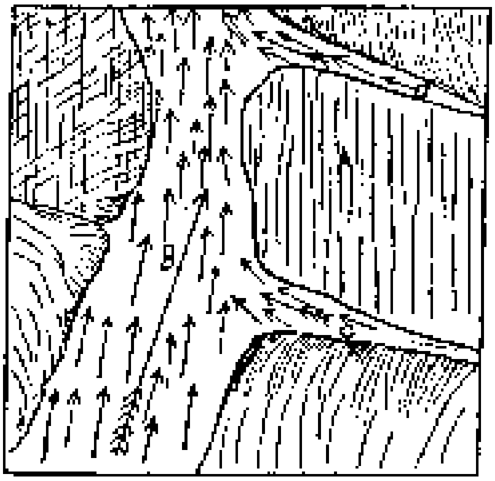


Fig. 16

This arrangement is illustrated in Fig. 16, where A represents a horizontal section of a Capitan rock, exposing the edges of the cleavage planes which determined the character of its face; B, the main glacier sweeping down the valley in front; and C C, the tributaries isolating it from the adjacent softer granite. The three Capitans figured stand thus related to the glaciers of the region where they are found. I have met with many others, all of which are thus situated, though in some instances one or both of the side glaciers had been wanting, leaving the resulting Capitan less perfect, considering the bold advancing Yosemite Capitan as a typical form.

When the principal surface features of the Sierra were being blocked out, the main ice-sheet was continuous and moved in a southerly direction, therefore the most perfect Capitans are invariably found on the north sides of valleys trending east and west. The reason will be readily perceived by referring to Fig. 8 of Chapter I.

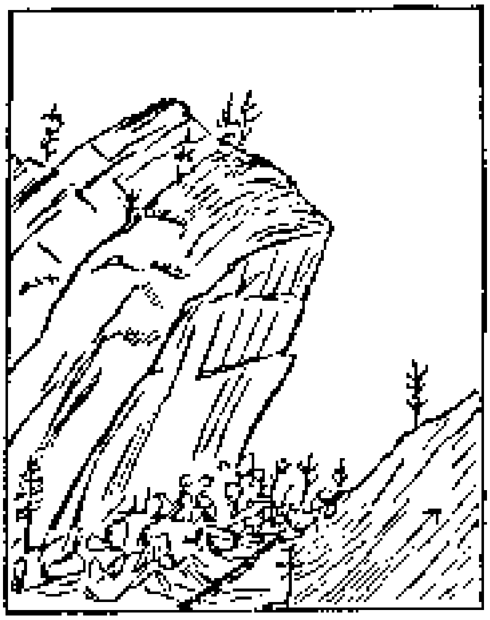


Fig. 17

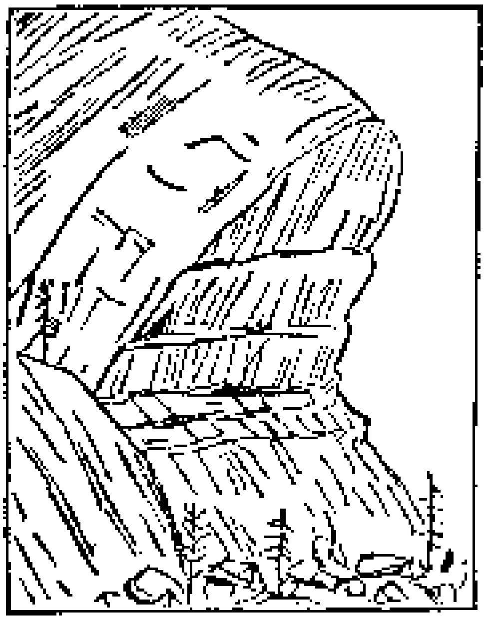


Fig. 18

To illustrate still further how fully the split fronts of rocks facing deep cañons have the angles at which they stand measured by their cleavage planes, we give two examples (Figs. 17 and 18) of leaning fronts from the cañon of the north fork of the San Joaquin River. Sentinel and Cathedral rocks also are found in other glacial cañons, and in every instance their forms, magnitudes, and positions are obviously the necessary result of the internal structure and general mechanical characters of the rock; out of which they were made, and of the glacial energy that has beer brought to bear on them. The abundance, therefore, of lofty angular rocks instead of rendering Yosemite unique, is the characteristic which unites it most intimately with all the other similarly situated valleys in the range.

III

Ancient Glaciers and Their Pathways

Though the gigantic glaciers of the Sierra are dead, their history is indelibly recorded in characters of rock, mountain, cañon, and forest; and, although other hieroglyphics are being incessantly engraved over these, “line upon line,” the glacial characters are so enormously emphasized that they rise free and unconfused in sublime relief, through every after inscription, whether of the torrent, the avalanche, or the restless heaving atmosphere.

In order to give the reader definite conceptions of the magnitude and aspect of these ancient ice-rivers, I will briefly outline those which were most concerned in the formation of Yosemite Valley and its cañon branches. We have seen (in the previous chapter) that Yosemite received the simultaneous thrust of the Yosemite Creek, Hoffmann, Tenaya, South Lyell, and Illilouette glaciers. These welded themselves together into one huge trunk, which swept down through the valley, receiving small affluents in its course from Pohono, Sentinel, and Indian cañons, and those on both sides of El Capitan Rock. At this period most of the upper portions of the walls of the valley were bare; but during its earliest history, the wide mouths of these several glaciers formed an almost uninterrupted covering of ice. All the ancient glaciers of the Sierra fluctuated in depth and width, and in degree of individuality, down to the latest glacial days. It must, therefore, be distinctly borne in mind that the following sketches of these upper Merced glaciers relate only to their separate condition, and to that phase of their separate condition which they presented toward the close of the period when Yosemite and its branches were works nearly accomplished.

Yosemite Creek Glacier

The broad, many-fountained glacier to which the basin of Yosemite Creek belonged, was about fourteen miles in length by four in width, and in many places was not less than a thousand feet in depth. Its principal tributaries issued from lofty amphitheatres laid well back among the northern spurs of the Hoffmann range. These at first pursued a westerly course; then, uniting with each other and absorbing a series of small affluents from the Tuolumne divide, the trunk thus formed swept round to the south in a magnificent curve, and poured its ice into Yosemite in cascades two miles wide. This broad glacier formed a kind of wrinkled ice-cloud. As it grew older, it became more regular and riverlike; encircling peaks overshadowed its upper fountains, rock islets rose at intervals among its shallowing currents, and its bright sculptured banks, nowhere overflowed, extended in massive simplicity all the way to its mouth. As the ice-winter drew near a close, the main trunk, becoming torpid, at length wholly disappeared in the sun, and a waiting multitude of plants and animals entered the new valley to inhabit the mansions prepared for them. In the meantime the chief tributaries, creeping slowly back into the shelter of their fountain shadows, continued to live and work independently, spreading moraine soil for gardens, scooping basins for lakelets, and leisurely completing the sculpture of their fountains. These also have at last vanished, and the whole basin is now full of light. Forests flourish luxuriantly over all its broad moraines, lakes and meadows nestle among its domes, and a thousand flowery gardens are outspread along its streams.

Hoffmann Glacier

The short, swift-flowing Hoffmann Glacier offered a striking contrast to the Yosemite Creek, in the energy and directness of its movements, and the general tone and tendencies of its life. The erosive energy of the latter was diffused over a succession of low boulderlike domes. Hoffmann Glacier, on the contrary, moved straight to its mark, making a descent of 5,000 feet in about five miles, steadily deepening and contracting its current, and finally thrusting itself against the upper portion of Yosemite in the form of a wedge of solid ice, six miles in length by four in width. The concentrated action of this energetic glacier, combined with that of the Tenaya, accomplished the greater portion of the work of the disinterment and sculpture of the great Half Dome, North Dome, and the adjacent rocks. Its fountains, ranged along the southern slopes of the main Hoffmann ridge, gave birth to a series of flat, wing-shaped tributaries, separated from one another by picturesque walls built of massive blocks, bedded and jointed like masonry. The story of its death is not unlike that of the Yosemite Creek, though the declivity of its channel and equal exposure to sun-heat prevented any considerable portion from passing through a torpid condition. It was first burned off on its lower course; then, creeping slowly back, lingered a while at the base of its mountains to finish their sculpture, and encircle them with a zone of moraine soil for gardens and forests.

The gray slopes of Mount Hoffmann are singularly barren in aspect, yet the traveler who is so fortunate as to ascend them will find himself in the very loveliest gardens of the Sierra. The lower banks and slopes of the basin are plushed with chaparral rich in berries and bloom—a favorite resort for bears; while the middle region is planted with the most superb forest of silver-fir I ever beheld. Nowhere are the cold footsteps of ice more warmly covered with light and life.

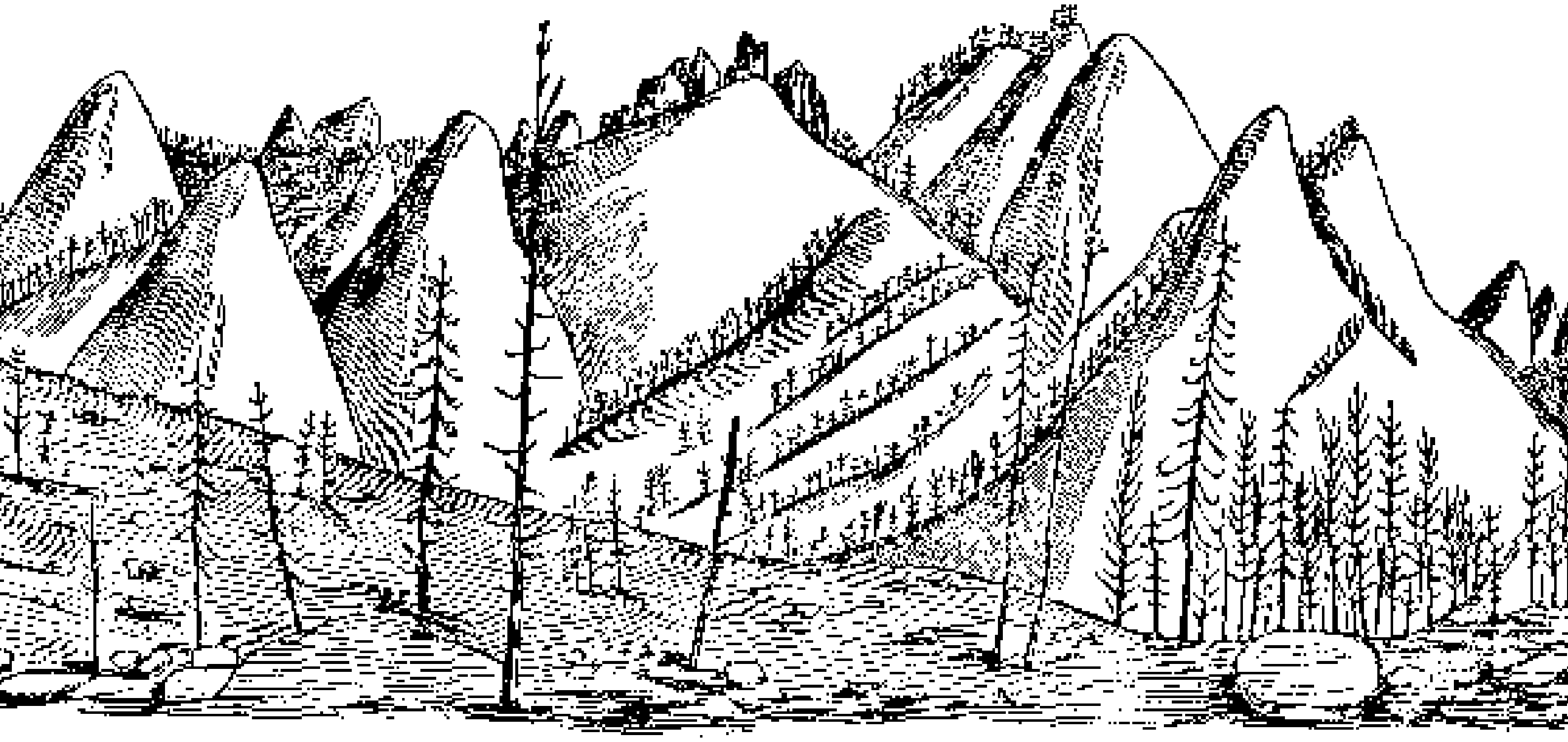
Tenaya Glacier

The rugged, strong-limbed Tenaya Glacier was about twelve miles long, and from half a mile to two and a half miles wide. Its depth varied from near 500 to 2,000 feet, according as its current was outspread in many channels or compressed in one. Instead of drawing its supplies directly from the summit fountains, it formed one of the principal outlets of the Tuolumne *mer de glace*, issuing at once from this noble source a full-grown glacier two miles wide and more than a thousand feet deep. It flowed in a general southwesterly direction, entering Yosemite at the head, between Half and North Domes. In setting out on its life-work it moved slowly, spending its strength in ascending the Tuolumne divide, and in eroding a series of parallel sub-channels leading over into the broad, shallow basin of Lake Tenaya. Hence, after uniting its main current, which had been partially separated in crossing the divide, and receiving a swift-flowing affluent from the fountains of Cathedral Peak, it set forth again with renewed vigor, pouring its massive floods over the southwestern rim of the basin in a series of splendid cascades; then, crushing heavily against the ridge of Clouds Rest, curved toward the west, quickened its pace, focalized its wavering currents, and bore down upon Yosemite with its whole concentrated energy. Toward the end of the ice-period, and while the upper tributaries of its Hoffmann companion continued to grind rock-meal for coming forests, the whole body of Tenaya became torpid, withering simultaneously from end to end, instead of dying gradually from the foot upward. Its upper portion separated into long parallel strips extending between the Tenaya basin and Tuolumne *mer de glare*. These, together with the shallow ice-clouds of the lake-basin melted rapidly, exposing broad areas of rolling rock-waves and glossy pavements, on whose channelless surface water ran everywhere wild and free. There are no very extensive morainal accumulations of any sort in the basin. The largest occur on the divide, near the Big Tuolumne Meadows, and on the sloping ground northwest of Lake Tenaya.* [* Because the main trunk died almost simultaneously throughout its whole extent, we, of course, find no terminal moraines curved across its channels, nor, since its banks were in most places too steeply inclined for their disposition, do we find much of the two laterals. One of the first Tenaya glacierets was developed in the shadow of Yosemite Half Dome. Others were formed along the bases of Coliseum Peak, and the long, precipitous walls extending from near Lake Tenaya to the Big Tuolumne Meadows. The latter, on account of the uniformity and continuity of their protecting shadows, formed moraines of considerable length and regularity, that are liable to be mistaken for portions of the left lateral moraine of the main glacier.]

For a distance of six miles from its mouth the pathway of this noble glacier is a simple trough from 2,000 to 3,000 feet deep, countersunk in the solid granite, with sides inclined at angles with the horizon of from thirty to fifty degrees. Above this its grand simplicity is interrupted by huge moutonéed ridges extending in the general direction of its length over into the basin of Lake Tenaya. Passing these, and crossing the bright glacial pavements that border the lake, we find another series of ridges, from 500 to 1,200 feet in height, extending over the divide to the ancient Tuolumne ice-fountain. Their bare moutonéed forms and polished surfaces indicate that they were overswept, existing at first as mere boulders beneath the mighty glacier that flowed in one unbroken current between Cathedral Peak and the southeast shoulder of the Hoffmann range.

Nevada or South Lyell Glacier

The South Lyell Glacier was less influential than the last, but longer and more symmetrical, and the only one of the Merced system whose sources extended directly to the main summits on the axis of the chain. Its numerous ice-wombs, now mostly barren, range side by side in three distinct series at an elevation above sea-level of from 10,000 to 12,000 feet. The first series on the right side of the basin extends from the Matterhorn to Cathedral Peak in a northwesterly direction a distance of about twelve miles. The second series extends in the same direction along the left side of the basin in the summits of the Merced group, and is about six miles in length. The third is about nine miles long, and extends along the head of the basin in a direction at right angles to that of the others, and unites with them at their southeastern extremities. The three ranges of summits in which these fountains are laid, and the long continuous ridge of Clouds Rest, enclose a rectangular basin, leaving an outlet near the southwest corner opposite its principal nave fountains, situated in the dark jagged peaks of the Lyell group. The main central trunk, lavishly fed by these numerous fountains, was from 1,000 to 1,400 feet in depth, from three-fourths of a mile to a mile and a half in width, and about fifteen miles in length. It first flowed in a northwesterly direction for a few miles, then curving toward the left, pursued a westerly course, and poured its shattered cascading currents down into Yosemite between Half Dome and Mount Starr King.



Portion of the Left Bank of the Channel of the South Lyell Glacier,
near the Mouth of Cathedral Tributary.

Could we have visited Yosemite toward the close of the glacial period, we should have found its ice-cascades vastly more glorious than their tiny water representatives of the present hour. One of the most sublime of these was formed by that portion of the South Lyell current which descended the broad, rounded shoulder of Half Dome. The whole glacier resembled an oak with a gnarled swelling base and wide-spreading branches. Its banks, a few miles above Yosemite, were adorned with groups of picturesque rocks of every conceivable form and mode of combination, among which glided swift-descending affluents, mottled with black slates from the summits, and gray granite blocks from ridges and headlands. One of the most interesting facts relating to the early history of this glacier is, that the lofty cathedral spur forming the northeast boundary of its basin was broken through and overflowed by deep ice-currents from the Tuolumne region. The scored and polished gaps eroded by them in their passage across the summit of the spur, trend with admirable steadiness in a northeasterly and southwesterly direction; a fact of great importance, considered in its bearings upon questions relating to the universal ice-sheet. *Traces of a similar overflow from the northeast occur on the edges of the basins of all the Yosemite glaciers*.

