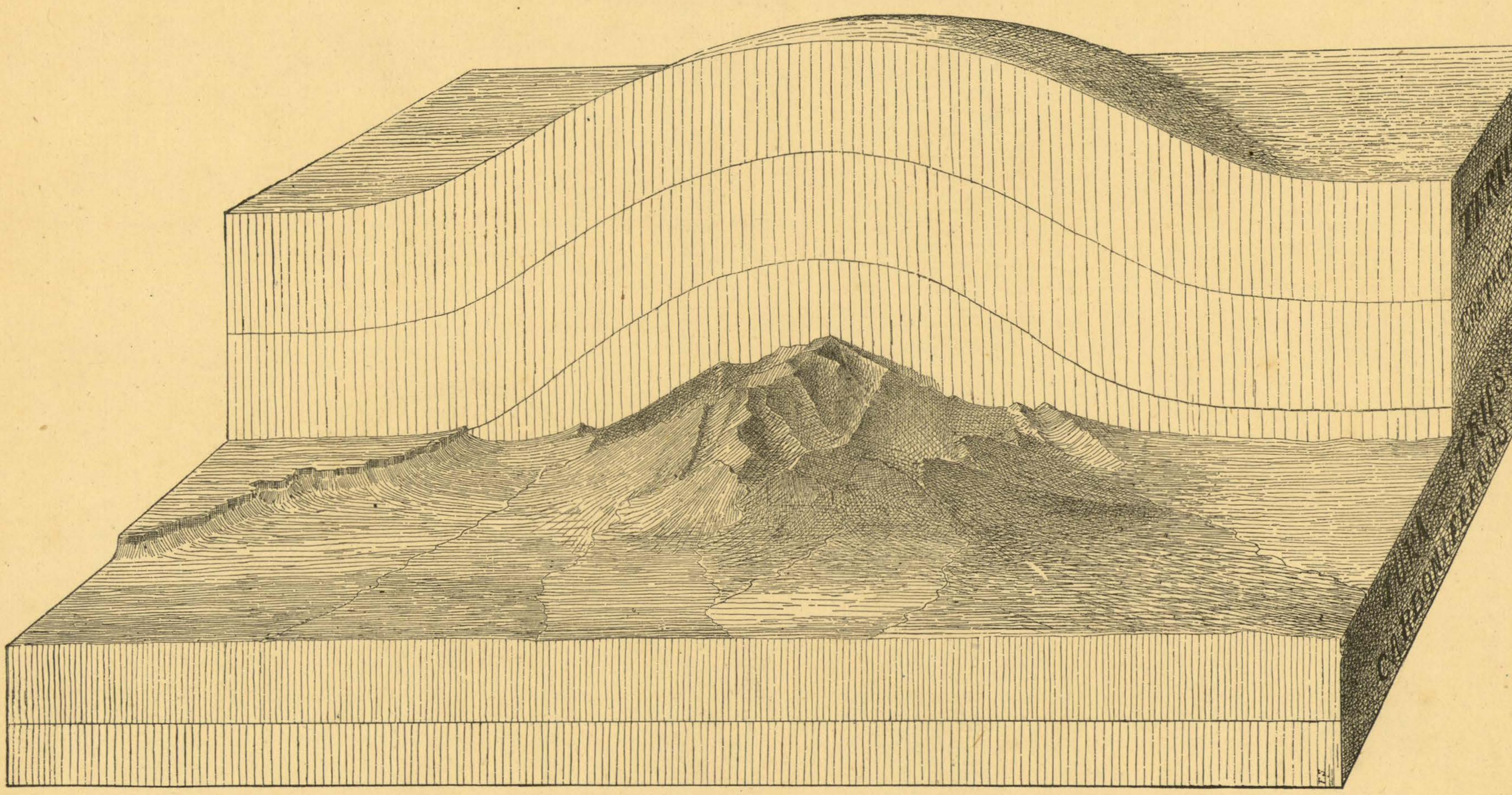


FRONTISPIECE.—Half-stereogram of Mount Ellsworth, drawn to illustrate the form of the displacement and the progress of the erosion.

The base of the figure represents the sea-level. The remote half shows the result of uplift alone; the near half, the result of uplift and erosion, or the actual condition. (See page 95.)

DEPARTMENT OF THE INTERIOR.

U. S. GEOGRAPHICAL AND GEOLOGICAL SURVEY OF THE ROCKY MOUNTAIN REGION.

J. W. POWELL, IN CHARGE.

REPORT

ON THE

GEOLOGY OF THE HENRY MOUNTAINS.

By G. K. GILBERT.

WASHINGTON:
GOVERNMENT PRINTING OFFICE.
1877.

DEPARTMENT OF THE INTERIOR,
U. S. GEOGRAPHICAL AND GEOLOGICAL SURVEY
OF THE ROCKY MOUNTAIN REGION,
Washington, D. C., March 5, 1877.

SIR: I have the honor to transmit herewith a report on the Geology of the Henry Mountains, by Mr. G. K. Gilbert.

I am, with great respect, your obedient servant,

J. W. POWELL,
In charge.

The Hon. SECRETARY OF THE INTERIOR,
Washington, D. C.

DEPARTMENT OF THE INTERIOR,
U. S. GEOGRAPHICAL AND GEOLOGICAL SURVEY
OF THE ROCKY MOUNTAIN REGION,
Washington, D. C., March 1, 1877.

DEAR SIR: I submit herewith my report on the Geology of the Henry Mountains, prepared from material gathered under your direction in the years 1875 and 1876.

I am, with great respect, your obedient servant,

G. K. GILBERT.

Prof. J. W. POWELL,
In charge.

PREFACE.

If these pages fail to give a correct account of the structure of the Henry Mountains the fault is mine and I have no excuse. In all the earlier exploration of the Rocky Mountain Region, as well as in much of the more recent survey, the geologist has merely accompanied the geographer and has had no voice in the determination of either the route or the rate of travel. When the structure of a mountain was in doubt he was rarely able to visit the points which should resolve the doubt, but was compelled to turn regretfully away. Not so in the survey of the Henry Mountains. Geological exploration had shown that they were well disposed for examination, and that they promised to give the key to a type of structure which was at best obscurely known; and I was sent by Professor Powell to make a study of them, without restriction as to my order or method. I was limited only in time, the snow stopping my work two months after it was begun. Two months would be far too short a period in which to survey a thousand square miles in Pennsylvania or Illinois, but among the Colorado Plateaus it proved sufficient. A few comprehensive views from mountain tops gave the general distribution of the formations, and the remainder of the time was spent in the examination of the localities which best displayed the peculiar features of the structure. So thorough was the display and so satisfactory the examination, that in preparing my report I have felt less than ever before the desire to revisit the field and prove my conclusions by more extended observation.

In the description of the details of the structure a demand arose for a greater number of geographic titles than were readily suggested by natural forms or other accidents, and recourse was had to the names of geologists. Except that the present members of my own corps are not included, the names chosen are of those whose cognate studies have given me most aid. Mr. Steward and Mr. Howell saw the Henry Mountains before I did, and gleaned something of their structure from a distance; Dr. Newberry, Mr. Marvine, Dr. Peale, and Mr. Holmes have described allied phenomena in Colorado and New Mexico; and the works of Messrs. Jukes, Geikie, Scrope, and Dana have been among my chief sources of information in regard to igneous mountains in general. If any of these gentlemen feel offended that their names have been attached to natural features so insignificant, I can assure them that the affront will never be repeated by the future denizens of the region. The herders who build their hut at the base of the Newberry Arch are sure to call it "the Cedar Knoll"; the Jukes Butte will be dubbed "Pilot Knob", and the Scrope, "Rocky Point".