The principal moraines of the basin occur in short, irregular sections scattered along the sides of the valleys, or spread in rough beds in level portions of their bottoms, without manifesting subordination to any system whatever. This fragmentary condition is due to interruptions caused by portions of the sides of the valleys being too precipitous for moraine matter to rest upon and to breakings and down-washings of torrents and avalanches of winter snow. The obscurity resulting from these causes is further augmented by forests and underbrush, making a patient study of details indispensable to the recognition of their unity and simple grandeur. The south lateral moraine of the lower portion of the trunk may be traced about five miles, from the mouth of the north tributary of Mount Clark to the cañon of Illilouette, though simplicity of structure has in most places been prevented by the nature of the ground and by the action of a narrow margin glacier which descended against it with variable pressure from cool, shadowy slopes above. The corresponding section of the right lateral, extending from the mouth of Cathedral tributary to Half Dome, is far more perfect in structure, because of the evenness of the ground, and because the ice-wing which curved against Clouds Rest and descended against it was fully exposed to the sun, and was, therefore, melted long before the main trunk, allowing the latter to complete the formation of this section of its moraine undisturbed. Some conception of its size and general character may be obtained by following the Clouds Rest and Yosemite trail, which crosses it obliquely, leading past several cross-sections made by small streams. A few slate boulders from the Lyell group may be seen, but the main mass of the moraine is composed of ordinary granite and porphyry, the latter having been derived from Feldspar and Cathedral valleys.

The elevation of the top of the moraine near Cathedral tributary is about 8,100 feet; near Half Dome, 7,600. It rests upon the side of the valley at angles varying from fifteen to twenty-five degrees, and in many places is straight and uniform as a railroad embankment. The greatest depth of the glacier between Clouds Rest and Mount Starr King, measuring from the highest points of its lateral moraines, was 1,300 feet. The recurrence of ridges and terraces on its sides indicate oscillations in the level of the glacier, probably caused by clusters of cooler or snowier seasons which no doubt diversified the great glacial winter, just as clusters of sunny or stormy days occasion fluctuations in the level of the streams and prevent monotony in our annual winters. When the depth of the South Lyell Glacier diminished to about 500 feet, it became torpid, on account of the retardation caused by the roughness and crookedness of its channel. But though it henceforth made no farther advance of its whole length, it possessed feeble vitality-in small sections, of exceptional slope or depth, maintaining a squirming and swedging motion, while it lay dying like a wounded serpent. The numerous fountain wombs continued fruitful long after the lower valleys were developed and vitalized with sun-heat. These gave rise to an imposing series of short residual glaciers, extending around three sides of the quadrangle basin, a distance of twenty-four miles. Most of them have but recently succumbed to the demands of the changing seasons, dying in turn, as determined by elevation, size, and exposure. A few still linger in the loftiest and most comprehensive shadows, actively engaged upon the last hieroglyphics which will complete the history of the South Lyell Glacier, forming one of the noblest and most symmetrical sheets of ice manuscripts in the whole Sierra.

Illilouette

The broad, shallow glacier that inhabited the basin of Illilouette more resembled a lake than a river, being nearly half as wide as it was long. Its greatest length was about ten miles, and its depth perhaps nowhere much exceeded 700 feet. Its chief fountains were ranged along the western side of the Merced spur at an elevation of about 10,000 feet. These gave birth to magnificent affluents, flowing in a westerly direction for several miles, in full independence, and uniting near the center of the basin. The principal trunk curved northward, grinding heavily against the lofty wall forming its left bank, and finally poured its ice into Yosemite by the South Cañon between Glacier Point and Mount Starr King. All the phenomena relating to glacial action in this basin are remarkably simple and orderly, on account of the sheltered positions occupied by its principal fountains with reference to the unifying effects of ice-currents from the main summits of the chain. A fine general view, displaying the principal moraines sweeping out into the middle of the basin from Black, Red, Gray, and Clark mountains may be obtained from the eastern base of the cone of Starr King. The right lateral of the tributary which took its rise between Red and Black mountains is a magnificent piece of ice-work. Near the upper end, where it is joined to the shoulder of Red Mountain, it is 250 feet in height, and displays three well marked terraces. From the first to the second of these, the vertical descent is eighty-five feet, and inclination of the surface fifteen degrees; from the second to the third, ninety-five feet, and inclination twenty-five degrees; and from the third to the bottom of the channel, seventy feet, made at an angle of nineteen degrees. The smoothness of the uppermost terrace shows that it is considerably more ancient than the others, many of the blocks of which it was composed having crumbled to sand.

A few miles farther down, the moraine has an average slope in front of about twenty-seven degrees, and an elevation above the bottom of the channel of six hundred and sixty-six feet. More than half of the side of the channel from the top is covered with moraine matter, and overgrown with a dense growth of chaparral, composed of manzanita, cherry, and castanopsis. Blocks of rose-colored granite, many of them very large, occur at intervals all the way from the western base of Mount Clark to Starr King, indicating exactly the course pursued by the ice when the north divide of the basin was overflowed, Mount Clark being the only source whence they could possibly have been derived.

Near the middle of the basin, just where the regular moraines flatten out and disappear, there is outspread a smooth gravel slope, planted with the olive-green *Arctostaphylos glauca* so as to appear in the distance as a delightful meadow. Sections cut by streams show it to be composed of the same material as the moraines, but finer and more water-worn. The main channel, which is narrow at this point, appears to have been dammed up with ice and terminal moraines, thus giving rise to a central lake, at the bottom of which moraine matter was re-ground and subsequently spread and leveled by the impetuous action of its outbreaking waters. The southern boundary of the basin is a strikingly perfect wall, extending sheer and unbroken from Black Mountain* [* This mountain occurs next south of Red Mountain, and must not be confounded with the Black Mountain six miles farther south.] to Buena Vista Peak, casting a long, cool shadow all through the summer for the protection of fountain snow. The northern rim presents a beautiful succession of smooth undulations, rising here and there to a dome, their pale gray sides dotted with junipers and silver-leafed pines, and separated by dark, feathery base-fringes of fir.

The ice-plows of Illilouette, ranged side by side in orderly gangs, have furrowed its rocks with admirable uniformity, producing irrigating channels for a brood of wild streams, and abundance of deep, rich soils, adapted to every requirement of garden and grove. No other section of the Yosemite uplands is in so high a state of glacial cultivation. Its clustering domes, sheer walls, and lofty towering peaks, however majestic in themselves, are only border adornments, submissively subordinate to their sublime garden center. The basins of Yosemite Creek, Tenaya, and South Lyell are pages of sculptured rocks embellished with gardens. The Illilouette basin is one grand garden embellished with rocks.

Nature manifests her love for the number five in her glaciers, as well as in the petals of the flowers which she plants in their pathways. These five Yosemite glaciers we have been sketching are as directly related to one another, and for as definite an object, as are the organs of a plant. After uniting in the valley, and expending the down-thrusting power with which they were endowed by virtue of the declivity of their channels, the trunk flowed *up out of* the valley without yielding much compliance to the crooked and comparatively small river cañon extending in a general westerly direction from the foot of the main valley. In effecting its exit a considerable ascent was made, traces of which are to be seen in the upward slope of the worn, rounded extremities of the valley walls. Down this glacier-constructed grade descend both the Coulterville and Mariposa trails; and we might further observe in this connection that, because the ice-sheet near the period of transition to distinct glaciers flowed southwesterly the south lips of all Yosemites trending east and west, other conditions being equal, are more heavily eroded, making the construction of trails on that side easier. The first trail, therefore, that was made into Yosemite, was of course made down over the south lip. The only trail entering the Tuolumne Yosemite descends the south lip, and so also does the only trail leading into the Kings River Yosemite. A large majority of deer and bear and Indian trails likewise descend the south lips of Yosemites. So extensively are the movements of men and animals controlled by the previous movements of certain snow-crystals combined as glaciers.

The direction pursued by the Yosemite trunk, after escaping from the valley, is unmistakably indicated by its immense lateral moraines extending from its lips in a west-southwesterly direction. The right moraine was disturbed by the large tributary of Cascade Creek, and is extremely complicated in structure. The left is simple until it comes under the influence of tributaries from the southeast, and both are further obscured by forests which flourish upon their mixed soil, and by the washing of rains and melting snows, and the weathering of their boulders, making a smooth, sandy, unmorainelike surface. It is, therefore, the less to be wondered at that the nature of these moraines, which represent so important a part of the chips hewn from the valley in the course of its formation, should not have been sooner recognized. *Similarly situated moraines extend from the lips of every Yosemite* wherever the ground admits of their deposition and retention. In Hetch-Hetchy and other smaller and younger Yosemites of the upper Merced, the ascending *striae* which measure the angle of ascent made by the bottom of their glaciers in their outflow are still clearly visible.

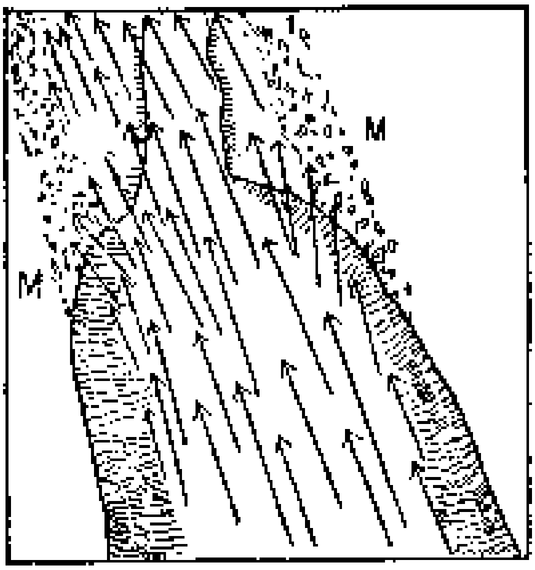


Fig. 1

Fig. 1 is the horizontal section of the end of a Yosemite valley, showing the ordinary boat-shaped edge, and lateral moraines (M M) extending from the lips. The moraines and arrows indicate the course pursued by the outflowing ice.

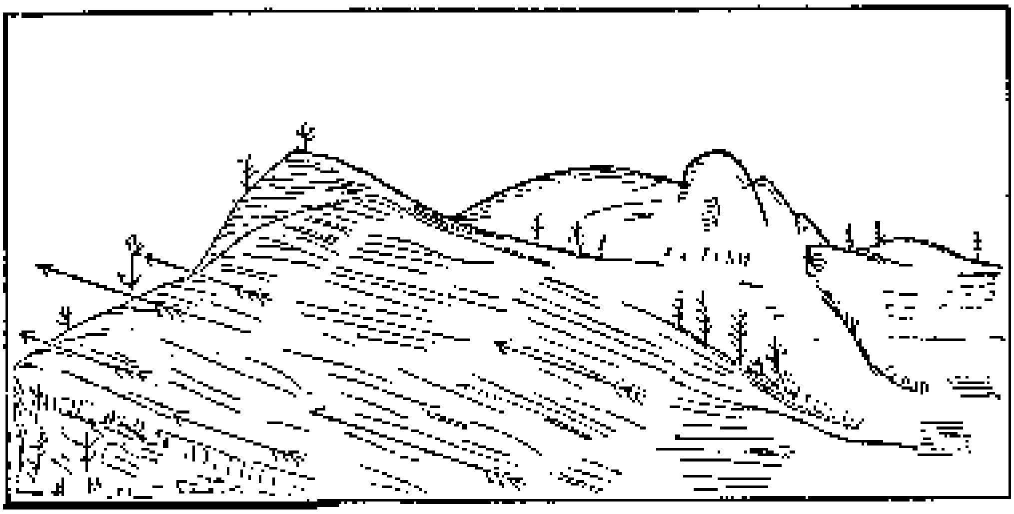


Fig. 2

Fig. 2 represents the right lip of Yosemite, situated on the upper Merced below the confluence of Cathedral tributary. The whole lip is polished and striated. The arrows indicate the direction of the *striae*, which measure the angle of ascent made by the outflowing ice.

In the presentation of these studies, we have proceeded thus far with the assumption that all the valleys of the region are valleys of erosion, and that glaciers were the principal eroding agents; because the intelligible discussion of these propositions requires some knowledge of the physiognomy and general configuration of the region, as well as of the history of its ancient glaciers. Our space is here available only for very brief outlines of a portion of the argument, which will be gradually developed in subsequent articles.

That fossils were created as they occur in the rocks, is an ancient doctrine, now so little believed that geologists are spared the pains of proving that nature ever deals in fragmentary creations of any sort. All of our valleys are clearly fragmentary in some degree.

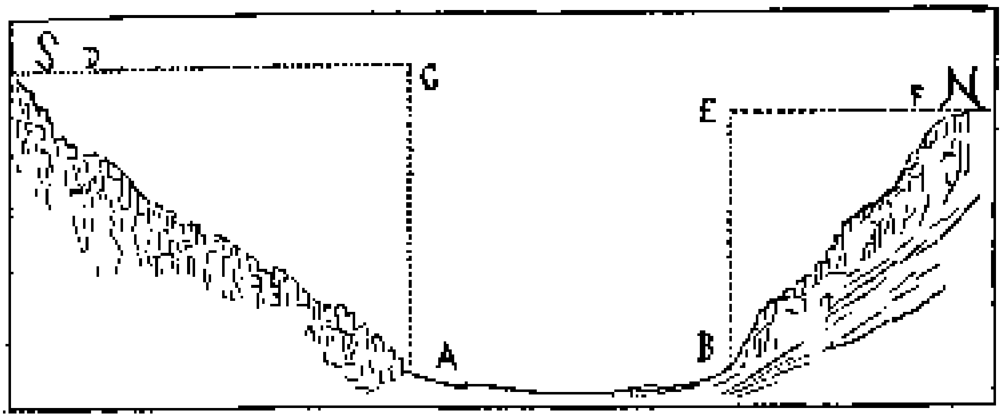


Fig. 3

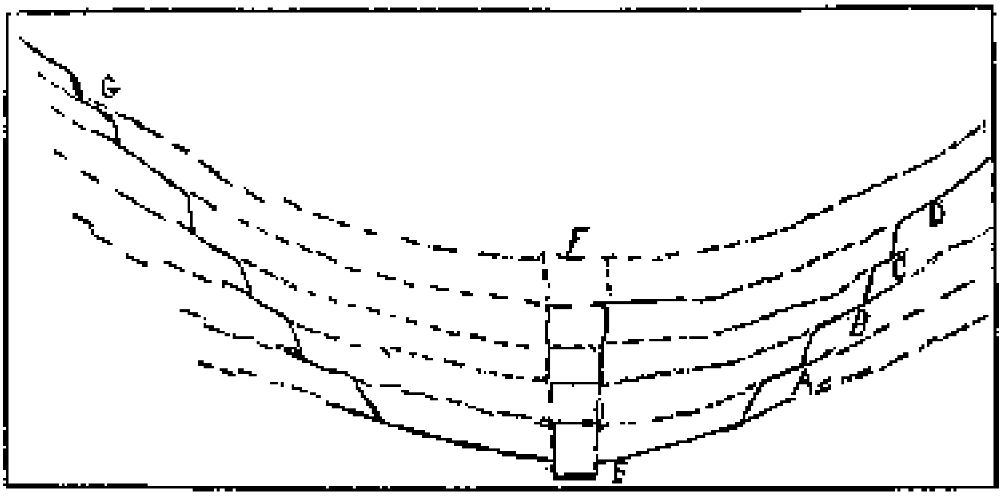


Fig. 4

Fig. 3 is a section across Yosemite Valley from Indian Cañon, which displays the stumps of slabs and columns of which the granite is here composed. Now, the complements of these broken rocks must have occupied all, or part, or more than all of the two portions of the valley, A C D and B E F. The bottom, A B, is covered with drift, but we may assume that if it were laid bare we would find it made up of the ends of slabs and columns like the sides, which filled the space A C E B; because in all valleys where the bottom is naked, the broken stumps *do* appear, showing that this valley was not formed by a fold in the mountain surface, or by a splitting asunder, or by subsidence, but by a breaking up and translation of rocks which occupied its place, or, in other words, by erosion.

Fig. 4 is a section across the lower portion of the valley of Illilouette south of Mount Starr King. In this case the bottom is naked, and the dotted reconstructed portions of the huge granite folds A B C D have evidently been eroded.* [* Water never erodes a wide **U**-shaped valley in granite, but always a narrow gorge like *E F*, in Fig. 4.] Even the smoothly curved trough of two rock-waves which afford sections like Fig. 5 can not be regarded as a valley originating in a fold of the surface, for we have shown in the first paper of this series that domes or extended waves, with a concentric structure like A C, may exist as concretionary or crystalline masses beneath the surface of granite possessing an entirely different structure or no determinate structure whatever, as in B.

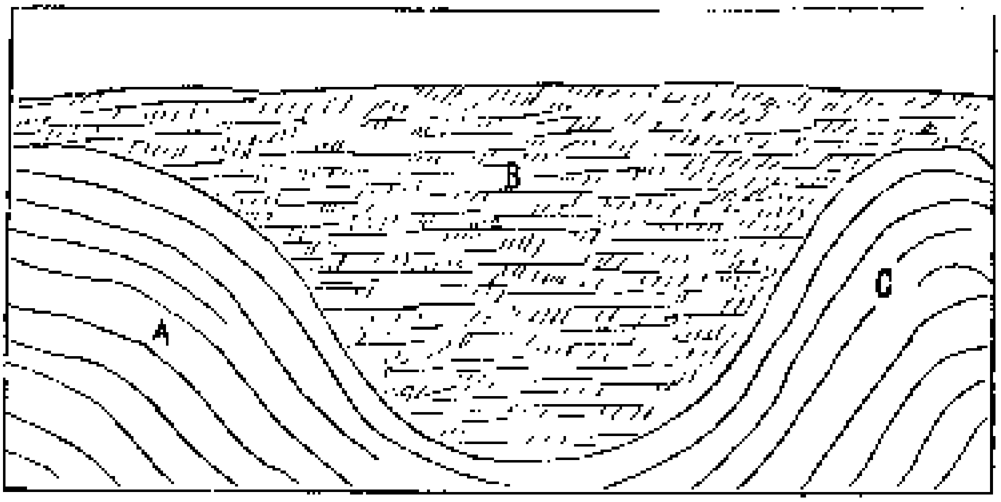


Fig. 5

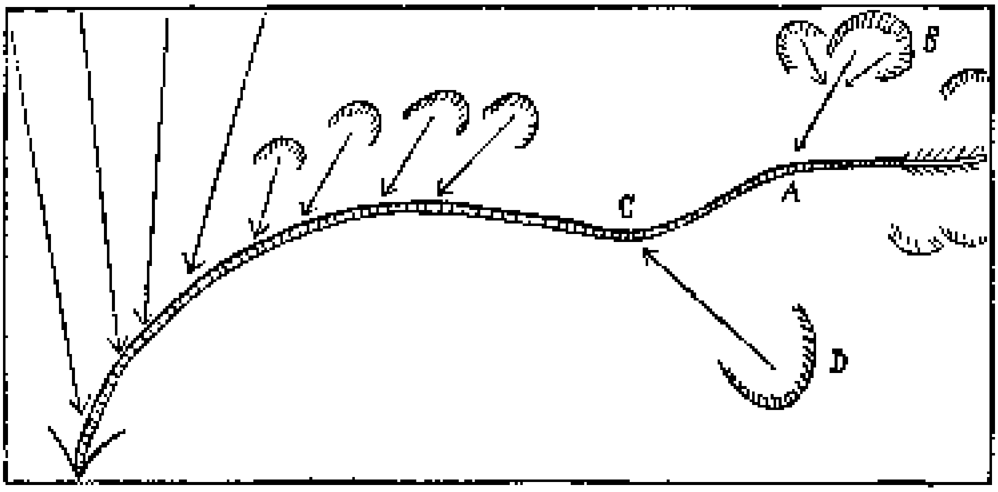


Fig. 6.—Illustrating Bend of Upper Tuolumne Valley

The chief valley-eroding agents are water and ice. Each has been vaguely considered the more influential by different observers, although the phenomena to which they give rise are immensely different. These workmen are known by their chips, and only glacier chips form moraines which correspond in kind and quantity to the size of the valleys and condition of their surfaces. Also their structure unfolds the secret of their origin. The constant and inseparable relations of trend, size, and form which these Sierra valleys sustain to the ice-fountains in which they all head, as well as their grooved and broken sides, proclaim the eroding force to be ice. We have shown in the second chapter that the trend of Yosemite valleys is always a direct resultant of the forces of their ancient glaciers, modified by obvious peculiarities of physical structure of their rocks. The same is true of all valleys in this region. We give one example, the upper Tuolumne Valley, which is about eight miles long, and from 2,000 to 3,000 feet deep, and trends in a generally northerly direction. If we go to its head on the base of Mount Lyell, and follow it down, we find that after trending steadily about two miles it makes a bend of a few degrees to the *left* (A, Fig. 6). Looking for the cause, we perceive a depression on the *opposite* or right wall; ascending to it, we find the depression to be the mouth of a tributary valley which leads to a crater-shaped ice-fountain (B) which gave rise to the tributary glacier that, in thrusting itself into the valley trunk, caused the bend we are studying. After maintaining the new trend thus acquired for a distance of about a mile and a half, the huge valley swerves lithely to the *right* at C. Looking for the cause, we find another tributary ice-grooved valley coming in on the *left*, which like the first conducts back to an ice-womb (D) which gave birth to a glacier that in uniting with the trunk pushed it aside as far as its force, modified by the direction, smoothness, and declivity of its channel, enabled it to do. Below this, the noble valley is again pushed round in a curve to the *left* by a series of small tributaries which, of course, enter on the *right*, and with each change in trend there is always a corresponding change in width or depth, or in both. *No valley changes its direction without becoming larger*. On nearing the Big Meadows it is swept entirely round to the west by huge glaciers, represented by the large arrows, which descended from the flanks of Mounts Dana, Gibbs, Ord, and others to the south. For thirty miles farther, we find everywhere displayed the same delicate yielding to glacial law, showing that, throughout the whole period of its formation, the huge granite valley was lithe as a serpent, and winced tenderly to the touch of every tributary. So simple and sublime is the dynamics of the ancient glaciers.

Every valley in the region gives understandable evidence of having been equally obedient and sensitive to glacial force, and to no other. The erosive energy of ice is almost universally underrated, because we know so little about it. Water is our constant companion, but we cannot dwell with ice. Water is far more human than ice, and also far more outspoken. If glaciers, like roaring torrents, were endowed with voices commensurate with their strength, we would be slow to question any ascription of power that has yet been bestowed upon them. With reference to size, we have seen that the greater the ice-fountains the greater the resulting valleys; but no such direct and simple proportion exists between areas drained by water streams and the valleys in which they flow. Thus, the basin of Tenaya is *not one-fourth the size* of the South Lyell, although *its cañon is much larger*. Indeed, many cañons have no streams at all, whose topographical circumstances are also such as demonstrate the impossibility of their ever having had any. This state of things could not exist if the water streams which succeeded the glaciers could follow in their tracks, but the mode and extent of the compliance which glaciers yield to the topography of a mountainside, is very different from that yielded by water streams; both follow the lines of greatest declivity, but the former in a far more general way. Thus, the greater portion of the ice-current which eroded Tenaya Cañon flowed over the divide from the Tuolumne region, *making an ascent of over 500 feet*. Water streams, of course, could not follow; hence the dry channels, and the disparity, to which we have called attention, between Tenaya Cañon and its basin.

Anyone who has attentively observed the habits and gestures of the upper Sierra streams, could not fail to perceive that they are young, and but little acquainted with the mountains; rushing wildly down steep inclines, whirling in pools, sleeping in lakes, often halting with an embarrassed air and turning back, groping their way as best they can, moving most lightly just where the glaciers bore down most heavily. With glaciers as a key the secrets of every valley are unlocked. Streams of ice explain all the phenomena; streams of water do not explain any; neither do subsidences, fissures, or pressure plications.

We have shown in the previous paper that *post-glacial streams have not eroded the 500,000th part of the upper Merced cañons*. The deepest water gorges with which we are acquainted are between the upper and lower Yosemite falls, and in the Tenaya Cañon about four miles above Mirror Lake. These are from twenty to a hundred feet deep, and are easily distinguished from ice-eroded gorges by their narrowness and the ruggedness of their washed and pot-holed sides.

The gorge of Niagara River, below the falls, is perhaps the grandest known example of a valley eroded by water in compact rock; yet, comparing equal lengths, the glacier-eroded valley of Yosemite is a hundred times as large, reckoning the average width of the former 900 feet, and depth 200. But the erosion of Yosemite Valley, besides being a hundred times greater, was accomplished in hard granite, while the Niagara was in shales and limestones. Moreover, Niagara cañon, as it now exists, expresses nearly the whole amount of erosion effected by the river; but the present Yosemite is by no means an adequate expression of the whole quantity of glacial erosion effected there since the beginning of the glacial epoch, or even from that point in the period when its principal features began to be developed, because the walls were being cut down on the top simultaneously with the deepening of its bottom. We may fairly ascribe the formation of the Niagara gorge to its river, because we find it at the upper end engaged in the work of its further extension toward Lake Erie; and for the same reason we may regard glaciers as the workmen that excavated Yosemite, for at the heads of some of its branches we find small glaciers engaged in the same kind of excavation. Merced cañons may be compared to mortises in the ends of which we still find the chisels that cut them, though now rusted and worn out. If Niagara River should vanish, or be represented only by a small brook, the evidence of the erosion of its gorge would still remain in a thousand water-worn monuments upon its walls. Nor, since Yosemite glaciers have been burned off by the sun, is the proof less conclusive that in their greater extension they excavated Yosemite, for, both in shape and sculpture, *every Yosemite rock is a glacial monument*.

When we walk the pathways of Yosemite glaciers and contemplate their separate works-the mountains they have shaped, the cañons they have furrowed, the rocks they have worn, and broken, and scattered in moraines—on reaching Yosemite, instead of being overwhelmed as at first with its uncompared magnitude, we ask, *Is this all?* wondering that so mighty a concentration of energy did not find yet grander expression.

IV

Glacial Denudation

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.

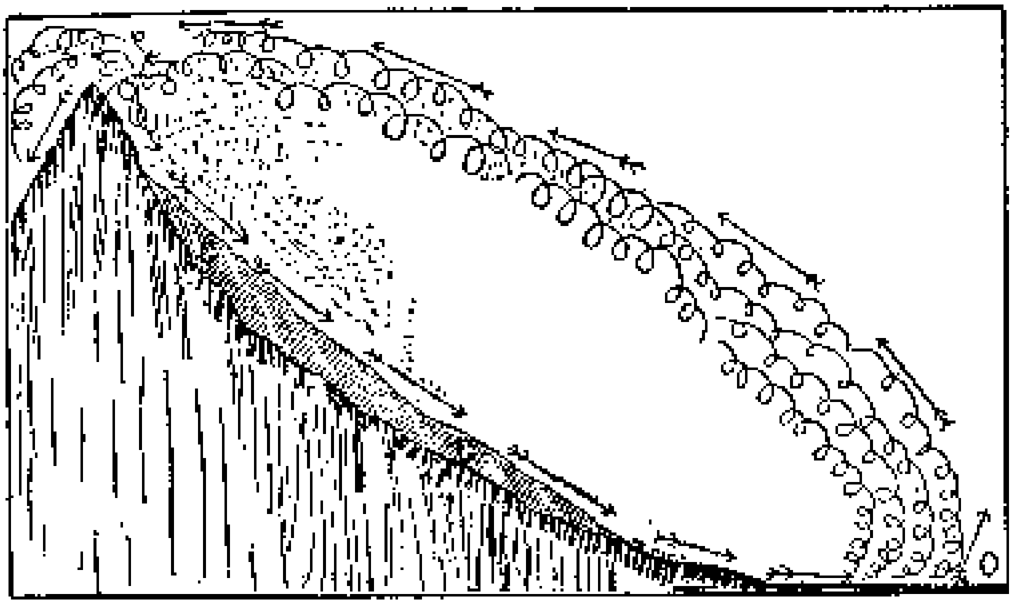


Fig. 1

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 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;* [*According to Captain Hodgson.] 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 the very important modifications in its general application. Subordinate ranges many hundred feet in height are frequently oversweptsmoothly and gracefully without any visible manifestations of power. Thus, the Tenaya outlet of the ancient Tuolumne *mer de glare* 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 cañons, 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.

The Present Sierra and 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 cañons, lake-basins, hills, ridges, and separate rocks, whose forms, trends, distribution, etc., are the peculiar offspring of glaciers.

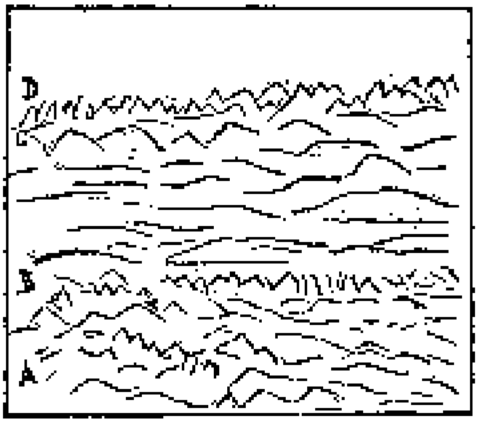


Fig. 2.

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 cañons 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 untrodden 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 cañons 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 cañons 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 glaciated surfaces become corroded sooner. The lowest patches are found at elevations of from 3,000 to 5,000 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 postglacial 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.

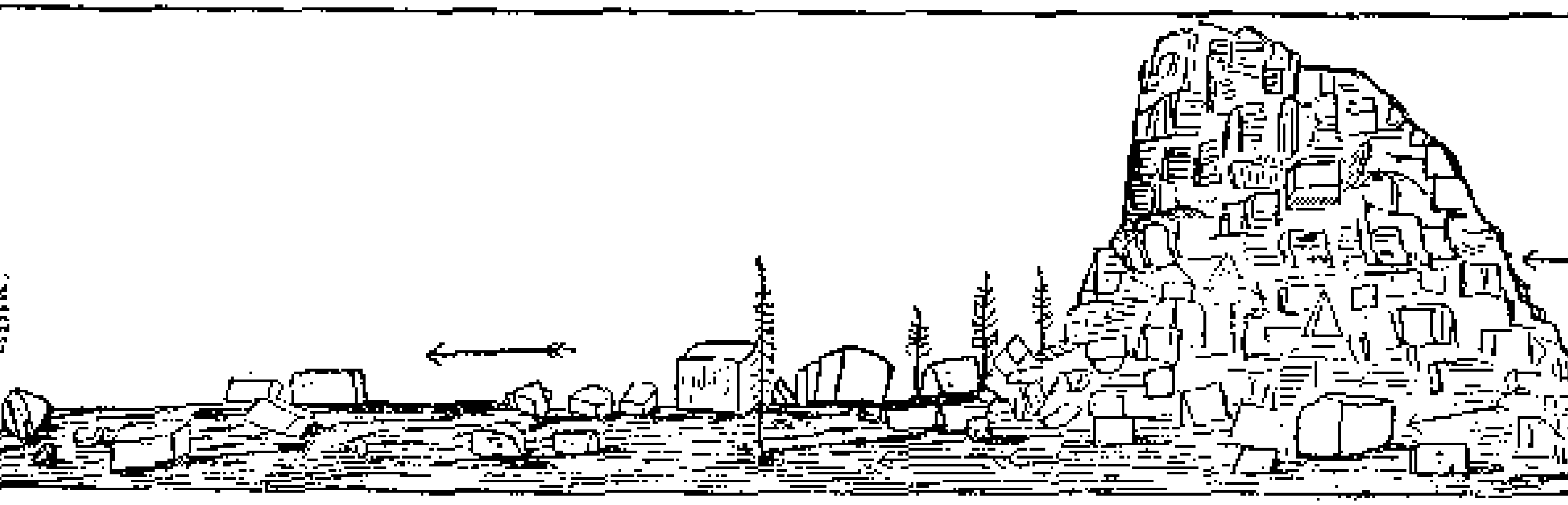


Fig. 3. Rock about two miles west of Lake Tenaya,
with a train of boulders derived from it.

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 sea sons 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 pave meets 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 parallelopipeds 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.

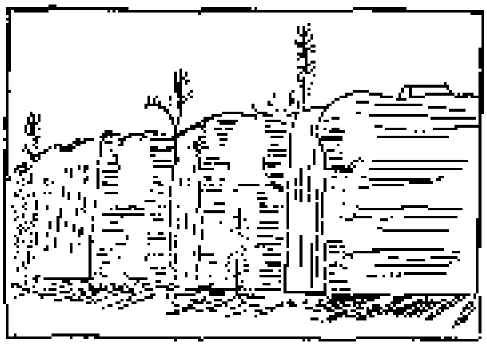


Fig. 4

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.

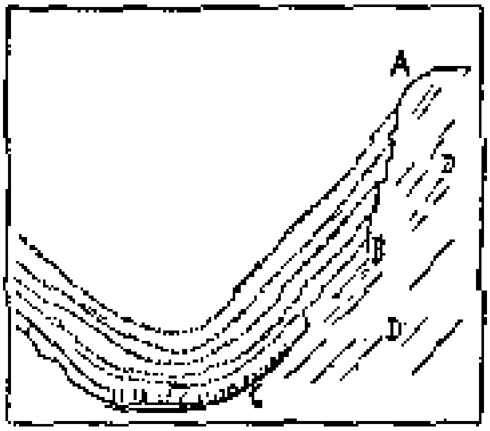


Fig. 5

Fig. 5 is a profile view of a past-flowed glacier rock, about 1,500 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.

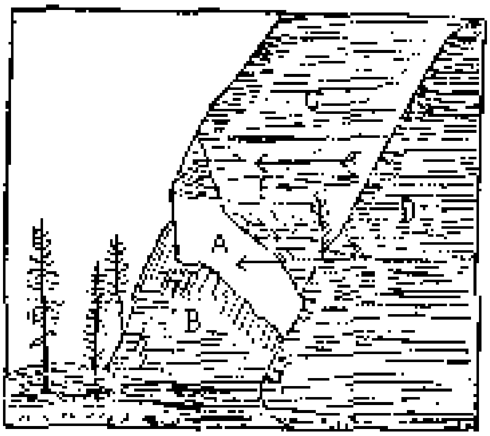


Fig. 6

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.

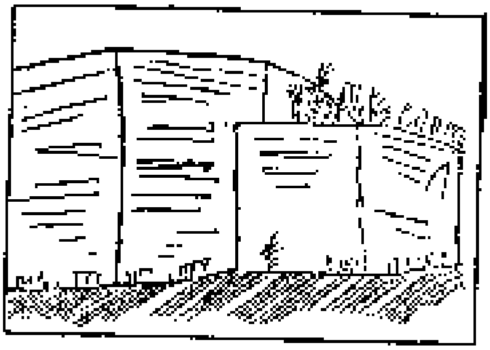


Fig. 7

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.

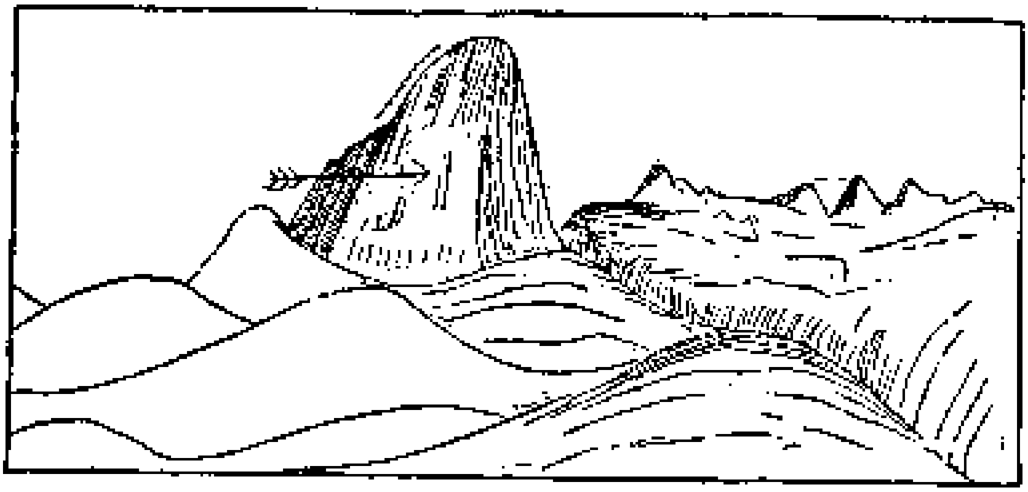


Fig. 8

Fig. 8 is a dome on the upper San Joaquin, the top of which is about 7,700 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*.