During the preparation of my report every part of the discussion has been submitted to Professor Powell for criticism, and many of his suggestions are embodied in the text. Similar and valuable aid was received from Capt. C. E. Dutton and Mr. William B. Taylor in the study of the physical problems to which the discussion of the intrusive phenomena gave rise. Captain Dutton rendered an important service also by the study of the collection of igneous rocks, and his report, included in the fourth chapter, testifies to the thoroughness of his work. The supervision of the publication has fallen in large share upon Mr. J. C. Pilling, and the text has had the advantage of his literary criticism, as well as of his watchful care.

G. K. G.

CONTENTS.

CHAPTER I.

INTRODUCTORY.

The Henry Mountains have been visited only by the explorer. Previous to 1869 they were not placed upon any map, nor was mention made of them in any of the published accounts of exploration or survey in the Rocky Mountain region. In that year Professor Powell while descending the Colorado River in boats passed near their foot, and gave to them the name which they bear in honor of Prof. Joseph Henry, the distinguished physicist. In 1872 Prof. A. H. Thompson, engaged in the continuance of the survey of the river, led a party across the mountains by the Penellen Pass, and climbed some of the highest peaks. Frontiersmen in search of farming and grazing lands or of the precious metals have since that time paid several visits to the mountains; but no survey was made of them until the years 1875 and 1876, when Mr. Walter H. Graves and the writer visited them for that purpose.

They are situated in Southern Utah, and are crossed by the meridian of 110° 45′ and the thirty-eighth parallel. They stand upon the right bank of the Colorado River of the West, and between its tributaries, the Dirty Devil and the Escalante.

At the time of their discovery by Professor Powell the mountains were in the center of the largest unexplored district in the territory of the United States—a district which by its peculiar ruggedness had turned aside all previous travelers. Up to that time the greater part of the knowledge that had been gained of the interior of the continent had been acquired in the search for routes for transcontinental railways; and the cañons of the Colorado Basin, opposing more serious obstacles to travel than the mountain ranges which were met in other latitudes, were by common consent avoided by the engineers.

The same general causes which have rendered the region so difficult of access and passage have made it a desert, almost without economic value. The physical conditions of elevation and aridity which have caused it to be so deeply carved in cañons, have prevented the streams with which it is scantily watered from being bordered by tracts of land which can be irrigated; and agriculture without irrigation being in that climate an impossibility, there is nothing to attract the farmer. As will be explained in the sequel, the mountains offer no inducements to the miner of the precious metals. There is timber upon their flanks and there is coal near at hand, but both are too far removed from other economic interests to find the market which would give them value. It is only for purposes of grazing that they can be said to have a money value, and so distant are they at present from any market that even that value is small.

But while the Henry Mountains contribute almost nothing to our direct material interests, they offer in common with the plateaus which surround them a field of surpassing interest to the student of structural geology. The deep carving of the land which renders it so inhospitable to the traveler and the settler, is to the geologist a dissection which lays bare the very anatomy of the rocks, and the dry climate which makes the region a naked desert, soilless and almost plantless, perfects the preparation for his examination.

The study of the mountains is further facilitated by their isolation. They mark a limited system of disturbances, which interrupt a region of geological calm, and structurally, as well as topographically, stand by themselves.

The Henry Mountains are not a range, and have no trend; they are simply a group of five individual mountains, separated by low passes and arranged without discernible system. The highest rise about 5,000 feet above the plateau at their base and 11,000 feet above the level of the ocean. Projecting so far above the surface of the desert, they act as local condensers of moisture, and receive a comparatively generous supply of rain. Springs abound upon their flanks, and their upper slopes are clothed with a luxuriant herbage and with groves of timber. The smaller mountains and the foot-hills of the larger are less generously watered and but scantily clothed with vegetation. Their extent is small. From Ellen Peak to Mount Ellsworth, the two summits which are the most widely separated, the distance is but twenty-eight miles, and a circle of eighteen miles radius will include the whole group.

Mount Ellen which is the most northerly of the group, has an extreme altitude of 11,250 feet, and surpasses all its companions in horizontal extent as well as altitude. Its crest-line is continuous for two miles, with an elevation varying little from 11,000 feet. From it there radiate spurs in all directions, descending to a series of foot-hills as conspicuous in their topography as they are interesting in their structure. In some places the base of the mountain is guarded by a continuous, steep ridge, through which a passage must be sought by the approaching traveler, but within which movement in any direction is comparatively unimpeded.

Mount Pennell is a single peak rising to an altitude of 11,150 feet. On one side its slopes join those of Mount Ellen in Pennellen Pass (7,550 feet), and on the other those of Mount Hillers in the Dinah Creek Pass (7,300 feet). Its profiles are simple, and it lacks the salient spurs that characterize Mount Ellen. From the west it is difficult of approach, being guarded by a barrier ridge continuous with that of Mount Ellen.

Mount Hillers is more rugged in its character, and although compact in its general form, is carved in deep gorges and massive spurs. Its rugosity is contrasted by the smoothness of its pedestal, which to the south and west and north is a sloping plain merging with the surrounding plateau.

Mount Ellsworth (8,000 feet) and Mount Holmes (7,750 feet) stand close together, but at a little distance from the others. The pass which separates them from Mount Hillers has an altitude of 5,250 feet. They are single peaks, peculiarly rugged in their forms, and unwatered by springs. They stand almost upon the brink of the Colorado, which here flows through a cañon 1,500 feet in depth.

THE ROCK SERIES.

The sedimentary rocks which occur in the Henry Mountains and their immediate vicinity, range from the summit of the Cretaceous to the summit of the Carboniferous. It is probable that they were covered at one time by some thousands of feet of Tertiary strata, but from the immediate banks of the Colorado these have been entirely eroded, and their nearest vestiges lie thirty miles to the westward, where they have been protected by the lava-beds of the Aquarius Plateau.

Cretaceous.—The Cretaceous strata do not reach to the Colorado River, but they extend to the Henry Mountains, and are well displayed upon the flanks. They include four principal sandstones, with intervening shales, in the following (descending) order:

1. The Ma-suk' Sandstone, yellow, heavy-bedded	500 feet.
2. The Ma-suk' Shale, gray, argillaceous, and toward the top slightly arenaceous	500 feet.
3. The Blue Gate Sandstone, yellow and heavy-bedded	500 feet.
4. The Blue Gate Shale, blue-black and argillaceous, weathering to a fine gray clay (*Inoceramus deformis* and *I. problematicus*)	1, 000 feet.
5. The Tu-nunk' Sandstone, yellow and heavy-bedded	100 feet.
6. The Tu-nunk' Shale, blue-black and argillaceous, weathering to a fine gray clay (*Inoceramus problematicus* and *Baculites anceps*)	400 feet.
7. The Henry's Fork Group, consisting of—	
a. Friable yellow sandstone with numerous fossils (*Ostrea prudentia*, *Gryphea Pitcheri*, *Exogyra læviuscula*, *Exogyra ponderosa*, *Plicatula hydrotheca*, *Camptonectes platessa*, and *Callista Deweyi*)	10 feet.
b. Arenaceous shales, purple, green, and white, with local beds of conglomerate	190 feet
c. Coarse sandstone and conglomerate, with many white grains and pebbles, interleaved with local beds of purple and red shale, and containing immense silicified tree-trunks	300 feet.
Total Cretaceous	3, 500 feet.