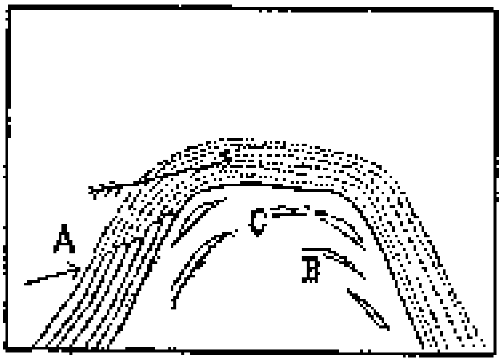


Fig. 9

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 illustration 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 cañons, 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 can not 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 Hoffman, 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.

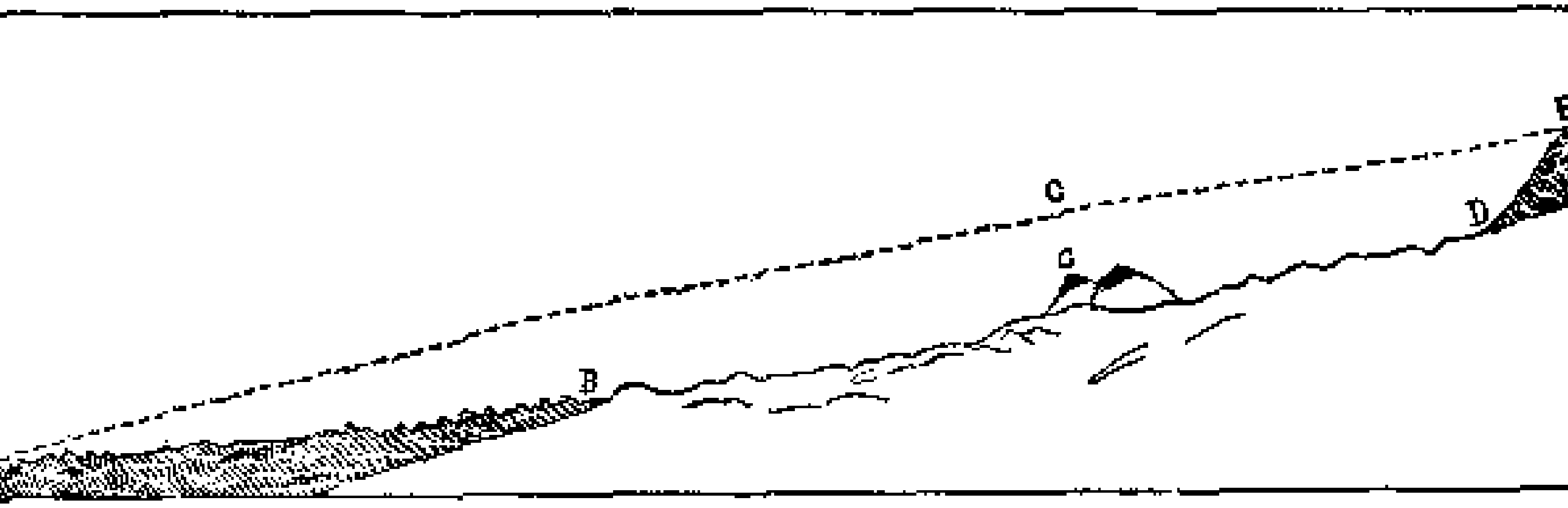


Fig. 10. Ideal section across range from base to summit.

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 cañons. 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.

V

Post-Glacial Denudation

When Nature lifted the ice-sheet from the mountains she may well be said not to have turned a new leaf, but to have made a new one of the old. Throughout the unnumbered seasons of the glacial epoch the range lay buried, crushed, and sunless. In the stupendous denudation to which it was then subjected, all its pre-glacial features disappeared Plants, animals, and landscapes were wiped from its flanks like drawings from a blackboard, and the vast page left smooth and clean, to be repictured with young life and the varied and beautiful inscriptions of water, snow, and the atmosphere.

The variability in hardness, structure, and mineralogical composition of the rocks forming the present surface of the range has given rise to irregularities in the amount of post-glacial denudation effected in different portions, and these irregularities have been greatly multiplied and augmented by differences in the kind and intensity of the denuding forces, and in the length of time that different portions of the range have been exposed to their action. The summits have received more snow, the foothills more rain, while the middle region has been variably acted upon by both of these agents. Again, different portions are denuded in a greater or less degree according to their relations to level. The bottoms of trunk valleys are swept by powerful rivers, the branches by creeks and rills, while the intervening plateaus and ridges are acted upon only by thin, feeble currents, silent and nearly invisible. Again some portions of the range are subjected every winter to the scouring action of avalanches, while others are entirely beyond the range of such action. But the most influential of the general causes that have conspired to produce irregularity in the quantity of post-glacial denudation is the difference in the length of time during which different portions of the range have been subjected to denuding agents. The ice-sheet melted from the base of the range tens of thousands of years ere it melted from the upper regions. We find, accordingly, that the foothill region is heavily weathered and blurred, while the summit, excepting the peaks, and a considerable portion of the middle region remain fresh and shining as if they had never suffered from the touch of a single storm.

Perhaps the least known among the more outspoken agents of mountain degradation are those currents of eroding rock called avalanches. Those of the Sierra are of all sizes, from a few sand-grains or crystals worked loose by the weather and launched to the bottoms of cliffs, to those immense earthquake avalanches that thunder headlong down amid fire and smoke and dust, with a violence that shakes entire mountains. Many avalanche-producing causes, as moisture, temperature, winds, and earthquakes are exceedingly variable in the scope and intensity of their action. During the dry, equable summers of the middle region, atmospheric distintegration goes silently on, and many a huge mass is made ready to be advantageously acted upon by the first winds and rains of winter. Inclined surfaces are then moistened and made slippery, decomposed joints washed out, frost-wedges driven in, and the grand avalanche storm begins. But though these stone-storms occur only in winter, the attentive mountaineer may have the pleasure of witnessing small avalanches in every month of the year. The first warning of the bounding free of a simple avalanche is usually a dull muffled rumble, succeeded by a ponderous crunching sound; then perhaps a single huge block weighing a hundred tons or more may be seen wallowing down the face of a cliff, followed by a train of smaller stones, which are gradually left behind on account of the greater relative resistance they encounter as compared with their weight. The eye may therefore follow the large block undisturbed, noting its awkward, lumbering gestures as it gropes its way through the air in its first wild journey, and how it is made to revolve like a star upon its axis by striking on projecting portions of the walls while it pursues the grand smooth curves of general descent. Where it strikes a projecting boss it gives forth an intense gasping sound, which, coming through the darkness of a storm-night, is indescribably impressive; and when at length it plunges into the valley, the ground trembles as if shaken by an earthquake.

On the 12th of March, 1873, I witnessed a magnificent avalanche in Yosemite Valley from the base of the second of the Three Brothers. A massive stream of blocks bounded from ledge to ledge and plunged into the talus below with a display of energy inexpressibly wild and exciting. Fine gray foam-dust boiled and swirled along its path, and gradually rose above the top of the cliff, appearing as a dusky cloud on the calm sky. Unmistakable traces of similar avalanches are visible here, probably caused by the decomposition of the feldspathic veins with which the granite is interlaced.

Earthquakes, though not of frequent occurrence in the Sierra, are powerful causes of avalanches. Many a lofty tower and impending brow stood firm through the storms of the first post-glacial seasons. Torrents swept their bases, and winds and snows slipped glancingly down their polished sides, without much greater erosive effect than the passage of cloud-shadows. But at length the new-born mountains were shaken by an earthquake-storm, and thousands of avalanches from cañon walls and mountain sides fell in one simultaneous crash. The records of this first post-glacial earthquake present themselves in every cañon and around the bases of every mountain summit that I have visited; and it is a fact of great geological interest that to it alone more than nine-tenths of all the cliff taluses which form so strikingly a characteristic of cañon scenery are due. The largest of these earthquake taluses are from 500 to 1,000 feet in height, and are timbered with spruce, pine, and live-oak over their entire surfaces, showing that they have not been disturbed since their formation, either by denudation or accessions of fresh material.

The earthquake which destroyed the village of Lone Pine, in March, 1872, shook the Sierra with considerable violence, giving rise to many new taluses, the formation of one of which I was so fortunate as to witness.

The denuding action of avalanches is not unlike that of water-torrents. They are frequently seen descending the summit peaks, flowing in regular channels, the surfaces of which they erode by striking off large chips and blocks, as well as by wearing off sand and dust.

A considerable amount of grinding also goes on in the body of the avalanche itself, reducing the size of the masses, and preparing them for the action of other agents. Some avalanches hurl their *detritus* directly into the beds of streams, thus bringing it under the influence of running water, by which a portion of it is carried into the ocean.

The range of rock avalanches, however produced, is restricted within comparatively narrow bounds. The shattered peaks are constant fountains, but the more powerful mountain-shaking avalanches are confined to the edges of deep cañons in a zone twelve or fifteen miles wide, and gradually merge into land-slips along their lower limits.

Large rock avalanches pour freely through the air from a height of hundreds or thousands of feet, and on striking the bottom of the valley are dashed into a kind of coarse stone foam. Or, they make the descent in several leaps, or rumble over jagged inclines in the form of cascades. But in any case they constitute currents of loose-flowing fragments. Landslips, on the contrary, slip in one mass, and, unless sheer cliffs lie in their paths, may come to rest right-side up and undivided. There is also a marked difference in their geographical distribution, land-slips being restricted to deeply eroded banks and hillsides of the lower half of the range, beginning just where rock avalanches cease. Again, the material of land-slips is chiefly fine soil and decomposing boulders, while that of rock avalanches is mostly of unweathered angular blocks.

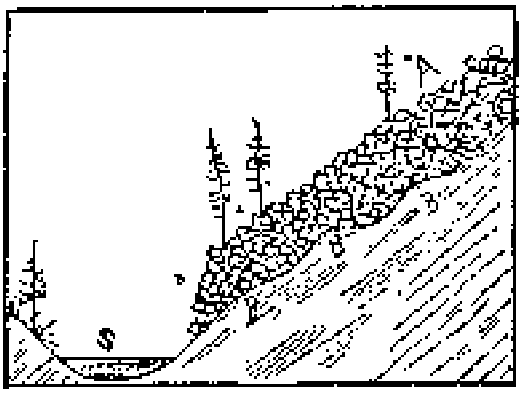


Fig. 1

Let Figure 1 represent a section across a valley in which moraine matter, A, is deposited upon the inclined bed-rock, B B B. Now, strong young moraine material deposited in this way, in a kind of rude masonry, always rests, or is capable of resting, at a much steeper angle than the same material after it has grown old and rotten. If a poultice of acid mud be applied to a strong boulder, it will not be much affected in an hour or day, but if kept on for a few thousands or tens of thousands of years, it will at length soften and crumble. Now, Nature thus patiently poultices the boulders of the moraine banks under consideration. For many years subsequent to the close of the ice period very little acid for this purpose was available, but as vegetation increased and decayed, acids became more plentiful, and boulder decomposition went on at an accelerated rate, until a degree of weakness was induced that caused the sheerest portions of the deposits, as A B D (Fig. 1), to give way, perhaps when jarred by an earthquake, or when burdened with snow or rain, or partially undermined by the action of a stream.

It appears, therefore, that the main cause of the first post-glacial landslips is old age. They undoubtedly made their first appearance in moraine banks at the foot of the range, and gradually extended upward to where, we now find them, at a rate of progress measured by that of the recession of the ice-sheet, and by the durability of moraines and the effectiveness of the corroding forces brought into action upon them. In those portions of the Sierra where the morainal deposits are tolerably uniform in kind and exposure, the upper limits of the land-slip are seen to stretch along the range with as great constancy of altitude as that of the snow-line.

The above-described species of land-slip is followed up the range by another of greater size, just as the different forest trees follow one another in compliance with conditions of soil and climate. After the *sheer end* the deposit (A B D, Fig. 1) has slipped, the *whole mass* may finally slip on the bed-rock by the further decomposition, not only of the deposit itself, but of the bed-rock on which it rests. Bed-rocks are usually more or less uneven. Now, it is plain that when the inequalities B B B crumble by erosion, the mass of the deposit will not be so well supported; moreover, the weight of the mass will continue to increase as its material is more thoroughly pulverized, because a greater quantity of moisture will be required to saturate it. Thus it appears that the support of moraine deposits diminishes, just as the necessity for greater support increases, until a slip is brought on.

Slips of this species are often of great extent, the surface comprising several acres overgrown with trees, perhaps moving slowly and coming to rest with all their load of vegetation uninjured, leaving only a yawning rent to mark their occurrence. Others break up into a muddy disorderly flood, moving rapidly until the bottom of the wall is reached. Land-slides occur more frequently on the north than on the south sides of ridges because of the greater abundance of weight-producing and decomposing moisture. One of the commonest effects of land-slips is the damming of streams, giving rise to large accumulations of water, which speedily burst the dams and deluge the valleys beneath, sweeping the finer *detritus* before them to great distances, and at first carry boulders tons in weight.

The quantity of denudation accomplished by the Sierra land-slips of both species is very small. Like rock-falls, they erode the surface they slip upon in a mechanical way, and also bring down material to lower levels, where it may be more advantageously exposed to the denuding action of other agents, and open scars whereby rain-torrents are enabled to erode gullies; but the sum of the areas thus affected bears an exceedingly small proportion to the whole surface of the range.

The part which snow avalanches play in the degradation of mountains is simpler than that of free-falling or cascading rocks, or either species of land-slip; these snow avalanches being external and distinct agents. Their range, however, is as restricted as that of either of the others, and like them they only carry their *detritus* a short distance and leave it in heaps at the foot of cliffs and steep inclines. There are three well-marked and distinct species of snow avalanche in the upper half of the Sierra, differing widely in structure, geographical distribution, and in the extent and importance of the geological changes they effect. The simplest and commonest species is formed of fresh mealy snow, and occurs during and a short time after every heavy snow-fall wherever the mountain slopes are inclined at suitable angles. This species is of frequent occurrence throughout all the steep-flanked mountains of the summit of the range, where it reaches perfection, and is also common throughout the greater portion of the middle region. Avalanches are the feeders of the glaciers, pouring down their dry mealy snow into the womb-amphitheaters, where it is changed to *névé* and ice. Unless distributed by storm-winds, they cascade down the jagged heights in regular channels, and glide gracefully out over the glacier slopes in beautiful curves; which action gives rise in summer to a most interesting and comprehensive system of snow-sculpture. The *detritus* discharged upon the surface of the glaciers forms a kind of stone-drift which is floated into moraines like the straws and chips of rivers.

Few of the defrauded toilers of the plain know the magnificent exhilaration of the boom and rush and outbounding energy of great snow avalanches. While the storms that breed them are in progress, the thronging flakes darken the air at noonday. Their muffled voices reverberate through the gloomy cañons, but we try in vain to catch a glimpse of their noble forms until rifts appear in the clouds, and the storm ceases. Then in cliff-walled valleys like Yosemite we may witness the descent of half a dozen or more snow avalanches within a few hours.

The denuding power of this species of avalanche is not great, because the looseness of the masses allows them to roll and slip upon themselves. Some portions of their channels, however, present a roughly scoured appearance, caused by rocky *detritus* borne forward in the under portion of the current. The avalanche is, of course, collected in a heap at the foot of the cliff, and on melting leaves the *detritus* to accumulate from year to year. These taluses present striking contrasts to those of rock avalanches caused by the first great pre-glacial earthquake. The latter are gray in color, with a covering of slow-growing lichens, and support extensive groves of pine, spruce, and live-oak; while the former, receiving additions from year to year, are kept in a raw formative state, neither trees nor lichens being allowed time to grow, and it is a fact of great geological significance that no one of the Yosemite snow avalanches, although they have undoubtedly flowed in their present channels since the close of the glacial period, has yet accumulated so much *débris* as some of the larger earthquake avalanches which were formed in a few seconds.

The next species of avalanche in natural order is the annual one, composed of heavy crystalline snows which have been subjected to numerous alternations of frost and thaw. Their development requires a shadowed mountain side 9,000 or 10,000 feet high, inclined at such an angle that loose fresh snow will lodge and remain upon it, and bear repeated accessions throughout the winter without moving; but which, after the spring thaws set in, and the mountain side thus becomes slippery, and the nether surface of the snow becomes icy, will then give way.

One of the most accessible of the fountains of annual avalanches is the northern slope of Cloud’s Rest, above the head of the Yosemite Valley. Here I have witnessed the descent of three within half an hour. They have a vertical descent of nearly a mile on a smooth granite surface. Fine examples of this species of avalanche may also be observed upon the north side of the dividing ridge between the basins of Ribbon and Cascade creeks, and in some portions of the upper Nevada Cañon. Their denuding power is much greater than that of the first species, on account of their greater weight and compactness. Where their pathways are not broken by precipices, they descend all or part of their courses with a hard snout kept close down on the surface of the rock, and because the middle of the snout is stronger, the *detritus* heaps are curved after the manner of terminal moraines. These *detritus* heaps also show an irregularly corrugated and concentric structure. An examination of the avalanche pathways shows conclusively that the annual accretions of *detritus,* scraped from their surfaces, are wholly insufficient to account for the several large concentric deposits. But when, after the *detritus* of many years has been accumulated by avalanches of ordinary magnitude, a combination of causes, such as rain, temperature, and abundant snow-fall, gives rise to an avalanche of extraordinary size, its superior momentum will carry it beyond the limits attained by its predecessors, and sweep forward the accumulations of many years concentric with others of like magnitude into a single mass. A succession of these irregularities will obviously produce results corresponding in every particular with the observed phenomena.

What we may call century avalanches, as distinguished from annual, are conceived and nourished on cool mountain sides 10,000 or 12,000 feet in height, where the snow falling from winter to winter will not slip, and where the exposure and temperature are such that it will not always melt off in summer. Snow accumulated under these conditions may linger without seeming to greatly change for years, until some slowly organized group of causes, such as temperature, abundance of snow, condition of snow, or the mere occurrence of an earthquake, launches the grand mass. In swooping down the mountain flanks they usually strip off the forest trees in their way, as well as the soil on which they were growing.