The three upper sandstones, the Masuk, the Blue Gate, and the Tununk, are so nearly identical in their lithologic characters that I was unable to discriminate them in localities where their sequence was unknown. This was especially the case upon the summits of Mounts Ellen and Pennell where they occur in a somewhat metamorphosed condition. All of them contain thin beds of coal, none of which are continuous over large areas, and only one of which was observed of workable thickness. At the western foot of Mount Ellen, a bed four feet thick lies at the base of the Blue Gate Sandstone.

There is almost equal difficulty in discriminating the Masuk, the Blue Gate, and the Tununk shales. The first is usually of a paler color and is more apt to include arenaceous bands. It has not been found to contain fossils, while the lower shales rarely fail to afford them when search is made. The Blue Gate and Tununk shales are typical examples of fine argillaceous sediments. They are beautifully laminated and are remarkably homogeneous. It is only in fresh escarpments that the lamination is seen, the weathered surface presenting a structureless clay. The fossils of these shales are so numerous, when they have been sought out and studied, that they will probably serve not merely to discriminate the two, but also to correlate them with some of the beds which have been examined elsewhere in the Colorado Basin. For the present I am unable to refer any of the Cretaceous rocks above the Henry's Fork Group to the divisions which have been recognized elsewhere, and it is for this reason that I have given local, and perhaps temporary names to such beds as I have need to mention in the discussion of the structure of the mountains.

The fossils of the Henry's Fork Group have been more fully collected, and they have been referred without question by Dr. White to the group of that name, as recognized in the Green River Basin (Geology of the Uinta Mountains, pp. 82 and 94). The white grit which lies at the base of the group is a conspicuous bed of unusual persistence, and is recognized wherever Cretaceous rocks are found in the upper basin of the Colorado.

Jura-Trias.—The rocks which intervene between the base of the Cretaceous and the summit of the Carboniferous are of doubtful age, having been referred to the Trias by one geologist and to the Jura and Trias by others, while the fossils recently discovered by Mr. Howell (Geology of Uinta Mountains, page 80) lead to the suspicion at least that they are all

Jurassic. It is probable that the uncertainty will soon be dispelled by the more thorough working of Mr. Howell's new localities; but while it remains, it seems best to recognize its existence in our nomenclature, and I shall include the whole of the doubtful series under the title of *Jura-Trias.* At the Henry Mountains it is easily divided into four groups, as follows:

1. Flaming Gorge Group; arenaceous shales or bad-land sandstones, purple and white at top and red below	1, 200 feet.
2. Gray Cliff Group; massive cross-laminated sandstone, buff to red in color	500 feet.
3. Vermilion Cliff Group; massive cross-laminated sandstone, red, with a purple band at the top	500 feet.
4. Shin-ar′-ump Group; consisting of—	
a. Variegated clay shale; purple and white above and chocolate below, with silicified wood	300 feet.
b. Gray conglomerate, with silicified wood; the "Shinarump Conglomerate"	30 feet.
c. Chocolate-colored shale, in part sandy	400 feet.
Total Jura-Trias	2, 930 feet.

The rock of the Flaming Gorge Group is of a peculiar character. It is ordinarily so soft that in its manner of weathering it appears to be a shale. It is eroded so much more rapidly than the Henry's Fork conglomerate above it, that the latter is undermined, and always appears in the topography as the cap of a cliff. Nevertheless, it is not strictly speaking a shale. The chief product of its weathering is sand, and wherever it can be examined in an unweathered condition it is found to be a fine-grained sandstone, massive and cross-laminated like those of the Gray and Vermilion Cliffs, but devoid of a firm cement. In a number of localities it has acquired, locally and accidentally, a cement, and it is there hardly distinguishable from the firmer sandstones which underlie it. In the immediate vicinity of the Henry Mountains it varies little except in color from summit to base, but in other localities not far distant it is interrupted near the base by thick beds of gypsum and gypsiferous clays, and by a sectile, fossiliferous limestone.

The Gray Cliff and Vermilion Cliff sandstones are often difficult to distinguish, but the latter is usually the firmer, standing in bold relief in the topography, with level top, and at its edge a precipitous face. The former is apt to weather into a wilderness of dome-like pinnacles, so steep-sided that they cannot often be scaled by the experienced mountaineer, and separated by narrow clefts which are equally impassable.

The colors of the two sandstones are not invariable. The lower, which although not reddened throughout its mass is usually stained upon its surface with a uniform deep color, appears in Mount Ellsworth and at other points of elevation with as pale a tint as that of the Gray Cliff. The latter sandstone, on the other hand, where it lies low, is often as deep in color as the Vermilion. Standing upon one of the summits of the Henry Mountains and looking eastward, I found myself unable to distinguish the Gray Cliff Sandstone by color either from the lower part of the Flaming Gorge Group or from the Vermilion Sandstone. The bleaching of the redder sandstone in Mount Ellsworth is probably a result of metamorphism; the reddening of the gray sandstone may depend on the hydration of the iron which it contains.

The thickness of individual strata in these great sandstones is remarkable, and is one of the elements which must be taken into account in the discussion of the problem—which to my mind is yet unsolved—of the manner in which such immense quantities of homogeneous sand were accumulated. Ordinarily the depth of strata is indefinable, on account of the impossibility of distinguishing stratification from lamination; but where, as in this case, the lamination is oblique to the stratification, the upper and lower limits of each stratum are definitely marked. I have at several points measured single strata with thicknesses of about fifty feet, and near Waterpocket Cañon a stratum of Vermilion Cliff sandstone was found to be 105 feet thick.

One other measurement is worthy of record; the inclination which oblique lamination bears to the plane of the stratum in which it occurs appears to have a definite limit. The maximum of a series of measurements made at points where to the eye the dip seemed to be unusually great, is 24°.

The sandy layers at the base of the Shinarump Group are characterized by profuse ripple-marks.

Carboniferous.—Beneath the Jura-Trias is the Carboniferous. A few hundred feet of its upper member, the Aubrey Sandstone, are exposed near the summit of Mount Ellsworth. At that point the sandstone is altered to the condition of a quartzite, but where it is cut by the upper and lower cañons of the Dirty Devil River it is massive and cross-laminated, differing from the Gray Cliff sandstone chiefly in the abundance of its calcareous cement.

UNCONFORMITIES.

From the Masuk Sandstone to the Aubrey Sandstone, inclusive, there is perfect conformity of dip. The fold system of the region, of which a description will be found in succeeding pages, was established after the deposition of all these strata, and the whole series were flexed together. Nevertheless, the strata do not represent continuous deposition. There were intervals in which the sea receded and exposed to erosion the sediments which it had accumulated. Shallow valleys and water-ways were excavated, and when the sea returned it deposited new sediments upon the somewhat uneven surface of the old.

The first occurrence of this sort was at the close of the Aubrey epoch. Its evidence was not found in the Henry Mountains; but at the confluence of the Paria with the Colorado, eighty miles to the southeast, the surface of the upper member of the Aubrey Group, which is there a cherty limestone, is unevenly worn, and in its depressions are beds of conglomerate, the pebbles of which are derived from the chert of the limestone itself. The shaly, rippled sandstones which succeed this conglomerate indicate that the water remained shallow for a time, and in the middle of the Shinarump epoch the region was once more abandoned by the sea. The chocolate shales and shaly sands were unevenly worn, and the first deposit that the returning sea spread over them was a conglomerate. The evidence of this break is found at many points. The Shinarump conglomerate although remarkably persistent for a conglomerate thins out and disappears at a number of points, and at the margins of its areas it is evident to the eye that it occupies depressions of the surface on which it rests

The next break is at the base of the Vermilion Cliff Group. In the region of the Virgin River and Kanab Creek the change from the variegated shales of the Upper Shinarump to the homogeneous sandstone of the Vermilion Cliff is gradual, the interval being filled by a series of alternating shales and sandstones; but further to the east, in the region of the Henry Mountains and Waterpocket Cañon, the change is abrupt, and the firm sandstone rests directly upon the soft shale. The abruptness of the change would suggest that the currents which brought the sand had swept away all evidence of the intermediate conditions which are likely to have connected the epochs represented by the two sediments; but in one locality, at least, there is direct evidence that the surface of the clay was exposed to the air before it was covered by the sand. On the northern flank of Mount Ellsworth are the vestiges of a system of mud-cracks, such as form

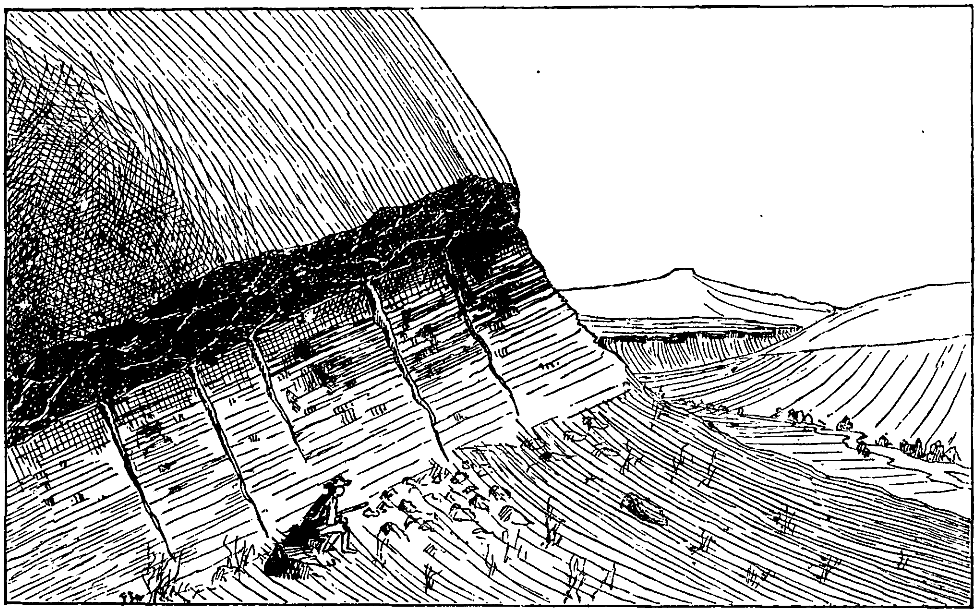


FIG. 1.—Fossil Suncracks in the Shinarump Shale.

where wet clays are dried in the sun. Where the under surface of the Vermilion sandstone is exposed to view, it is seen to be marked by a network of ridges which once occupied the sun-cracks of the Shinarump clay; and where the clay is seen in juxtaposition, tapering fillets of sand can be traced from the ridges downward ten feet into the clay.

From the base of the Vermilion to the summit of the Cretaceous no evidence of land erosion has been found; but the association of coal seams with all of the Cretaceous sandstones except the lowest, shows that the sea-bottom was frequently brought to the surface of the water if it was not carried above.

Thus it is evident that the strata of the Henry Mountain region do not represent continuous sedimentation. At the close of the Aubrey epoch, in the middle of the Shinarump, and again at the close of the Shinarump, not merely was the accumulation of sediments interrupted, but the process was reversed, and a portion of the deposits which had already been formed were excavated by the agency of rains and rivers, and swept away to some other region. Each break is indefinite, alike as regards the interval during which the record of the sea was interrupted and as regards the extent of the record which was at the same time obliterated. And yet the evidence of these breaks is of such nature that it would probably elude observation if a single section only were examined, and in a region masked by the soil and vegetation of a humid climate it would hardly be discovered except by accident. The parallelism of contiguous strata is not alone sufficient evidence that they were consecutive in time.

At the close of the Cretaceous period there came an epoch of disturbance. The system of strata which has been described was bent into great waves, and the crests of the waves were lifted so high above the sea that they lost thousands of feet by erosion.

In the troughs between the waves lakes remained, in which the material removed from the crests was redeposited, and by a later change the lake waters rose so as to cover the truncated crests, and deposit upon the worn edges of the upbent strata a series of unconforming, fresh-water, Tertiary sediments.

Thus was produced the only *unconformity of dip* which involves the Henry Mountain rocks, and even this is not to be observed in the immediate vicinity of the mountains, for a later erosion has thence removed all of the Tertiary strata, and has resumed the degradation of the older beds.

THE GREAT FOLDS.

The disturbances at the close of the Cretaceous period were of the Kaibab type*. It seems as though the crust of the earth had been divided into great blocks, each many miles in extent, which were moved from their original positions in various ways. Some were carried up and others down, and the majority were left higher at one margin than at the other. But although they moved independently, they were not cleft asunder. The strata remained continuous, and were flexed instead of faulted at the margins of the blocks. Subsequent erosion has obliterated in great part the inequality of the surface, and the higher-lying blocks do not stand as mountains, but are outlined by zones of tilted strata which mark the flexures by which the blocks are separated. Along the zones of flexure it frequently happens that a hard stratum outcropping between two that are softer will be preserved from erosion and form a long, continuous ridge. Such ridges, and other forms produced by the erosion of the flexures, are conspicuous features of the topography, and the tracing out of the limits of the blocks is a simple matter. Indeed the flexures are the first elements of the structure to attract attention, and it is easy in studying them to overlook the fact that they merely mark the limits between displaced masses of great extent. If the reader will examine Plate I at the end of the volume, he will observe that the system of parallel ridges and valleys which follow the line of the Waterpocket flexure are very conspicuous features; but it is only by some such generalization as that given in the stereogram of the same region (Plate II) that the full structural significance of the flexures can be realized. Each map was obtained by photography from a model in relief, in which the proportionate heights of the several features were not exaggerated. The stereogram was produced by the restoration of the top of the Cretaceous, the Masuk sandstone, in the form and position it would have, had there been no erosion of the region, but displacement only.

I must caution the reader against an implication of rigidity which might attach to the meaning of the word "block", as I have used it in speaking

* For a definition of the Kaibab structure, see "Geology of the Uinta Mountains," pp. 14 and 17, and American Journal of Science for July and August, 1876, pp. 21 and 85.

of the great displaced rock-masses. To what extent they may be regarded as rigid is uncertain, but the presence upon their surfaces of numerous minor flexures, such as appear in the stereogram, would seem to imply that their rigidity is not of a high order.

In the northwest corner of the area represented by the stereogram are a few faults belonging to a system which occupies a large area in that direction. The system of faults and the system of flexures are independent, the latter having originated at the close of the Cretaceous period, and the former after the formation of the Tertiary rocks of the region, which are referred by Professor Powell to the Bitter Creek epoch. Over a large district the Tertiary strata were covered by a deep mantle of lava, which has protected them from erosion to such an extent that the structure of the district is portrayed in its topography. The district is its own stereogram, each uplifted block constituting a mountain and each depressed block flooring a valley.

Not all the displacements of the later system are by faulting, but by far the greater number. Of the earlier system of displacements none are simple faults, but a few are combinations of fault and flexure.