Some of these avalanche pathways are 200 yards wide, and extend from the upper limit of the tree-line to the bottom of the valleys. They are all well “blazed” on both sides by descending trunks, many of which carry sharp stones clutched in their up-torn roots. The height of these “blazes” on the trees bordering the avalanche gap measures the depth of the avalanche at the sides, while in rare instances some noble silver-fir is found standing out in the channel, the only tree sufficiently strong to withstand the mighty onset; the scars upon which, or its broken branches, recording the depth of the current. The ages of the trees show that some of these colossal avalanches occur only once in a century, or at still wider intervals. These avalanches are by far the most powerful of the three species, although from the rarity of their occurrence and the narrowness of the zone in which they find climatic conditions suited to their development, the sum of the denudation accomplished by them is less than that of either of the others.

We have seen that water in the condition of rain, dew, vapor, and melting snow, combined with air, acts with more or less efficiency in corroding the whole mountain surface, thus preparing it for the more obviously mechanical action of winds, rivers, and avalanches. Running water is usually regarded as the most influential of all denuding agents. Those regions of the globe first laid bare by the melting of the ice-sheet present no unchanged glaciated surfaces from which, measuring down, we may estimate the amount of post-glacial denudation. The streams of these old eroded countries are said by the poets to "go on forever," and the conceptions of some geologists concerning them are scarcely less vague.

Beginning at the foot of the Sierra glaciers, and following the torrents that rush out from beneath them down the valleys, we find that the rocks over which they flow are weathered gradually, and increasingly, the farther we descend; showing that the streams in coming into existence grew like trees from the foot of the range upward, gradually ramifying higher and wider as the ice-sheet was withdrawn—some of the topmost branchlets being still in process of formation.

Rivers are usually regarded as irregular branching strips of running water, shaped somewhat like a tree stripped of its leaves. As far as more striking features and effects are concerned, the comparison is a good one; for in tracing rivers to their fountains we observe that as their branches divide and redivide, they speedily become silent and inconspicuous, and apparently channelless; yet it is a mistake to suppose that streams really terminate where they become too small to sing out audibly, or erode distinct channels. When we stoop down and closely examine any portion of a mountain surface during the progress of a rain-storm, we perceive minute water-twigs that continue to bifurcate until like netted veins of leaves the innumerable currentlets disappear in a broad universal sheet.

It would appear, therefore, that rivers more nearly resemble certain gigantic *algae* with naked stalks, and branches webbed into a flat *thallus*. The long unbranched stalks run through the dry foothills; the webbed branches frequently overspread the whole surface of the snowy and rainy alpine and middle regions, as well as every moraine, bog, and *névé* bank. The gently gliding rain-*thallus* fills up small pits as lakelets and carries away minute specks of dust and mica. Larger sand-grains are overflowed without being moved unless the surface be steeply inclined, while the rough grains of quartz, hornblende, and feldspar, into which granite crumbles, form obstacles around which it passes in curves. Where the currentlets concentrate into small rills, these larger chips and crystals are rolled over and over, or swept forward partly suspended, just as dust and sand-grains are by the wind.

The transporting power of steeply inclined torrents is far greater than Is commonly supposed. Stones weighing several tons are swept down steep cañon gorges and spread in rugged deltas at their mouths, as if they had been floated and stranded like blocks of wood. The denudation of gorges by the friction of the boulders thus urged gratingly along their channels is often quite marked.

Strong torrents also denude their channels by the removal of blocks made separable from the solid bed-rock by the development of cleavage planes. Instructive examples of this species of denudation may be studied m the gorges between the upper and lower Yosemite falls and the Tenaya Cañon, four miles above Mirror Lake. This is the most rapid mode of torrent denudation I have yet observed, but its range is narrowly restricted, and its general denuding effects inappreciable.

Water-streams also denude mountains by dissolving them and carrying them away in solution, but the infinite slowness of this action on hard porphyritic granite is strikingly exemplified by the fact that in the upper portion of the middle region granite ice-planed pavements have been flowed upon incessantly since they were laid bare on the breaking up of the glacial winter without being either decomposed, dissolved, or mechanically eroded to the depth of the one-hundredth part of an inch.

Wind-blown dust, mica flakes, sand, and crumbling chips are being incessantly moved to lower levels wherever wind or water flows. But even in the largest mountain rivers the movement of large boulders is comparatively a rare occurrence. When one lies down on a river-bank opposite a boulder-spread incline and listens patiently for a day or two, a dull thumping sound may occasionally be heard from the shifting of a boulder, but in ordinary times few streams do much boulder work; all the more easily moved blocks having been adjusted and readjusted during freshets, when the current was many times more powerful. All the channels of Sierra streams are subjected to the test action of at least one freshet per season, on the melting of the winter snow, when all weakly constructed dams and drift-heaps are broken up and re-formed.

It is a fact of great geological interest that only that portion of the general *detritus* of post-glacial denudation—that is, in the form of mud, sand, fine gravel, and matter held in solution—has ever at any time been carried entirely out of the range into the plains or ocean. In the cañon of the Tuolumne River, we find that the chain of lake basins which stretch along the bottom from the base of Mount Lyell to the Hetch-Hetchy Valley are filled with *detritus*, through the midst of which the river flows; but the washed boulders, which form a large portion of this *detritus*, instead of being constantly pushed forward from basin to basin, lie still for centuries at a time, as is strikingly demonstrated by an undisturbed growth of immense sugar-pines and firs inhabiting the river-banks. But the presence of these trees upon water-washed boulders only shows that no displacement has been effected among them for a few centuries. They still must have been swept forward and outspread in some grand flood prior to the planting of these trees. But even this grand old flood of glacial streams, whose magnificent traces occur everywhere on both flanks of the range, *did not remove a single boulder from the higher to the lower Sierra in that section of the range drained by the Tuolumne and Merced, much less into the ocean,* because the lower portion of the Hetch-Hetchy basin, situated about half-way down the western flank, is *still in process of filling up,* and as yet contains only sand and mud to as great a depth as observation can reach in river sections. The river flows slowly through this alluvial deposit and out of the basin *over a lip of solid bed-rock, showing that not a single high Sierra boulder ever passed it since the dose of the glacial period;* and the same evidence is still more strikingly exhibited in similarly situated basins in the Merced Valley.

Frost plays a very inferior part in Sierra degradation. The lower half of the range is almost entirely exempt from its disruptive effects, while the upper half is warmly snow-mantled throughout the winter months. At high elevations of from ten to twelve thousand feet, sharp frosts occur in the months of October and November, before much snow has fallen; and where shallow water-currents flow over rocks traversed by open divisional joints, the freezing that ensues forces the blocks apart and produces a ruinous appearance, without effecting much absolute displacement. The blocks thus loosened are, of course, liable to be moved by flood-currents. This action, however, is so limited in range, that the general average result is inappreciable.

Atmospheric weathering has, after all, done more to blur and degrade the glacial features of the Sierra than all other agents combined, because of the universality of its scope. No mountain escapes its decomposing and mechanical effects. The bases of mountains are mostly denuded by streams of water, their summits by streams of air. The winds that sweep the jagged peaks assume magnificent proportions, and effect changes of considerable importance. The smaller particles of disintegration are rolled or shoved to lower levels just as they are by water currents, or they are caught up bodily in strong, passionate gusts, and hurled against trees or higher portions of the surface. The manner in which exposed tree-trunks are thus wind-carved and boulders polished will give some conception of the force with which this agent moves.

Where boulders of a form fitted to shed off snow and rain have settled protectingly upon a polished and striated surface, then the protected portion will, by the erosion and removal of the unprotected surface around it, finally come to form a pedestal for the stone which saved it. Figure 2 shows where a boulder, B. has settled upon and protected from erosion a portion of the original glaciated surface until the pedestal, A, has been formed, the height of which is of course the exact measure of the whole quantity of post-glacial denudation at that point. These boulder pedestals, furnishing so admirable a means of gauging atmospheric erosion, occur throughout the middle granitic region in considerable numbers: some with their protecting boulders still poised in place, others naked, their boulders having rolled off on account of the stool having been eroded until too small for them to balance upon. It is because of this simple action that all very old, deeply weathered ridges and slopes are boulderless, Nature having thus leisurely rolled them off, giving each a whirling impulse as it fell from its pedestal once in hundreds or thousands of years.

Moutonnéed rock forms shaped like Figure 3 are abundant in the middle granitic region. They frequently wear a single pine, jauntily wind-slanted, like a feather in a cap, and a single large boulder, poised by the receding ice-sheet, that often produces an impression of having been thus placed artificially, exciting the curiosity of the most apathetic mountaineer. Their occurrence always shows that the surfaces they are resting upon are not yet deeply eroded.

Ice-planed veins of quartz and feldspar are frequently weathered into relief by the superior resistance they offer to erosion, but they seldom attain a greater height than three or four inches ere they become weather-cracked and lose their glacial polish, thus becoming useless as means of gauging denudation. Ice-burnished feldspar crystals are brought into relief in the same manner to the height of about an inch, and are available to this extent in determining denudation over large areas in the upper portion of the middle region.

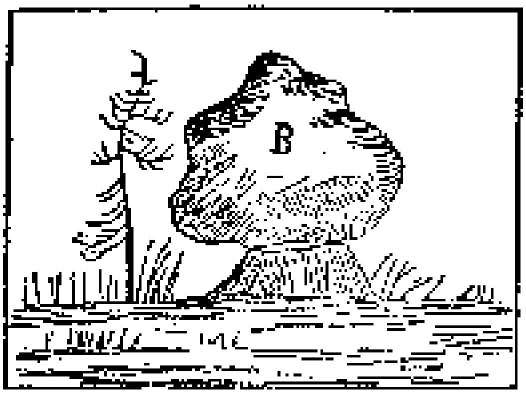


Fig. 2.

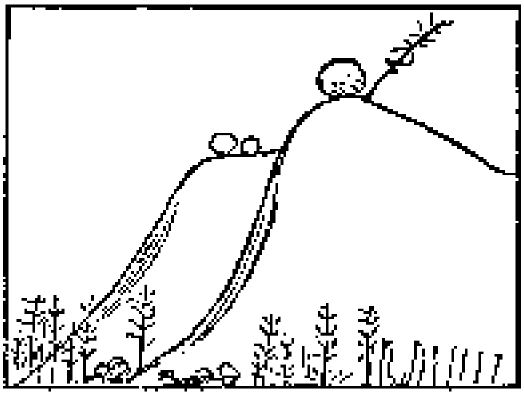


Fig. 3.

This brief survey of the various forces incessantly or occasionally at work wasting the Sierra surface would at first lead us to suppose that the sum total of the denudation must be enormous; but, on the contrary, so indestructible are the Sierra rocks, and so brief has been the period through which they have been exposed to these agents, that the general result is found to be comparatively insignificant. The unaltered polished areas constituting so considerable a portion of the upper and middle regions have not been denuded the one-hundredth part of an inch. Farther down measuring tablets abound bearing the signature of the ice. The amount of torrential and avalanchial denudation is also certainly estimated within narrow limits by measuring down from the unchanged glaciated surfaces lining their banks. Farther down the range, where the polished surfaces disappear, we may still reach a fair approximation by the height of pot-holes drilled into the walls of gorges, and by the forms of the bottoms of the valleys containing these gorges, and by the shape and condition of the general features.

Summing up these results, we find that the average quantity of post-glacial denudation in the upper half of the range, embracing a zone twenty-five or thirty miles wide, probably does not exceed a depth of three inches. That of the lower half has evidently been much greater—probably several feet—but certainly not so much as radically to alter any of its main features. In that portion of the range where the depth of glacial denudation exceeds a mile, that of post-glacial denudation is less than a foot.

From its warm base to its cold summit, the physiognomy of the Sierra is still strictly glacial. Rivers have only traced shallow wrinkles, avalanches have made scars, and winds and rains have blurred it, but the change, as a whole, is not greater than that effected on a human countenance by a single year of exposure to common alpine storms.

VI

Formation of Soils

Nature has plowed the Sierra flanks more than a mile deep through lava, slate, and granite, thus giving rise to a most lavish abundance of fruitful soils. The various methods of detachment of soil-fragments from the solid rocks have been already considered in the foregoing studies on glacial and post-glacial denudation. It now remains to study the formation of the variously eroded fragments into beds available for the uses of vegetable life.

If all the soils that now mantle the Sierra flanks were spread out in one sheet of uniform thickness, it would measure only a few feet in depth, and its entire removal would not appreciably affect the configuration of any portion of the range. The largest beds rarely exceed a hundred feet in average thickness, and a very considerable proportion of the whole surface is naked. But we have seen that glaciers alone have ground the west flank of the range into soil to a depth of more than a mile, without taking into account the work of other soil-producing agents, as rains, avalanches, torrents, earthquakes, etc. It appears, therefore, that not the one-thousandth part of the whole quantity of soil eroded from the range since the beginning of the glacial epoch is now left upon its flanks.

The cause of this comparative scantiness of the Sierra soil-beds will be readily apprehended when we reflect that the glacier, which is the chief soil-producing agent, no sooner detaches a soil-fragment than it begins to carry it away. During the long glacial winter, soil-material was poured from the range as from a fountain, borne outward by the mighty currents of the ice-sheet to be deposited in its terminal moraines. The only one of these ancient ice-sheet moraines which has retained its principal characteristics unaltered down to the present time is that magnificent belt of soil upon which all the majestic forests of the Sierra are growing. It stretches along the west flank of the range like a smooth-flowing ribbon, waving compliantly up and down over a thousand hills and hollows, at an elevation of from four to seven thousand feet above the level of the sea. In some places it is more than a hundred feet deep and twenty miles wide, but it is irregular as a sun-wasted snow-wreath both in width and in depth, on account of the configuration of the surface upon which it rests, and the varying thickness and declivity of the ice-sheet at the period of its deposition. The long weathering and the multitude of storm-washings to which it has been subjected have made its outlines still more indefinite and variable. Furthermore, its continuity is interrupted at intervals of fifteen or twenty miles by the river cañons which cross it nearly at right angles. For, at the period of the deposition of the main soil-belt as a terminal moraine of the ice-sheet, long finger-like glaciers extended down every one of these cañons, thus effectually preventing the continuance of the main terminal moraine across the cañon channels.

The method of the deposition of broad belts of terminal-moraine soil will be made plain by reference to Figure 1, which represents a deposit of this kind lying at the foot of Moraine Lake, made by the Bloody Cañon glacier in its recession toward the period of its extinction. A A are the main lateral moraines extending from the jaws of the cañon out into the Mono Plain; 1, 2, 3, 4, 5, 6 are concentric belts of terminal-moraine soil deposited by the glacier in its retreat.

These soil-belts, or furrows, are twenty or thirty yards apart. After belt number 1 was laid down, the glacier evidently withdrew at a faster rate, until a change of climate as regards heat or cold, or the occurrence of a cluster of snowier years, checked its backward motion sufficiently to afford it time to deposit belt number 2, and so on; the speed of the dying glacier's retreat being increased and diminished in rhythmic alternations of frost and thaw, sunshine and snow, all of which found beautiful and enduring expression in its ridged moraines. The promontories P P are portions of a terminal soil-belt, part of which is covered by the lake.

Similar fields of corrugated moraine matter occur farther down, marking lingering and fluctuating periods in the recession of the glacier similar to the series we have been studying. Now, it is evident that if, instead of thus dying a lingering death, the glacier had melted suddenly while it extended into the Mono plain, these wide soil-fields could not have been made. Neither could the grand soil-belt of the western flank have existed if the ice-sheet had melted in one immense thaw while it extended as a seamless mantle over all the western flank. Fortunately for Sierra vegetation and the life dependent upon it, this was not the case; instead of disappearing suddenly, like a sun-stricken cloud, it withdrew from the base of the great soil-belt upward, in that magnificently deliberate way so characteristic of nature—adding belt to belt in beautiful order over lofty plateaus and rolling hills and valleys, wherever soil could be made to lie.

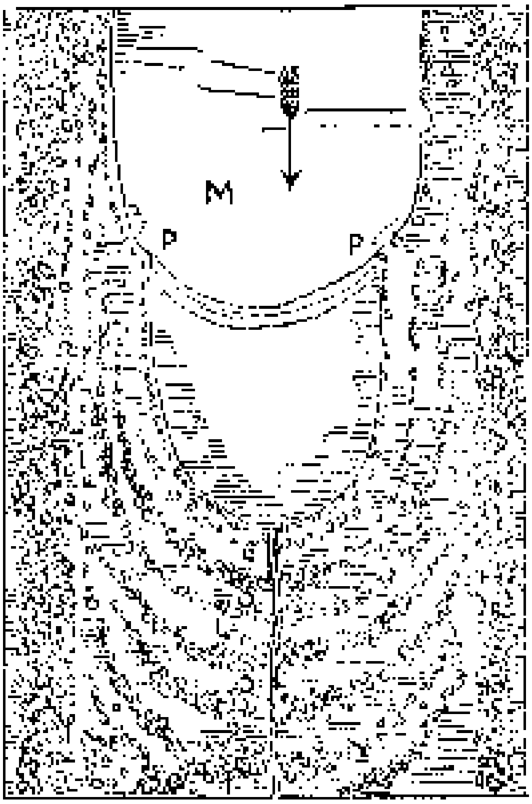


Fig. 1

Winds and rains, acting throughout the ample centuries, smooth rough glacial soils like harrows and rollers. But this culture is carried on at an infinitely slow rate, as we measure time. Comparing the several moraine-fields of Bloody Cañon, we observe that the ridged concentric structure (Fig. 1) becomes gradually less distinct the farther we proceed out into the plain, just as the plow-ridges in a farmer's field become less distinct the more they are harrowed. Now, the difference in time between the deposition of contiguous moraine-fields in Bloody Cañon is probably thousands of years, yet the difference as regards smoothness and freshness of aspect corresponding to this difference in time is in some instances scarcely discernible. In the field represented in Figure 1 these leveling operations may be studied to excellent advantage. The furrows between the several ridges are leisurely filled up by the inblowing and washing of leaves and the finer material of the adjacent ridges. As the weathering of the surface boulders goes on, the crumbling material which falls from them collects about their bases, thus tending to bury them, and produce that smoothness of surface which characterizes all the more ancient moraine-fields of the Sierra. The great forest soil-belt of the west flank has not been hitherto recognized as a moraine at all, because not only is it so immensely extended that general views of it can not be easily obtained, but it has been weathered until the greater portion of its surface presents as smooth an appearance as a farmer's wheat-field.