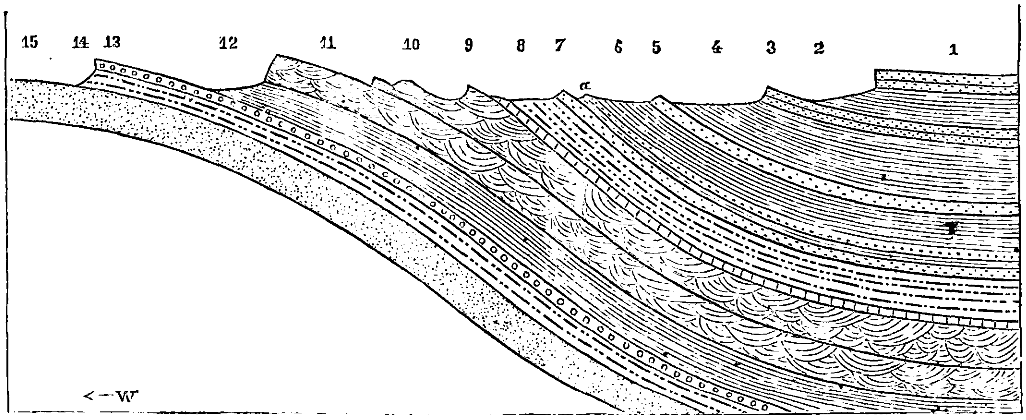


FIG. 2.—Cross-section of the Waterpocket Flexure, opposite the Masuk Plateau. Scale, one inch = 3,500 feet. 1, Masuk Sandstone. 2, Masuk Shale. 3, Blue Gate Sandstone. 4, Blue Gate Shale. 5, Tununk Sandstone. 6, Tununk Shale. *a*, Gryphea Sandstone. 7, Henry's Fork Conglomerate. 8, Flaming Gorge Shale. 9, Fossiliferous Limestone. 10, Gray Cliff Sandstone. 11, Vermilion Cliff Sandstone. 12, Upper Shinarump Shale. 13, Shinarump Conglomerate. 14, Lower Shinarump Shale. 15, Aubrey Sandstone.

The Waterpocket flexure, represented in the stereogram (Plate II), is better known in detail than any other of the great flexures of Southern Utah. It is far from following a straight line, but like most lines of oro-

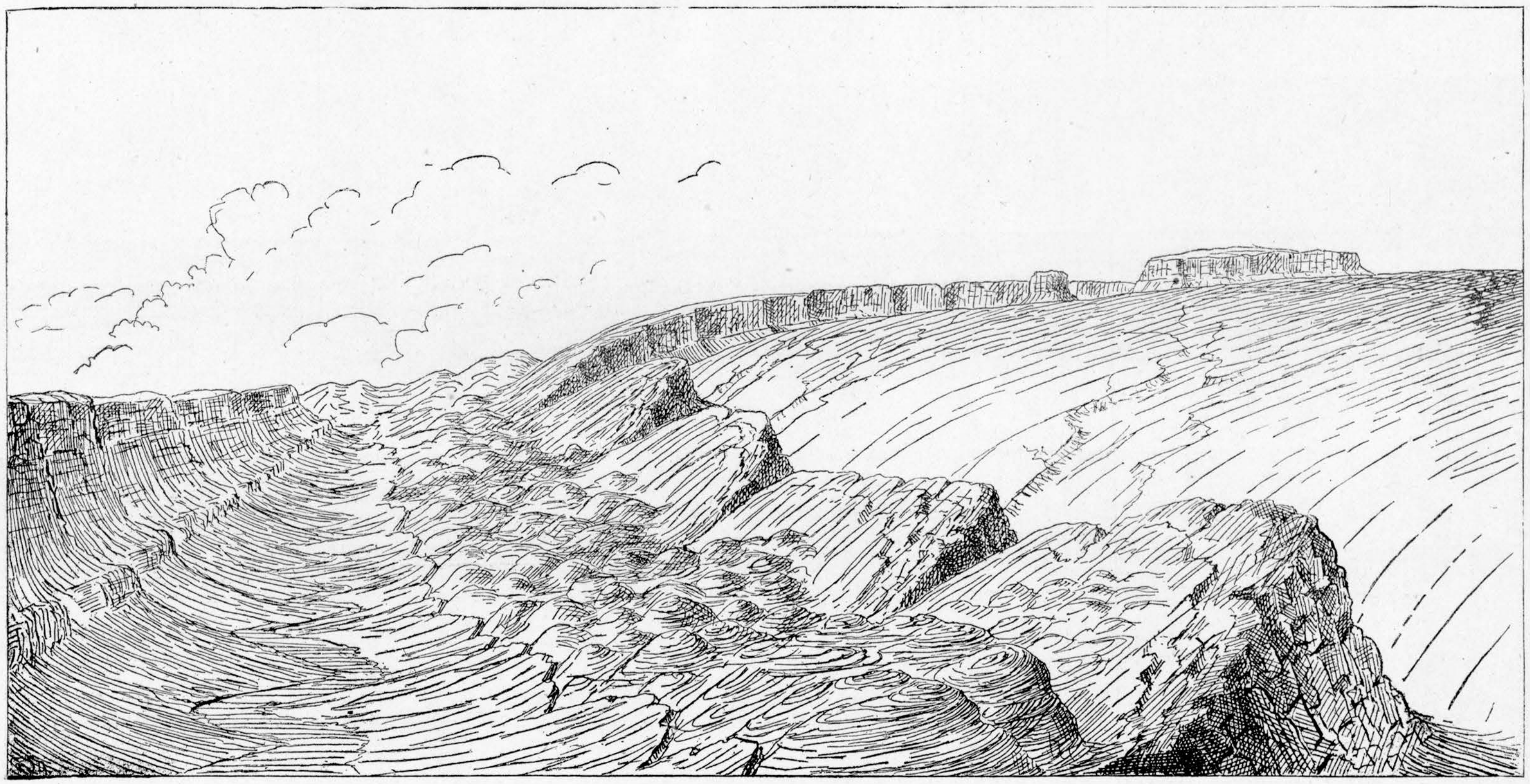


Fig. 3.—View of the Waterpocket Cañon and the Waterpocket Flexure. The cliff at the left is capped by the Henry's Fork Conglomerate. The arched rocks at the right are the Gray and Vermilion Cliff Sandstones.