It may be urged against the morainal origin of the forest belt that its sections exposed by freshet streams present a quite different appearance from similar sections of more recent moraine-beds unmistakably such; but careful inspection shows the same gradual transition from the boulder roughness of the one to the crumbled earthiness of the other that we have already traced between the superficial roughness and smoothness of moraines according to age.

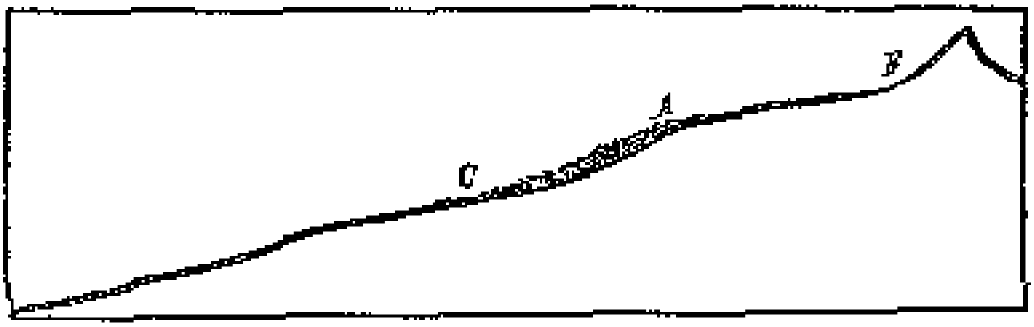


Fig. 2

Under certain conditions moraine boulders decompose more rapidly beneath than upon the surface. Almost every section of the forest belt presents specimens in every stage of decay, and, because those that are water-rounded and polished are more enduring than others, they occur in comparatively greater abundance as the soil becomes more ancient. The position of the soil-belt is given in the ideal cross-section of the range (Fig. 2). *Its upper limit nearly coincides with the edge of a comparatively level bench,* A B, *extending back to the summit peaks*. Upon this lofty, gently inclined bed the waning ice-sheet lay nearly motionless, shallowing simultaneously across its whole breadth, and finally broke up into distinct ice-streams which occupied the present river cañons. These have left their lateral moraines in the form of long branching ridges of soil, several miles apart, extending from the summit ice-wombs down to the main soil-belt, into which they blend and disappear. But if the ice-sheet had maintained its continuity to the very end of the glacial epoch, soil would evidently have been laid down in one continuous bed all the way back to the summit, because under these conditions every portion of the surface in succession would have been loaded with terminal moraine-belts pressed one against the other like plow-ridges. Under the conditions which prevailed toward the close of the great winter, the separate glaciers as well as the ice-sheet shallowed, became torpid, and died away simultaneously throughout all this upper region; no terminal moraine; are therefore to be met until we reach those of the small residual glaciers which took shelter in the loftiest and coolest shadows of the summit peaks. Nor will this state of things be wondered at, when we consider how slight is the difference in elevation, and consequently in climate, between the upper and lower limits (A and B. Fig. 2) of this bare alpine bench, as compared with that of the slope (C A) beneath it, upon which the soil-belt lies.

The effect of shadows in determining the formation, size, and distribution of glacial soil-beds must not be overlooked. When the seasons grew warm and the long crooked glaciers were driven from the sun-beaten summit bench, thousands of small residual glaciers, from half a mile to two or three miles in length, lingered on through many a century in the shelter of frosty shadows. Accordingly, we find the moraines of these hiding glaciers in the highest and coolest recesses, shaped and measured with strict reference to their adjacent shadows. A considerable number of these interesting shadow-moraines are still in process of formation, presenting a raw and rubbish-like appearance, as if the boulders, mud, and sand of which they are composed had been newly mined from the mountain's flank, and dumped loosely from a car. Ancient shadow-moraines, delightfully gardened and forested, occur in all deep Yosemitic cañons trending in an east and west direction; but their first forms are so heavily obscured by thousands of years of weathering that their shadow-glacial origin would scarcely be suspected.

In addition to these broad zones and fields and regularly deposited moraine ridges, glacial soil occurs in isolated strips and patches upon the wildest and most unlikely places-aloft on jutting crags, and along narrow horizontal benches ranged one above another, on sheer-fronted precipices, wherever the strong and gentle glaciers could get a boulder to lie. To these inaccessible soil-beds companies of pines and alp-loving flowers have found their way, and formed themselves into waving fringes and rosettes, whose beauty is strikingly relieved upon the massive ice-sculptured walls.

Nothing in the history of glacial soil-beds seems more remarkable than their durability in the forms in which they were first laid down. The wild violence of mountain storms would lead one to fancy that every moraine would be swept from plateau and ridge in less than a dozen seasons, yet we find those of the upper half of the range scarcely altered by the tear and wear of thousands of years. Those of the lower half are far more ancient, and their material has evidently been shifted and re-formed until their original characteristics are almost entirely lost.

These fresh glacier-formed soils are subject to modifications of various kinds. After the coarse, unbolted moraine soils derived from granite, slate, and lava have been well watered and snow-pressed, they are admirably adapted for the ordinary food and anchorage of coniferous trees, but further manipulation is required to fit them for special grove and garden purposes. The first and most general action to which they are subjected is that of slow atmospheric decomposition, which mellows and smooths them for the reception of blooming robes of under-shrubs and grasses, and up to a certain point augments their capacity for the support of pines and firs. Streams of rain and melting snow rank next in importance as modifiers of glacial soils. Powerful torrents waste and change the most compact beds with great rapidity, but the work done by small rain-currents and low-voiced brooks is very much less than is vaguely supposed. The brook which drains the south flank of the Clouds' Rest ridge, above Yosemite Valley, in making its way southward to join the Nevada Creek, is deflected to the west by the right lateral moraine of the ancient Nevada glacier, and compelled to creep and feel its way along the outside of the moraine as far as to where it is caught between the moraine and an escarpment which advances from the Clouds' Rest crest. When halted here, it spread into a pool, and rose until it was able to effect its escape over the lowest portion of the barrier. Now, this stream, which in ordinary stages is about five feet wide and a foot deep, seems to have flowed unfailingly in one channel throughout all the long post-glacial centuries, but the only erosion the moraine has suffered is the removal of sand, mud, and some of the smaller boulders, while the large stones, jammed into a kind of wall, are merely polished by the friction of the stream, and bid fair to last tens of thousands of years. The permanence of soils depends more upon their position and mechanical structure than upon their composition. Coarse porous moraine matter permits rains and melting snows to percolate unimpeded, while muddy and impermeable beds are washed and wasted on the surface.

Snow avalanches more resemble glaciers in their methods of soil formation and distribution than any other of the post-glacial agents. The century avalanche sweeps down all the trees that chance to stand in its path, together with soils of every kind, mixing all together without reference to the size of their component fragments. Most of the uprooted trees are deposited in lateral windrows, heads downward, piled upon each other, and tucked snugly in alongside the clearing; while a few are carried down into the valley on the snout of the avalanche, and deposited with stones, leaves, and burs, in a kind of terminal moraine.

The soil accumulations of annual avalanches are still more moraines like in form, and frequently attain a depth of from forty to fifty feet. They are composed of mud, sand, coarse granules, and rough angular blocks, avalanched from the mountain side, and sometimes water-washed pebbles also, derived from the channels of streams.

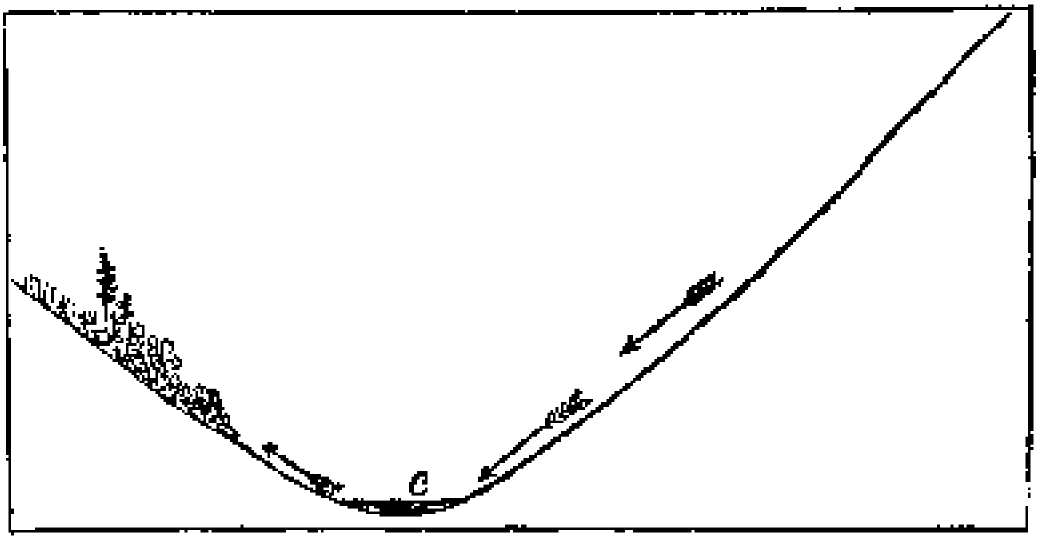


Fig. 3.

Thus, the largest of the Clouds' Rest avalanches, in rushing down their magnificent pathway of nearly a mile in vertical depth, on their arrival at the Tenaya Creek (Fig. 3) dash across its channel and up the opposite bank to a height of more than a hundred feet, pushing all the pebbles and boulders of the stream up with them. Spring freshets bring down a fresh supply of pebbles and boulders from year to year, which the avalanches patiently add to their moraine, until in a few thousand years these washed pebbles form a considerable proportion of the mass. Trees over a hundred years old occur upon the upper portions of some of these avalanche-beds, showing that no avalanche of sufficient power to disturb them had occurred since they began to grow. The lower portions of these beds are, on the contrary, in a raw formative condition, and about as plantless as the shining boulder-beds in the bottoms of rivers.

Again, stone avalanches have their share in depositing soil. The observer among beetling Yosemitic cliffs occasionally sees a single boulder eight or ten feet in diameter whizzing down the sky like a comet with a tail of dust two thousand feet long. When these huge soil-grains strike among other boulders at the end of their course, they make a sound deeper and heavier than thunder; the ground trembles, and stone-spray is whirled and spattered like water-spray at the foot of a fall.

The crushed and pounded soil-beds to which avalanches of this kind give rise seem excellently well adapted to the growth of forest trees, but few of them are sufficiently matured to be available, and the trees that venture upon them are in constant danger of their lives. These unplanted beds occur most commonly at the base of cliffs intersected by feldspathic veins, the decomposition of which causes the downfall of additional material from year to year. On the contrary, the rougher and far more important soil-beds resulting from earthquake avalanches are formed almost instantaneously, without being subsequently augmented in any appreciable degree for centuries. The trees, therefore, and various shrubs and flowers which find them tolerable or congenial dwelling-places soon take possession of them, and soothe their rugged features with a mantle of waving verdure.

At first thought no one would suppose that in a tumultuous pellmell down-crash of rifted rocks any specialization could be accomplished in their deposition. Both the suddenness and the violence of the action would seem to preclude the possibility of the formation of any deposit more orderly than a battered rubbish-heap. Every atom, however, whether of the slow glacier or swift avalanche, is inspired and directed by law. The larger blocks, because they are heavier in proportion to the amount of surface they present to the impeding air, bound out farther; and, because obstructions of surface irregularities have less effect upon larger blocks, they also *roll* farther on the bottom of the valley. The small granules and sand-grains slip and roll close to the cliff, and come to rest on the top of the talus, while the main mass of the talus is perfectly graduated between these extremes. Besides this graduation accomplished in a vertical and forward direction, beautiful sections are frequently made in a horizontal and lateral direction, as illustrated in Figure 4. A B is a kind of natural trough or spout near the base of the cliff, directed obliquely downward, into which a portion of the avalanche-stream, F. falls, and is spouted to the left of its original course. Because the larger boulders composing the spouted portion of the current move faster, their momentum carries them farther toward H. giving rise to the talus E, while the finer material is deposited at D. Again, the blocks sufficiently large to bound out beyond the deflecting spout from the rough talus C, while the smallest fragments of all—namely, the fine dust derived from chafing—float out far beyond, and settle in thin films silently as dew.

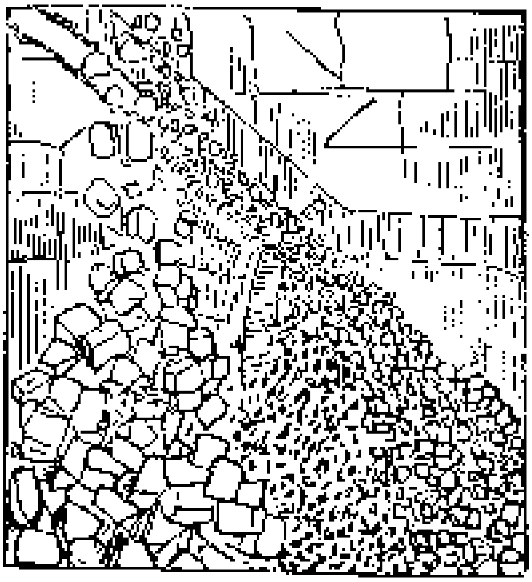


Fig. 4

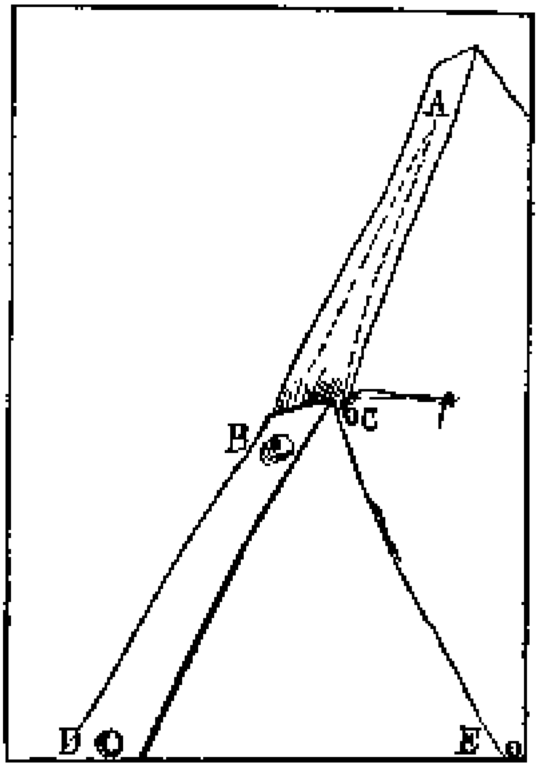


Fig. 5

In portions of cañon walls where diagonal cleavage is developed, inclines such as A B (Fig. 5) are common. If two boulders in falling from the heights above should strike glancingly at A, the greater mass or more favorable form of boulder B might cause it to bound sufficiently far to reach the second incline, which would carry it toward D; while the smaller boulder, C, falling short, might fall under the guidance of a third incline, and be shed off toward E, the two boulders finally coming to rest a hundred yards or more apart. By these means the most delicate decompositions of stone-torrents are effected, the various resulting soils being delivered at different shoots and spouts, like the bran, shorts, and fine flour of a gristmill. The ages of the oldest trees growing upon these soils furnish data by which some approximation to the time of their formation may be made.

The first post-glacial earthquake sufficiently severe to produce large avalanches occurred at least three centuries ago, and no other of equal power has occurred since. By this earthquake alone, thousands of acres of noble soil-beds were suddenly and simultaneously deposited throughout all the deep cañons of the range. Though thus hurled into existence at a single effort, they are the most changeless and indestructible soil formations in the Sierra. Excepting those which were launched directly into the channels of rivers, scarcely one of their wedged and locked boulders has been moved since the day of their creation. In striking contrast with these terrible demonstrations of mechanical energy, made the deposition of earthquake soils, is the silent and motionless transformation of solid granite into loose fine soil-beds by oozing water and the tranquil play of the atmosphere. Beds eight or ten feet deep occur on Mounts Watkins and El Capitan, on the edge of the Yosemite Valley, where the decomposition had been effected so calmly that the physical structure presents no conspicuous change; the quartz, mica, and horn-blende retaining the same relative positions as when solid, yet so perfectly disintegrated that, like sand, it may be cut into with a spade. But these unmoved beds created on the spot are of relatively small extent, and as yet play an insignificant part in the support of Sierra vegetation. The main body of the smaller soil-fragments, weathered loose by the atmosphere, are transported and redeposited by winds and rains. Magnificent wind-rivers sweep the high Sierra, carrying large quantities of sand, dust, and mica flakes, besides larger fragments in the form of rough grains. These are distributed in smooth undulating fields and patches, adapted to the wants of the dwarf *Pinus albicaulis* and many of the most precious of Sierra shrubs and flowers. Many of the smaller alpine wind-beds are exceedingly beautiful nestling in the lee of rough beaten rocks, their edges waved and embroidered, and their surfaces delicately dinted and ruffled like the garden-plats of children. During the post-glacial eruptions of the volcanoes of the Mono basin, winds distributed showers of cinders and ashes upon all the soil-beds of the adjacent Sierra. Hundreds of square miles of area are thus sprinkled on the upper basins of the San Joaquin, Merced, and Tuolumne rivers; the copiousness of the cinder-showers increasing the nearer the Mono volcanoes are approached as a center.

The numerous domes and castellated rocks distributed over the ridges and divides of the middle region abound in garnet, tourmaline, quartz, mica, and feldspar crystals, which, as the mass of the rocks decompose, are set free and fall in minute avalanches, and gradually accumulate until they come to form belts of crystalline soil. In some instances, the various crystals occur only here and there, sprinkled in the gray gravel like daisies in a sod; but in others, half or more of the encircling talus seems to be made up of crystals, tilted at all angles, and laid open to the sun. And whether in the mild flush of morning or evening, or in the dazzling white of high noon, they manifest themselves as the most exquisitely beautiful of all the soil-beds in the range.