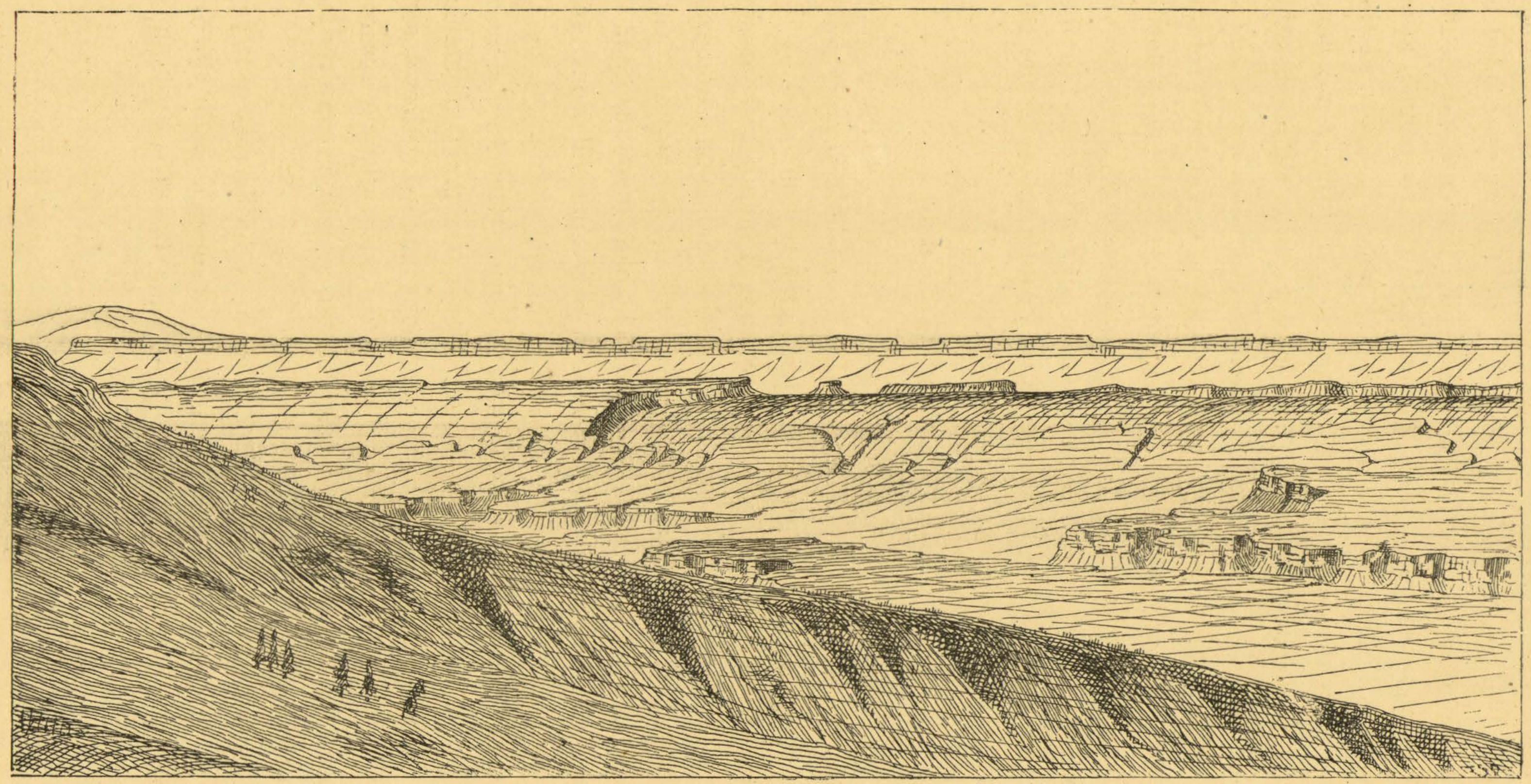


Fig. 4.—Waterpocket Flexure, as seen from the south end of Mount Ellen.

graphic disturbance swerves to the right and left, while maintaining a general trend. The amount of its "throw", or the difference in level between adjacent parts of the two blocks which it divides, is inconstant, its maximum being 7,000 feet. At some points the flexed strata are inclined at an angle of 50° while at others their greatest dip is but 15°. Toward the north the flexure twice divides. One of its branches, the Blue Gate flexure, has a throw in the same direction, and by its separation diminishes the throw of the main flexure. The other, the Red Gate flexure, has a throw in the opposite direction, and by its separation increases the throw of the main flexure. Or in other words, the blocks at the west of the main flexure stand higher than those at the east; and of two blocks which lie at the west, that at the north of the Red Gate flexure stands higher than that at the south; while of two blocks at the east, that which lies northwest of the Blue Gate flexure is higher than the one at the southeast.

CLIFFS AND PLATEAUS.

Let us now return to the topographic map (Plate I) and examine the forms into which erosion has wrought the disturbed strata. Thanks to the aridity of the climate, the erosion has been greatly influenced by the varying texture of the rocks. Every hard stratum, if inclined, stands forth in a ridge, or if level, caps a plateau. The Masuk Sandstone, undermined by the weathering of the Masuk Shale, breaks off everywhere in a cliff which completely encircles the Masuk Plateau. The plateau stands upon the Blue Gate Sandstone, and this breaking off in a cliff upon all sides constitutes another plateau. The Blue Gate Plateau, in turn, rests upon the Tununk, and that again upon the Henry's Fork. Passing either to the north or to the south from the Masuk Plateau, one descends a great geological stairway, of which each step is a hard sandstone and each riser a soft shale. Toward the Waterpocket flexure the edge of each plateau is upturned, and if one goes westward from the Masuk Plateau, he will cross in the first mile the upturned rocks of all the lower tables.

The preservation of the Masuk Plateau is due in part to the fact that it lies in a slight synclinal, but chiefly to the arrangement of the drainage-lines. No streams cross the Henry Mountains, but all go around, and the plateau occupies the divide between those which flow southward to the Colorado and those which flow northward to the Dirty Devil.

The antithesis of the Masuk Plateau is to be seen in the Circle Cliffs, on the summit of the Waterpocket fold. At the lowest point of the Masuk synclinal a circling cliff has been formed, which facing outward surrounds a plateau. At the highest point of the Waterpocket fold, which is in a certain sense anticlinal, a circling cliff has been formed which, facing inward, surrounds a valley. The two phenomena are alike illustrations of the law that in regions of inclined strata cliffs face toward districts of elevation and away from districts of depression.

HOW TO REACH THE HENRY MOUNTAINS.

No one but a geologist will ever profitably seek out the Henry Mountains, and I will therefore, in marking out a route by which they may be reached, select whenever there is option those paths which will give him the best introduction to this wonderful land. There is no wagon-road to the mountains, and although a wagon might carry his baggage the greater part of the way, he must provide himself with other means of tranportation. At Salt Lake City he can procure pack-mules and pack-saddles, or *apparajos*, and everything necessary for a mountain "outfit". His route southward follows the line of the Utah Southern Railway to Juab Valley, and then touches the Mormon towns of Nephi, Gunnison, and Salina. At Salina he halts his train for a day while he rides a few miles up the creek to see the unconformity between the Tertiary above, and the Jura-Trias and Cretaceous below. This is at present the last settlement on the route, but there are "ranches" as far as Rabbit Valley, and if he delays a few years he will find a town there. By way of the "Twist" road and King's Meadows he goes to Grass Valley, and thence to Fish Lake. The lake lies between two upheaved blocks of trachyte, and covers one which is relatively depressed, and tilted to the north. At the south end of the lake he stands on the higher end of the depressed block, and if he follows the shore to the outlet at the north he will find that the water is contained by a

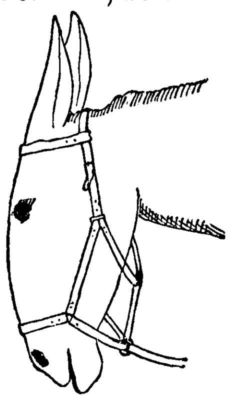


FIG. 5.—Ways and Means.

moraine, which has been thrown across the valley by an ancient glacier, descending from the mountain at the west. From Fish Lake he goes to Rabbit Valley, and there delays a day or two to climb Thousand Lake Mountain. Looking west from the summit he sees the lava-capped plateaus of the faulted district among which he has journeyed since he left the "Twist"—huge tables of trachyte bounded by cliffs of displacement, of which only the sharpest edges have been worn away; and when his eye has become accustomed to the *facies* of the faults, he perceives that there