In the hollows and levels we find soil-beds that have been compounded and laid down by streams of water. But these may be regarded as little more than reformations of glacial deposits; for the quantity of soil material eroded from solid rock by post-glacial agents is as yet hardly appreciable. Water-beds present a wide range of variability both in size and structure. Some of the smallest, each sustaining a tuft or two of grass, have scarcely a larger area than the flower-plats of gardens; while others are miles in extent, and support luxuriant groves of pine trees two hundred feet in height. Some are composed of mud and sand-grains, others of ponderous boulders, according to the power of the depositing current and the character of the material that chanced to lie in its way.

Glaciers are admirably calculated for the general distribution of soils in consequence of their rigidity and independence of minor inequalities of surface. Streams of water, on the contrary, are fitted only for special work. Glaciers give soil to high and low places almost alike; water-currents are dispensers of special blessings, constantly tending to make the ridges poorer and the valleys richer. Glaciers mingle all kinds of materials together, mud particles and rock blocks a hundred feet in diameter; water, whether in oozing currents or passionate torrents, constantly discriminates both with regard to size and shape of material, and acts as a series of sieves for its separation and transportation.

Glacial mud is the finest mountain meal ground for any purpose, and its transportation into the still water of lakes, where it is deposited in layers of clay, was the first work that the young post-glacial streams of the Sierra were called upon to do. Upon the clay-beds thus created avalanches frequently pile tangled masses of tree-trunks, mingled with burs and leaves and rocky *detritus* scraped from the mountain side. Other layers of mud are deposited in turn, together with freshet-washings of sand and gravel. This goes on for centuries from season to season, until at length the basin is filled and gradually becomes drier. At first, the soil is fit only for sedges and willows, then for grasses and pine-trees. This, with minor local modifications, is the mode of creation of the so-called flat and meadow soil so abundantly distributed over all parts of the range.

Genuine bogs in this period of Sierra history occur only in shallow alpine basins, where the climate is sufficiently cool for the growth of sphagnum, and where the surrounding topographical conditions are such that they are safe, even in the most copious rains and thaws, from the action of flood-currents capable of carrying stones and sand, but where the water supply is nevertheless sufficiently constant and abundant for the growth of sphagnum and a few other plants equally fond of cold water. These dying from year to year—ever dying beneath and living above—gradually give rise to those rich spongy peat-soils that are the grateful abodes of so many of the most delightful of alpine plants.

Beds of sloping bog-soil, that seem to hang like ribbons on cool mountain sides, are originated by the fall of trees in the paths of small creeks and rills, in the same climates with level bogs. The interlaced trunks and branches obstruct the feeble streams and dissipate them into oozing webs and stagnant pools. Sphagnum speedily discovers and takes possession of them, absorbing every pool and driblet into its spongy stems, and at length covers the muddy ground and every log and branch with its rich rounded bosses.

Here the attentive observer is sure to ask the question, Are the fallen trees more abundant in bogs than elsewhere in the surrounding forest?—and if so, then, why? We *do* find the fallen trees in far greater abundance in sloping bogs, and the cause is clearly explained by young illustrative bogs in process of formation. In the first place, a few chance trees decay and fall in such a manner as to dam the stream and flood the roots of other trees. Every tree so flooded dies, decays, and falls. Thus, the so-called chance-falling of a few causes the fall of many, which form a network, in the meshes of which the entangled moisture is distributed with a considerable degree of uniformity, causing the resulting bog to be evenly inclined, instead of being cast into a succession of irregular terraces, one for each damming log.

Black flat meadow deposits, largely composed of *humus*, are formed in lake basins that have reached the last stage of filling up. The black vegetable matter is derived from rushes and sedges decaying in shallow water for long periods. It is not essential that these beds be constantly covered with water during their deposition, but only that they be subject to frequent inundations and remain sufficiently moist through the driest seasons for the growth of sedges. They must, moreover, be exempt from the action of overflowing flood-currents strong enough to move gravel and sand. But no matter how advantageous may be the situation of these *humus* beds, their edges are incessantly encroached upon, making their final burial beneath drier mineral formations inevitable. This obliterating action Is going on at an accelerated rate on account of the increasing quantity of transportable material rain-streams find in their way. For thousands of years subsequent to the close of the ice-winter, a large proportion of the Sierra presented a bare, polished surface, and the streams that flowed over it came down into the meadows about as empty-handed as if their courses had lain over clean glass. But when at length the glacial hard-finish was weathered off, disintegration went on at a greatly accelerated speed, and every stream found all the carrying work it could do.

Bogs die also, in accordance with beautiful laws. Their lower limit constantly rises as the range grows older. The snow-line is not a more trustworthy exponent of climate than the bog-line is of the age of the regions where it occurs, dating from the end of the ice epoch.

Besides bogs, meadows, and sandy flats, water constructs soil-beds with washed pebbles, cobblestones, and large boulders. The former class of beds are made deliberately by tranquil currents; the latter by freshets, caused by the melting of the winter snow, severe rain-storms, and by floods of exceptional power, produced by rare combinations of causes, which in the Sierra occur only once in hundreds of years. So vast is the difference between the transporting power of rivers in their ordinary every-day condition and the same rivers in loud-booming flood, that no definite gradation exists between their level silt-beds and rugged boulder deltas. The ordinary power of Sierra streams to transport the material of boulder soils is very much overestimated. Throughout the greater portion of their channels they can not, in ordinary stages of water, move pebbles with which a child might play; while in the sublime energy of flood they toss forward boulders tons in weight without any apparent effort. The roughly imbricated flood-beds so commonly found at the mouths of narrow gorges and valleys are the highest expressions of torrential energy with which I am acquainted. At some time before the occurrence of the grand soil-producing earthquake, thousands of magnificent boulder-beds were simultaneously hurried into existence by one noble flood. These ancient boulder and cobble beds are distributed throughout the deep valleys and basins of the range between latitude 39° and 36° 30’; how much farther I am unable to say. They are now mostly overgrown with groves of oak and pine, and have as yet suffered very little change. Their distinguishing characteristics are, therefore, easily readable, and show that the sublime outburst of mechanical energy developed in their creation was rivaled only in the instantaneous deposition of the grand earthquake beds.

Notwithstanding the many august implements employed as modifiers and reformers of soils, the glacier is the only great producer. Had the ice-sheet melted suddenly, leaving the flanks of the Sierra soilless, her far-famed forests would have had no existence. Numerous groves and thickets would undoubtedly have established themselves on lake and avalanche beds, and many a fair flower and shrub would have found food and a dwelling-place in weathered nooks and crevices. Yet the range, as a whole, would seem comparatively naked. The tattered alpine fringe of the Sierra forest, composed of *Pinus flexilis* and *P. aristate,* oftentimes ascends stormy mountain flanks above the upper limit of moraines, upon lean, crumbling rock; but when they have the opportunity, these little alpine pines show that they know well the difference between rich, mealy moraines and their ordinary meager fare. The yellow pine is also a hardy rock-climber, and can live on wind and snow, but it assembles in forests and attains noble dimensions only upon nutritious moraines; while the sugar pine and the two silver firs, which form so important a part of the grand forest belt, can scarcely maintain life upon bald rocks in any form, and reach full development only in the best moraine beds, no matter what the elevation may be. The mass of the Sierra forests indicates the extent and position of the moraine-beds far more accurately than it does lines of climate. No matter how advantageous the conditions of temperature and moisture, forests can not exist without soil, and Sierra soils have been laid down upon the solid rock. Accordingly, we find luxuriant forests two hundred feet high terminated abruptly by bald glacier-polished pavements.

Man also is dependent upon the bounty of the ice for the broad fields of fertile soil upon which his wheat and apples grow. The wide plains extending along the base of the range on both sides are mostly reformations of morainal *detritus* variously sorted and intermixed. The valleys of the Owens, Walker, and Carson rivers have younger soils than those of the Sacramento and San Joaquin—that is, those of the former valleys are of more recent origin, and are less changed by post-glacial washings and decomposition. All the soil-beds remaining upon the Sierra flanks, when comprehended in one view, appear like clouds in a sky half-clear; the main belt extending along the middle, with long branching mountains above it, a web of washed patches beneath, and with specialized meadow and garden flecks everywhere.

When, after the melting of the winter snow, we walk the dry channel of a stream that we love, its beds of pebbles, dams of boulders, its pool-basins and potholes and cascade inclines, suggest all its familiar forms and voices, as if it were present in the full gush of spring. In like manner the various Sierra soil-beds vividly bring before the mind the noble implements employed by nature in their creation. The meadow recalls the still lake, the boulder delta, the gray booming torrent, the rugged talus, the majestic avalanche, and the moraine reveals the mighty glaciers silently spreading soil upon a thousand mountains. Nor in all these involved operations may we detect the faintest note of disorder; every soil-atom seems to yield enthusiastic obedience to law-boulders and mud-grains moving to music as harmoniously as the far-whirling planets.

VII
Mountain-Building

This study of mountain-building refers particularly to that portion of the range embraced between latitudes 36° 30’ and 39°. It is about 200 miles long, sixty wide, and attains an elevation along its axis of from 8,000 to nearly 15,000 feet above the level of the sea. The individual mountains that are distributed over this vast area, whether the lofty and precipitous alps of the summit, the more beautiful and highly specialized domes and mounts dotted over the undulating flanks, or the huge bosses and angles projecting horizontally from the sides of cañons and valleys, have all been sculptured and brought into relief during the glacial epoch by the direct mechanical action of the ice-sheet, with the individual glaciers into which it afterward separated. Our way to a general understanding of all this has been made clear by previous studies of valley formations—studies of the physical characters of the rocks out of which the mountains under consideration have been made, and of the widely contrasted methods and quantities of glacial and post-glacial denudation.

Notwithstanding the accessibility and imposing grandeur of the summit alps, they remain almost wholly unexplored. A few nervous raids have been made among them from random points adjacent to trails, and some of the more easily accessible, such as Mounts Dana, Lyell, Tyndall, and Whitney, have been ascended, while the vast wilderness of mountains in whose fastnesses the chief tributaries of the San Joaquin and Kings rivers take their rise, have been beheld and mapped from a distance, without any attempt at detail. Their echoes are never stirred even by the hunter’s rifle, for there is no game to tempt either Indian or white man as far as the frosty lakes and meadows that lie at their bases, while their avalanche-swept and crevassed glaciers, their labyrinths of yawning gulfs and crumbling precipices, offer dangers that only powerful motives will induce anyone to face.

The view southward from the colossal summit of Mount Humphreys is indescribably sublime. Innumerable gray peaks crowd loftily into the keen azure, infinitely adorned with light and shade; lakes glow in lavish abundance around their bases; torrents whiten their denuded gorges; while many a glacier and bank of fountain *névé* leans back in their dark recesses. Awe-inspiring, however, as these vast mountain assemblies are, and incomprehensible as they may at first seem, their origin and the principal facts of their individual histories are problems easily solved by the patient student.

Beginning with pinnacles, which are the smallest of the summit mountainets: no geologist will claim that these were formed by special upheavals, nor that the little chasms which separated them were formed by special subsidences or rivings asunder of the rock; because many of these chasms are as wide at the bottom as at the top, and scarcely exceed a foot in depth; and many may be formed artificially by simply removing a few blocks that have been loosened.

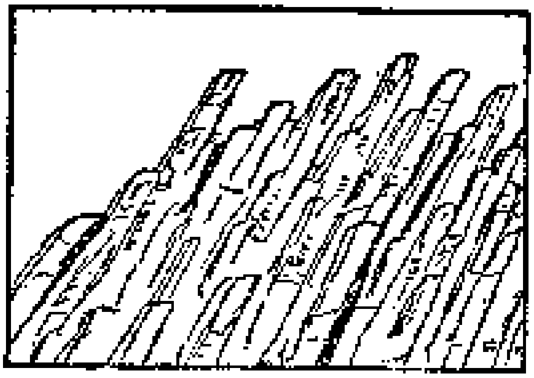


Fig. 1

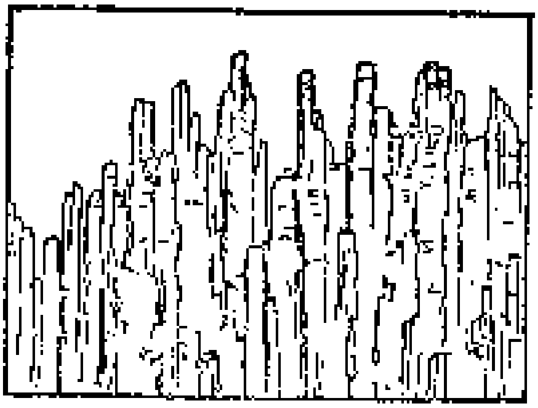


Fig. 2

The Sierra pinnacles are from less than a foot to nearly a thousand feet in height, and in all the cases that have come under my observation their forms and dimensions have been determined, not by cataclysmic fissures, but by the gradual development of orderly joints and cleavage planes, which gave rise to leaning forms where the divisional planes are inclined, as in Figure 1, or to vertical where the planes are vertical, as in Figure 2. Magnificent crests tipped with leaning pinnacles adorn the jagged flanks of Mount Ritter, and majestic examples of vertical pinnacle architecture abound among the lofty mountain cathedrals on the heads of Kings and Kern rivers. The minarets to the south of Mount Ritter are an imposing series of partially separate pinnacles about 700 feet in height, set upon the main axis of the range. Glaciers are still grinding their eastern bases, illustrating in the plainest manner the blocking out of these imposing features from the solid. The formation of small peaklets that roughen the flanks of large peaks may in like manner be shown to depend, not upon any up-thrusting or down-thrusting forces, but upon the orderly erosion and transportation of the material that occupied the intervening notches and gorges.

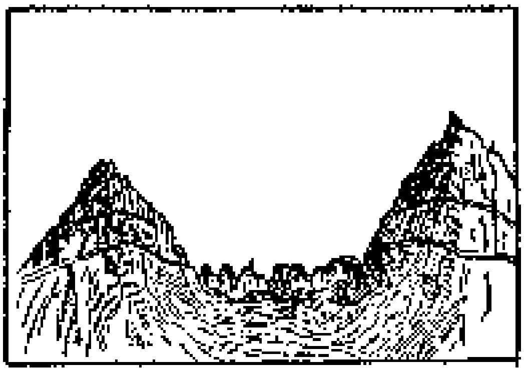


Fig. 3

Fig. 4

The same arguments we have been applying to peaklets and pinnacles are found to be entirely applicable to the main mountain peaks; for careful detailed studies demonstrate that as pinnacles are separated by eroded chasms, and peaklets by notches and gorges, so the main peaks are separated by larger chasms, notches, gorges, valleys, and wide ice-womb amphitheaters. When across hollows we examine continguous sides of mountains, we perceive that the same mechanical structure is continued across intervening spaces of every kind, showing that there has been a removal of the material that once filled them—the occurrence of large veins oftentimes rendering this portion of the argument exceedingly conclusive, as in two peaks of the Lyell group (Fig. 3), where the wide veins, N N, are continued across the valley from peak to peak. We frequently find rows of pinnacles set upon a base, the cleavage of which does not admit of pinnacle formation, and in an analogous way we find immense slate mountains, like Dana and Gibbs, resting upon a plain granite pavement, as if they had been formed elsewhere, transported and set down in their present positions, like huge erratic boulders. It appears, therefore, that the loftiest mountains as well as peaklets and pinnacles of the summit region are residual masses of the once solid wave of the whole range, and that all that would be required to unbuild and obliterate these imposing structures would simply be the filling up of the labyrinth of intervening chasms, gorges, cañons, etc., which divide them, by the restoration of rocks that have disappeared. Here the important question comes up, What has become of the missing material, not the millionth part of which is now to be seen? It has not been engulfed, because the bottoms of all the dividing valleys and basins are unmistakably solid. It must, therefore, have been carried away; and because we find portions of it scattered far and near in moraines, easily recognized by peculiarities of mineralogical composition, we infer that glaciers were the transporting agents. That glaciers have brought out the summit peaks from the solid with all their imposing architecture, simply by the formation of the valleys and basins in which they flowed, is a very important proposition, and well deserves careful attention.

We have already shown, in studies Nos. III and IV, that all the valleys of the region under consideration, from the minute strife and scratches of the polished surface less than a hundredth part of an inch in depth, to the Yosemitic gorges half a mile or more in depth, were all eroded by glaciers, and that post-glacial streams, whether small glancing brooklets or impetuous torrents, had not yet lived long enough to fairly make their mark, no matter how unbounded their eroding powers may be. Still, it may be conjectured that preglacial rivers furrowed the range long ere a glacier was born, and that when at length the ice-winter came on with its great skyfuls of snow, the young glaciers crept into these river channels, overflowing their banks, and deepening, widening, grooving, and polishing them without destroying their identity. For the destruction of this conjecture it is only necessary to observe that the trends of the present valleys are strictly glacial, and glacial trends are extremely different from water trends; preglacial rivers could not, therefore, have exercised any appreciable influence upon their formation.

Neither can we suppose fissures to have wielded any determining influence, there being no conceivable coincidence between the zigzag and apparently accidental trends of fissures and the exceedingly specific trends of ice-currents. The same argument holds good against primary foldings of the crust, dislocations, etc. Finally, if these valleys had been hewn or dug out by any preglacial agent whatever, traces of such agent would be visible on mountain masses which glaciers have not yet segregated; but no such traces of valley beginnings are anywhere manifest. The heads of valleys extend back into mountain masses just as far as glaciers have gone and no farther.

Granting, then, that the greater part of the erosion and transportation of the material missing from between the mountains of the summit was effected by glaciers, it yet remains to be considered what agent or agents shaped the upper portions of these mountains, which bear no traces of glacial action, and which probably were always, as they now are, above the reach of glaciers. Even here we find the glacier to be indirectly the most influential agent, constantly eroding backward, thus undermining their bases, and enabling gravity to drag down large masses, and giving greater effectiveness to the winter avalanches that sweep and furrow their sides. All the summit peaks present a crumbling, ruinous, unfinished aspect. Yet they have suffered very little change since the close of the glacial period, for if denudation had been extensively carried on, their separating pits and gorges would be choked with *debris;* but, on the contrary, we find only a mere sprinkling of post-glacial *detritus,* and that the streams could not have carried much of this away is conclusively shown by the fact that the small lake-bowls through which they flow have not beer filled up.

In order that we may obtain clear conceptions concerning the method of glacial mountain-building, we will now take up the formation of a fee specially illustrative groups and peaks, without, however, entering into the detail which the importance of the subject deserves.

The Lyell group lies due east from Yosemite Valley, at a distance of about sixteen miles in a straight course. Large tributaries of the Merced, Rush, Tuolumne, and San Joaquin rivers take their rise amid its ice and snow. Its geographical importance is further augmented by its having been a center of dispersal for some of the largest and most influential of the ancient glaciers. The traveler who undertakes the ascent of Mount Lyell, the dominating mountain of the group, will readily perceive that, although its summit is 13,200 feet above the level of the sea, all that individually pertains to it is a small residual fragment less than a thousand feet high, whose existence is owing to slight advantages of physical structure and position with reference to the heads of ancient glaciers, which prevented its being eroded and carried away as rapidly as the common mountain mass circumjacent to it.

Glacier wombs are rounded in a horizontal direction at the head, for the same reason that they are at the bottom; this being the form that offers greatest resistance to glacial erosion. The semicircular outline thus determined is maintained by the glaciers in eroding their way backward into the mountain masses against which they head; and where these curved basins have been continued quite through the axis of the chain or spur, separate mountains have been produced, the degree of whose individuality depends upon the extent and variation of this erosion. Thus, let A B (Fig. 4) represent a section of a portion of the summit of a mountain chain, and C D E F G H, etc., the wombs of glaciers dead or active, then the residual masses 1 2 3 will be the so-called mountains.

It may well excite surprise that snow collected in these fountain-wombs should pass so rapidly through the *névé* condition, and begin to erode at the very head; that this, however, was the case is shown by unmistakable traces of that erosion upon the sides and heads as well as bottoms of wombs now empty. The change of climate which broke up the glacial winter would obviously favor the earlier transformation of snow into eroding ice, and thus produce the present conditions as necessary consequences.

The geological effects of shadows in prolonging the existence and in guiding and intensifying the action of portions of glaciers are manifested in moraines, lake-basins, and the difference in form and sculpture between the north and south sides of mountains and valleys. Thus, the attentive observer will perceive that the architecture of deep valleys trending in a northerly and southerly direction, as Yosemite, abounds in small towers, crests, and shallow flutings on the shadowy south side, while the sun-beaten portions of the north walls are comparatively plain. The finer sculpture of the south walls is directly owing to the action of *small shadow-glacierettes*—which lingered long after the disappearance of the main glaciers that filled the valleys from wall to wall.

Every mountaineer and Indian knows that high mountains are more easily ascended on the south than on the north side. Thus, the Hoffmann spur may be ascended almost anywhere from the south on horseback, while it breaks off in sheer precipices on the north. There is not a mountain peak in the range which does not bear witness in sculpture and general form to this glacial-shadow action, which in many portions of the summit may still be observed in operation. But it is only to the effects of shadows in the segregation of mountain masses that I would now direct special attention. Figure 5 is a map of the Merced range adjacent to Yosemite Valley, with a portion of the ridge which unites it to the main axis. The arrows indicate the direction of extension of the deep glacial amphitheaters, and it will be at once seen that they all point in a southerly direction beneath the protection of shadows cast by the peaks and ridges. Again, it will be seen that because the Merced spur (S P) trends in a northerly direction, its western slopes are in shadow in the forenoon, its eastern in the afternoon, consequently it has a series of glacial wombs on *both* sides; but because the ridge (P G) trends in an easterly direction, its southern slopes are scarcely at all in shadow, consequently deep glacial wombs occur *only* upon the *northerly* slopes. Still further, because the Merced spur (S P) trends several degrees west of north, its eastern slopes are longer in shadow than the western, consequently the ice-wombs of the former are deeper and their head-walls are sheerer; and in general, because the main axis of the Sierra has a northwesterly direction, the summit peaks are more precipitous on the eastern than on the western sides.

In the case of ice-wombs on the north side of a mountain equally shadowed on the east and west, it will be found that such wombs, other conditions being equal, curve back in a direction a little to the west of south, because forenoon sunshine is not so strong as afternoon sunshine. The same admirable obedience to shadows* [* For further illustrations of the above observations on shadows, I would refer the reader to Gardiner and Hoffmann's map of the Sierra adjacent to Yosemite Valley, or, still better, to the mountains themselves.] is conspicuous in all parts of the summits of the range. Now, *glaciers are the only eroders that are thus governed by shadows*.

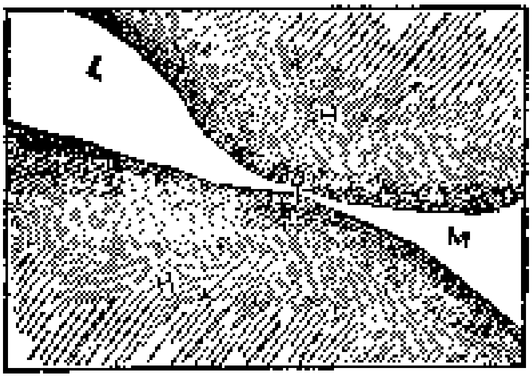


Fig. 6

Figure 6 is a section illustrating the mode in which the heads (H H) of tributaries of the Tuolumne and Merced glaciers have eroded and segregated the mountain mass (L M) into two mountains—namely, Lyell and McClure—by moving backward until they met at C, leaving only the thin crest as it now exists.

Mount Ritter lies a few miles to the south of Lyell, and is readily accessible to good mountaineers by way of the Mono plains. The student of mountain-building will find it a kind of text-book, abounding in wonderfully clear and beautiful illustrations of the principles of Sierra architecture we have been studying. Upon the north flank a small active glacier may still be seen at work blocking out and separating a peak from the main mass, and its whole surface is covered with clearly cut inscriptions of the frost, the storm-wind, and the avalanche. Though not the very loftiest, Ritter is to me far the noblest mountain of the chain. All its neighbors stand well back, enabling it to give full expression to its commanding individuality; while living glaciers, rushing torrents, bright-eyed lakes, gentian meadows; flecks of lily and anemone, shaggy thickets and groves, and polleny zones of sun-filled *compositae,* combine to irradiate its massive features, and make it as beautiful as noble.

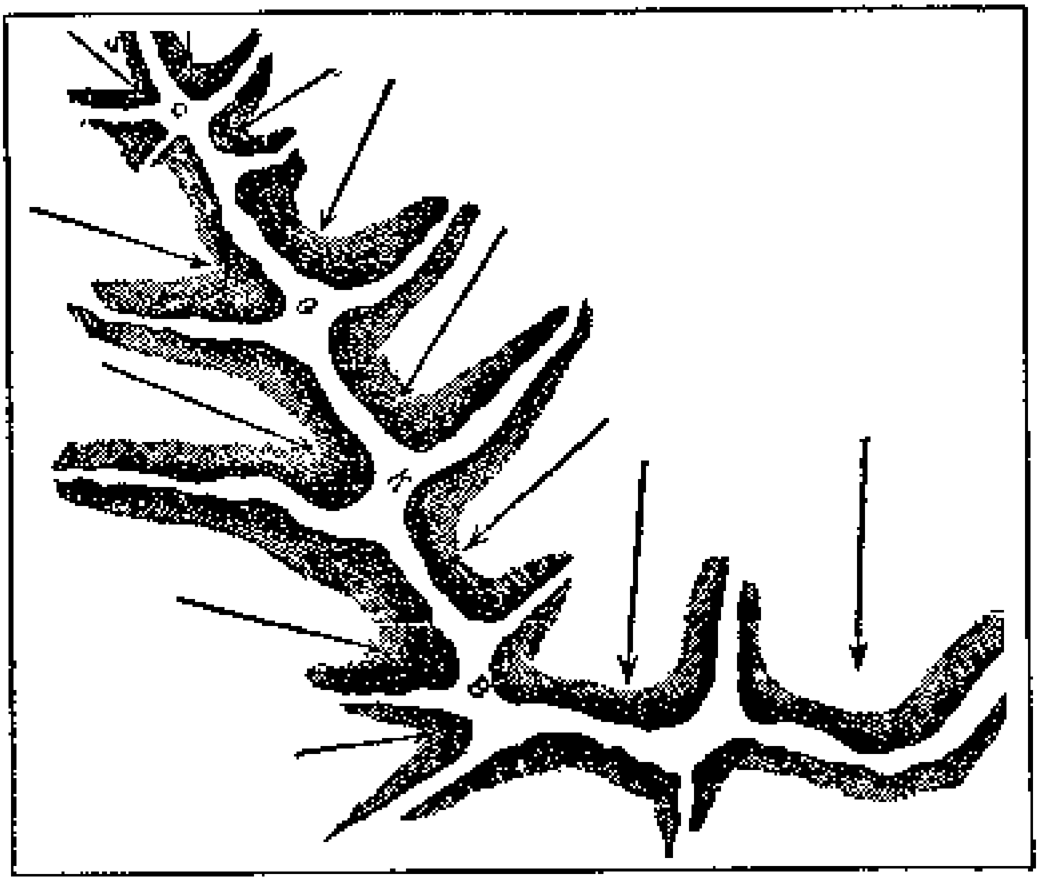


Fig. 5

The Merced spur (see Fig. 5), lying about ten miles to the southeast of Yosemite Valley and about the same distance from the main axis, presents a finely individualized range of peaks, 11,500 to 12,000 feet high, hewn from the solid. The authors of this beautiful piece of sculpture were two series of tributaries belonging to the glaciers of the Nevada and Illilouette.

The truly magnificent group of nameless granite mountains stretching in a broad swath from the base of Mount Humphreys forty miles southward, is far the largest and loftiest of the range. But when we leisurely penetrate its wild recesses, we speedily perceive that, although abounding in peaks 14,000 feet high, these, individually considered, are mere pyramids 1,000 to 2,000 feet in height, crowded together upon a common base, and united by jagged columns that swoop in irregular curves from shoulder to shoulder. That all this imposing multitude of mountains was chiseled from one grand preglacial mass is everywhere proclaimed in terms understandable by mere children.

Mount Whitney lies a few miles to the south of this group, and is undoubtedly the highest peak of the chain, but, geologically or even scenically considered, it possesses no special importance. When beheld either from the north or south, it presents the form of a helmet, or, more exactly, that of the Scotch cap called the “Glengarry.” The flattish summit curves gently toward the valley of the Kern on the west, but falls abruptly toward Owens River Valley on the east, in a sheer precipice near 2,000 feet deep. Its north and southeast sides are scarcely less precipitous, but these gradually yield to accessible slopes, round from southwest to northwest. Although highest of all the peaks, Mount Whitney is far surpassed in colossal grandeur and general impressiveness of physiognomy, not only by Mount Ritter, but by Mounts Dana, Humphreys, Emerson, and many others that are nameless. A few meadowless lakes shine around its base, but it possesses no glaciers, and, toward the end of summer, very little snow on its north side, and none at all on the south. Viewed from Owens Valley, in the vicinity of Lone Pine, it appears as one of many minute peaklets that adorn the massive uplift of the range like a cornice. Toward the close of the glacial epoch, the gray porphyritic summit of what is now Mount Whitney peered a few feet above a zone of *névé* that fed glaciers which descended into the valleys of the Owens and Kern rivers. These, eroding gradually deeper, brought all that specially belongs to Mount Whitney into relief. Instead of a vast upheaval, it is merely a remnant of the common mass of the range, which, from relative conditions of structure and position, has suffered a little less degradation than the portions circumjacent to it.

Regarded as measures of mountain-building forces, the results of erosion are negative rather than positive, expressing more directly what has *not* been done than what *has* been done. The difference between the peaks and the passes is not that the former are elevations, the latter depressions; both are depressions, differing only in degree. The abasement of the peaks having been effected at a slower rate, they were, of course, left behind as elevations.

The transition from the spiky, angular summit mountains to those of the flanks with their smoothly undulated outlines is exceedingly well marked; weak towers, pinnacles, and crumbling, jagged crests at once disappear,* [*For exceptions to this general law, real or apparent, see Chapter I.] leaving only hard, knotty domes and ridge-waves as geological illustrations, on the grandest scale, of the survival of the strongest.

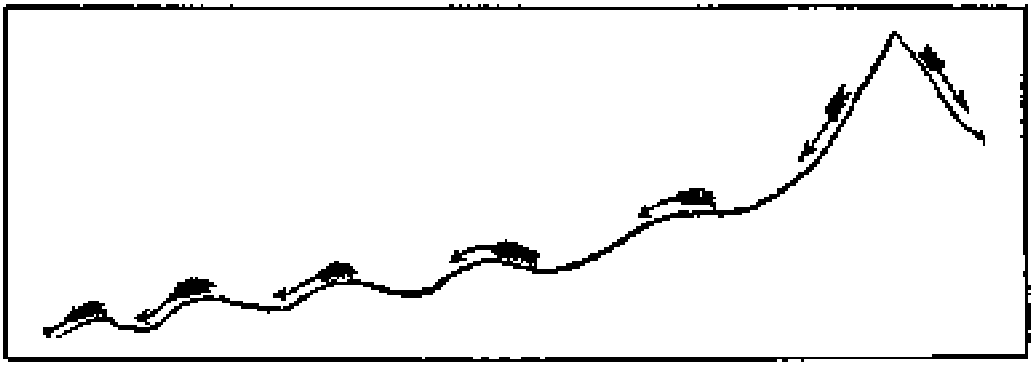


Fig. 7

Figure 7 illustrates, by a section, the general cause of the angularity of summit mountains, and curvedness of those of the flanks; the former having been *down*-flowed, the latter *over*flowed. As we descend from the alpine summits on the smooth pathways of the ancient ice-currents, noting where they have successively denuded the various rocks—first the slates, then the slaty-structured granites, then the curved granites—we detect a constant growth of specialization and ascent into higher forms. Angular masses, cut by cleavage planes begin to be comprehended in flowing curves. These masses, in turn, become more highly organized, giving rise by the most gradual approaches to that magnificent dome scenery for which the Sierra is unrivaled. In the more strongly specialized granite regions, the features, and, indeed, the very existence, of overflowed mountains are in great part due neither to ice, water, nor any eroding agent whatsoever, but to building forces—crystalline, perhaps—which put them together and bestowed all that is more special in their architectural physiognomy, while they yet lay buried in the common fountain mass of the range.

The same silent and invisible mountain-builders performed a considerable amount of work upon the down-flowed mountains of the summit, but these were so weakly put together that the heavy hand of the glacier shaped and molded, without yielding much compliance to their undeveloped forms. Had the unsculptured mass of the range been every way homogeneous, glacial denudation would still have produced summit mountains, differing not essentially from those we now find, but the rich profusion of flank mountains and mountainets, so marvelously individualized, would have had no existence, as the whole surface would evidently have been planed down into barren uniformity.

Thus the want of individuality which we have been observing among the summit mountains is obviously due to the comparatively uniform structure and credibility of the rocks out of which they have been developed; their forms in consequence being greatly dependent upon the developing glaciers; whereas the strongly structured and specialized flank mountains, while accepting the ice-currents as developers, still defended themselves from their destructive and form-bestowing effects.

The wonderful adaptability of ice to the development of buried mountains, possessing so wide a range of form and magnitude, seems as perfect as if the result of direct plan and forethought. Granite crystallizes into landscapes; snow crystallizes above them to bring their beauty to the light. The grain of no mountain oak is more gnarled and interfolded than that of Sierra granite, and the ice-sheet of the glacial period is the only universal mountain eroder that works with reference to the grain. Here it smooths a pavement by slipping flatly over it, removing inequalities like a carpenter’s plane; again it *makes* inequalities, gliding moldingly over and around knotty dome-clusters, groping out every weak spot, sparing the strong, crushing the feeble, and following lines of predestined beauty obediently as the wind.

Rocks are brought into horizontal relief on the sides of valleys wherever superior strength of structure or advantageousness of position admits of such development, just as they are elsewhere in a vertical direction. Some of these prejections are of a magnitude that well deserves the name of *horizontal mountain*. That the variability of resistance of the rocks themselves accounts for the variety of these horizontal features is shown by the prevalence of this law. *Where the uniformity of glacial pressure has not been disturbed by the entrance of tributaries, we find that where valleys are narrowest their walls are strongest; where widest, weakest.*

In the case of valleys with sloping walls, their salient features will be mostly developed in an oblique direction; but neither horizontal nor oblique mountainets or mountains can ever reach as great dimensions as the vertical, because the retreating curves formed in weaker portions of valley walls are less eroded the deeper they become, on account of receiving less and less pressure, while the alternating salient curves are more heavily pressed and eroded the farther they project into the past-squeezing glacier; thus tending to check irregularity of surface beyond a certain limit, which limit is measured by the resistance offered by the rocks to the glacial energy brought to bear upon them. So intense is this energy in the case of large steeply inclined glaciers, that many salient bosses are broken off on the lower or down-stream side with a fracture like that produced by blasting. These fractures occur in all deep Yosemitic cañons, forming the highest expressions of the intensity of glacial force I have observed.

The same tendency toward maintaining evenness of surface obtains to some extent in vertical erosion also; as when hard masses rise abruptly from a comparatively level area exposed to the full sweep of the over-passing current. If vertical cleavage be developed in such rocks, *moutonnéed* forms will be produced with a split face turned away from the direction of the flow, as shown in Figure 8, Study No. I. These forms, measuring from a few inches to a thousand feet or more in height, abound in hard granitic regions. If no cleavage be developed, then long ovals will be formed, with their greater diameters extended in the direction of the current. The general tendency, however, in vertical erosion is to make the valleys deeper and ridges relatively higher, the ice-currents being constantly attracted to the valleys, causing erosion to go on at an accelerated rate, and drawn away from the resisting ridges until they emerge from the ice-sheet and cease to be eroded; the law here applicable being, “to him that hath shall be given.”

Thus it appears that, no matter how the preglacial mass of the range came into existence, all the separate mountains distributed over its surface between latitude 36° 30’ and 39°, whether the lofty alps of the summit, or richly sculptured dome-clusters of the flank, or the burnished bosses and mountainets projecting from the sides of valleys—all owe their development to the ice-sheet of the great winter and the separate glaciers into which it afterward separated. In all this sublime fulfillment there was no upbuilding, but a universal razing and dismantling, and of this every mountain and valley is the record and monument.