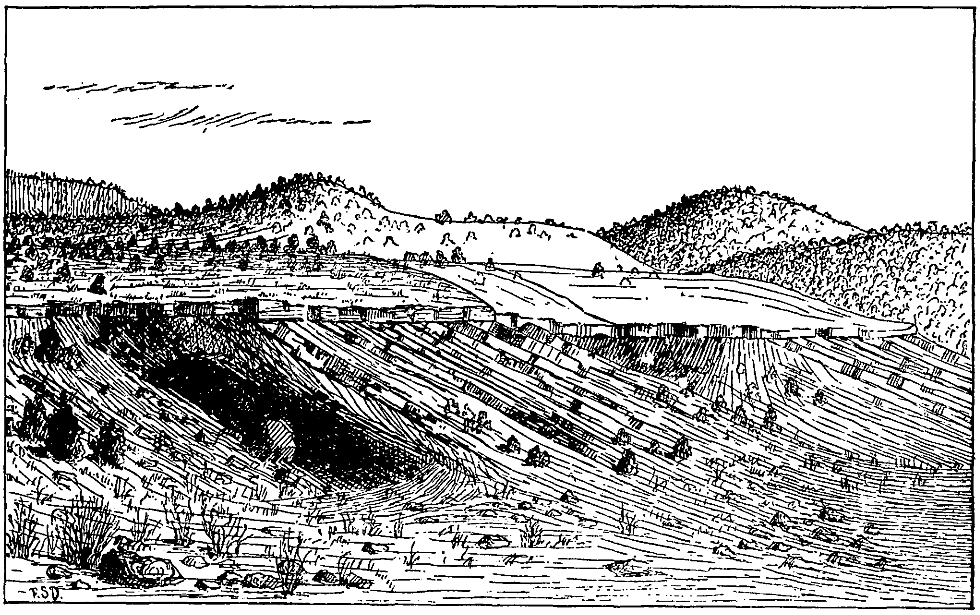


FIG. 6.—The Unconformity of the lower cañon of Salina Creek. The horizontal strata are Tertiary; the inclined, Cretaceous.

is an identity in structure between the great and the small features. Just as the whole district is divided into blocks, of which the dimensions are measured by miles, and the displacements by thousands of feet, so the greater blocks are sometimes divided into smaller, of which the dimensions are measured by rods and furlongs and the displacements by tens and hundreds of feet. Looking eastward he sees the region of the great flexures spread out before him like a map. The Waterpocket flexure starts from the very mountain beneath him, and curving to the right, runs far to the south and is lost in the distance. Beyond it are the Henry Mountains springing abruptly from the desert; and against the horizon are outlined other island mountains, gray in the distance. To the left is the San Rafael Fold, the rival of the Waterpocket in grandeur; and all about are tables and cliffs. The vivid hues of the naked rocks are obscured only by the desert haze, and the whole structure is pictured forth by form and color.

To reach the Henry Mountains from Rabbit Valley, he must cross the Waterpocket flexure; and so continuous and steep are the monoclinal ridges which follow the line of flexure, that there are but four points known where he can effect a passage. Except at these points, the barrier is impassable from Thousand Lake Mountain to the Colorado River, a distance of eighty miles. The most difficult and circuitous route I will not describe. The remaining three diverge but slightly from each other. Starting from Rabbit Valley he follows for a few miles the valley of the Dirty Devil, which here, through the "Red Gate", passes from the trachyte plateaus and enters the land of cañons. He does not follow it far, but where the river enters a cañon in the Aubrey Sandstone, bears to the left, and by the aid of a trail which Indians have made finds a sinuous but easy pathway along a monoclinal valley, following the outcrop of the lower Shinarump. At his right the Aubrey Sandstone rises to form the plateau through which the river defiles. At his left the Vermilion Sandstone stands in a vertical wall. Beneath his feet are the shaly sandstones of the Shinarump Group, bare of vegetation and displaying a profusion of ripple-marks, such as is rarely if ever equaled. A ride of twelve miles brings him once more to the Dirty Devil River, which emerging from its Carboniferous cañon dives at once into a still deeper cañon through the Vermilion and Gray Cliff Sandstones. He can follow the river if he tries, and emerge with it beyond the flexure; but the way is difficult and the Indian trail he has followed thus far leads on to another cañon. The monoclinal valley which has opened so easy a way continues for fifteen miles farther, and in that distance is crossed by four water-ways, each of which leads by a narrow cañon through the great sandstones. The first and fourth are impassable. The second carries no permanent stream, and is called the "Capitol Cañon". The third affords passage to Temple Creek. The smoothest road lies through Capitol Cañon, but the Temple Creek Cañon has an advantage in the presence of water, and is furthermore attractive by reason of the picture-writings on the walls.

He has now to cross the Blue Gate flexure, and to do this he leaves Temple Creek a little below the mouth of its cañon. Seeking once more the guidance of a trail, he journeys southeastward over the gypsum and sand of the Flaming Gorge Group to a pass which from a distance he has detected in the monoclinal ridge marking the Henry's Fork conglomerate. Through this pass Tantalus Creek sometimes runs on its way to join the Dirty Devil, and he may find a stream of muddy water; but the bottom is more likely to be dry with the exception of a few pools. Passing through the gap he finds before him a similar opening in the Tununk Ridge, and beyond that a break in the Blue Gate Cliff. From Tantalus Creek he ascends to the pass in the Blue Gate Cliff, and climbing to the summit of a sharp divide in the shales descends again to Lewis Creek, which there follows a cañon through the Blue Gate Plateau. Here he finds bowlders of the Henry Mountain trachyte—for Lewis Creek rises in the Henry Mountains—and a few hours' ride toward the sources of the stream brings him to the base of Mount Ellen.

Distances.

From Salt Lake City to Salina	155 miles.
From Salina to Fish Lake	38 miles.
From Fish Lake to Rabbit Valley	27 miles.
From Rabbit Valley to Temple Creek Cañon	27 miles.
From Temple Creek Cañon to Lewis Creek	18 miles.
Thence to the base of Mount Ellen	10 miles.
Total from Salt Lake City to the Henry Mountains	275 miles.

CHAPTER II.

THE STRUCTURE OF THE HENRY MOUNTAINS.

The mountains stand within the province of the great flexures, but are independent of them. Fifteen miles to the westward runs the Waterpocket flexure. Thirty miles to the north is the San Rafael fold. At the east the strata rise toward a great uplift, of which the full form is unknown. But where the Henry Mountains stand the rocks are unaffected by these disturbances. They have a uniform dip of about 45′ to the northwest, and form a perfect datum-plane from which to measure the magnitude of the displacements which have given rise to the mountains.

The mountains are composed of a large number of parts which are in a certain degree individual and homologous. By the generalization of the characters of those parts a conception has been obtained of a *type structure* to which the entire series of phenomena has been referred.

In laying the material before the reader, the following plan will be followed:

First. The type of structure will be briefly set forth.

Second. The phenomena by which the type is at once demonstrated and illustrated will be described in detail.

Third. The type of structure will be discussed.

If the structure of the mountains be as novel to the reader as it was to the writer, and if it be as strongly opposed to his preconception of the manner in which igneous mountains are constituted, he may well question the conclusions in regard to it while they are unsustained by proof. I can only beg him to suspend his judgment until the whole case shall have been presented. On some accounts it would have been well to follow in writing the order of investigation, and develop the general plan of structure as it was developed in the field, by the addition here of one element and there of another; or at least to assemble the facts before announcing my deductions. But such a course would be at the expense of an important element of convenience and brevity. As will appear in the sequel, the preliminary explanation of the type structure furnishes a complement of categories and terms by the aid of which the description of the details of observation, essentially tedious, is greatly abbreviated.

It is usual for igneous rocks to ascend to the surface of the earth, and there issue forth and build up mountains or hills by successive eruptions. The molten matter starting from some region of unknown depth passes through all superincumbent rock-beds, and piles itself up on the uppermost bed. The lava of the Henry Mountains behaved differently. Instead of rising through all the beds of the earth's crust, it stopped at a lower horizon, insinuated itself between two strata, and opened for itself a chamber by lifting all the superior beds. In this chamber it congealed, forming a massive body of trap. For this body the name *laccolite* (λάκκος, *cistern*, and λίθος, *stone*) will be used. Figure 7 and Figure 8 are ideal sections of a mountain of eruption and of a laccolite.

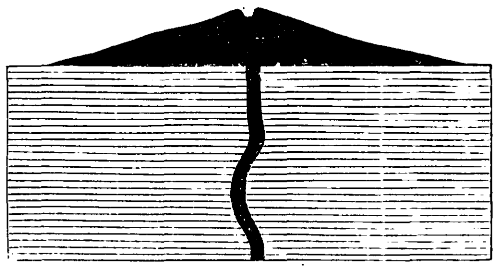


FIG. 7.—Ideal Cross-section of a Mountain of Eruption.

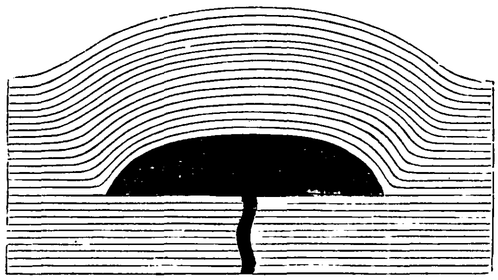


FIG. 8.—Ideal Cross-section of a Laccolite, showing the typical form and the arching of the overlying strata.

The laccolite is the chief element of the type of structure exemplified in the Henry Mountains.

It is evident that the intrusion of a laccolite will produce upon the surface as great a hill as the extrusion of the same quantity of matter, the mass which is carried above the original surface being precisely equivalent to that which is displaced by the laccolite; and it is further evident that where the superior rock is horizontally stratified every stratum above the laccolite will be uplifted, and, unless it is fractured, will be upbent, and will portray, more or less faithfully, by its curvature, the form of the body it covers.

Associated with the laccolites of the Henry Mountains are *sheets* and *dikes*.

The term *sheet* will be applied in this report to broad, thin, stratified bodies of trap, which have been intruded along the partings between sedimentary strata, and conform with the inclosing strata in dip. *Dikes* differ from sheets in that they intersect the sedimentary strata at greater or less angles, occupying fissures produced by the rupture of the strata.

The logical distinction between dike and sheet is complete, but in nature it not unfrequently happens that the same body of trap is a sheet in one place and a dike in another. Between the sheet and the laccolite there is a complete gradation. The laccolite is a greatly thickened sheet, and the sheet is a broad, thin, attenuated laccolite.

In the district under consideration the laccolite is usually, perhaps always, accompanied by dikes and sheets (see Figure 9). There are sheets beneath laccolites and sheets above them. The superior sheets have never been observed to extend beyond the curved portion of the superior strata. Dikes rise from the upper surfaces of the laccolites. They are largest and most numerous about the center, but, like the superior sheets, they often extend nearly to the limit of the flexure of the uplifted strata. The larger often radiate from the center outward, but there is no constancy of arrangement. Where they are numerous they reticulate.

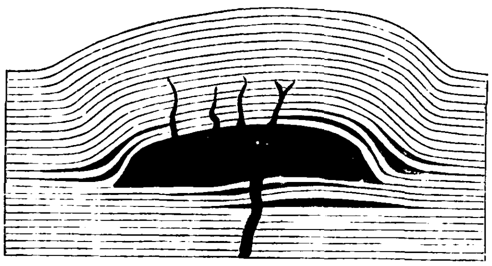


FIG. 9.—Ideal Cross-section of a Laccolite, with accompanying Sheets and Dikes.

In the accompanying diagrams dikes are represented beneath as well as above the laccolites. These are purely hypothetical, since they have not been seen. In a general way, the molten rock must have come from below, but the channel by which it rose has in no instance been determined by observation.

The horizontal distribution of the laccolites is as irregular as the arrangement of volcanic vents. They lie in clusters, and each cluster is marked by a mountain. In Mount Ellen there are perhaps thirty laccolites. In Mount Holmes there are two; and in Mount Ellsworth one. Mount Pennell and Mount Hillers each have one large and several smaller ones.

Their vertical distribution likewise is irregular. Some have intruded themselves between Cretaceous strata, others between Jura-Triassic, and others between Carboniferous. From the highest to the lowest the range is not less than 4,000 feet. Those which are above not unfrequently overlap those which lie below, as represented in the ideal section, Figure 10.

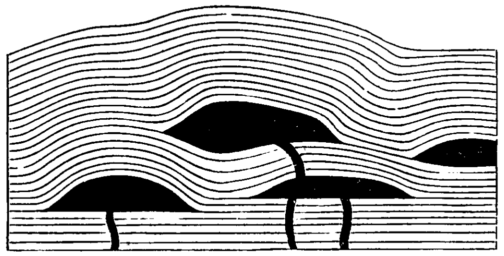


FIG. 10.—Ideal Cross-section of Grouped Laccolites.

The erosion of the mountains has given the utmost variety of exposure to the laccolites. In one place are seen only arching strata; in another, arching strata crossed by a few dikes; in another, arching strata filled with a net-work of dikes and sheets. Elsewhere a portion of the laccolite itself is bared, or one side is removed so as to exhibit a natural section. Here the sedimentary cover has all been removed, and the laccolite stands free, with its original form; there the hard trachyte itself has been attacked by the elements and its form is changed. Somewhere, perhaps, the laccolite has been destroyed and only a dike remains to mark the fissure through which it was injected

CHAPTER III.

DETAILED DESCRIPTION OF THE MOUNTAINS.

MOUNT ELLSWORTH.

It has already been stated that the strata about the bases of the Henry Mountains are nearly level; but the country which is built of them is far from level. The arrangement of the drainage lines has caused the degradation of some parts to greatly exceed that of others, so that while the district at the south, which borders the Colorado River, is paved with the red sandstones of the Jura-Trias series, the adjacent region at the north still carries the yellow sandstones and blue shales of the Cretaceous series. All about Mount Ellsworth are the upper strata of the Jura-Trias. The lower beds of the same series rise upon its flanks and arch over its summit.

A description of the structure of the mountain must include, first, the arch of the strata; second, the faults which modify the arch; third, the system of trachyte dikes and trachyte sheets; and fourth, the sculpture of the mountain. In its general proportions the arch is at once simple and symmetrical. From all sides the strata rise, slowly at first, but with steadily increasing rate, until the angle of 45° is reached. Then the dip as steadily diminishes to the center, where it is nothing. A model to exhibit the form of the dome would resemble a round-topped hat; only the level rim would join the side by a curve instead of an angle, and the sides would not be perpendicular, but would flare rapidly outward (see Figure 11). The base of the arch is not circular, but is slightly oval, the long diameter being one-third greater than the short. The length of the uplift is a little more than four miles; the width a little more than three miles, and the height about 5,000 feet. The curvature fades away so gradually at its outer limit that it is not easy to tell where it ends, and the horizontal dimensions assigned to the dome are no more than rude approximations. But there is another element which can be given more exactly.

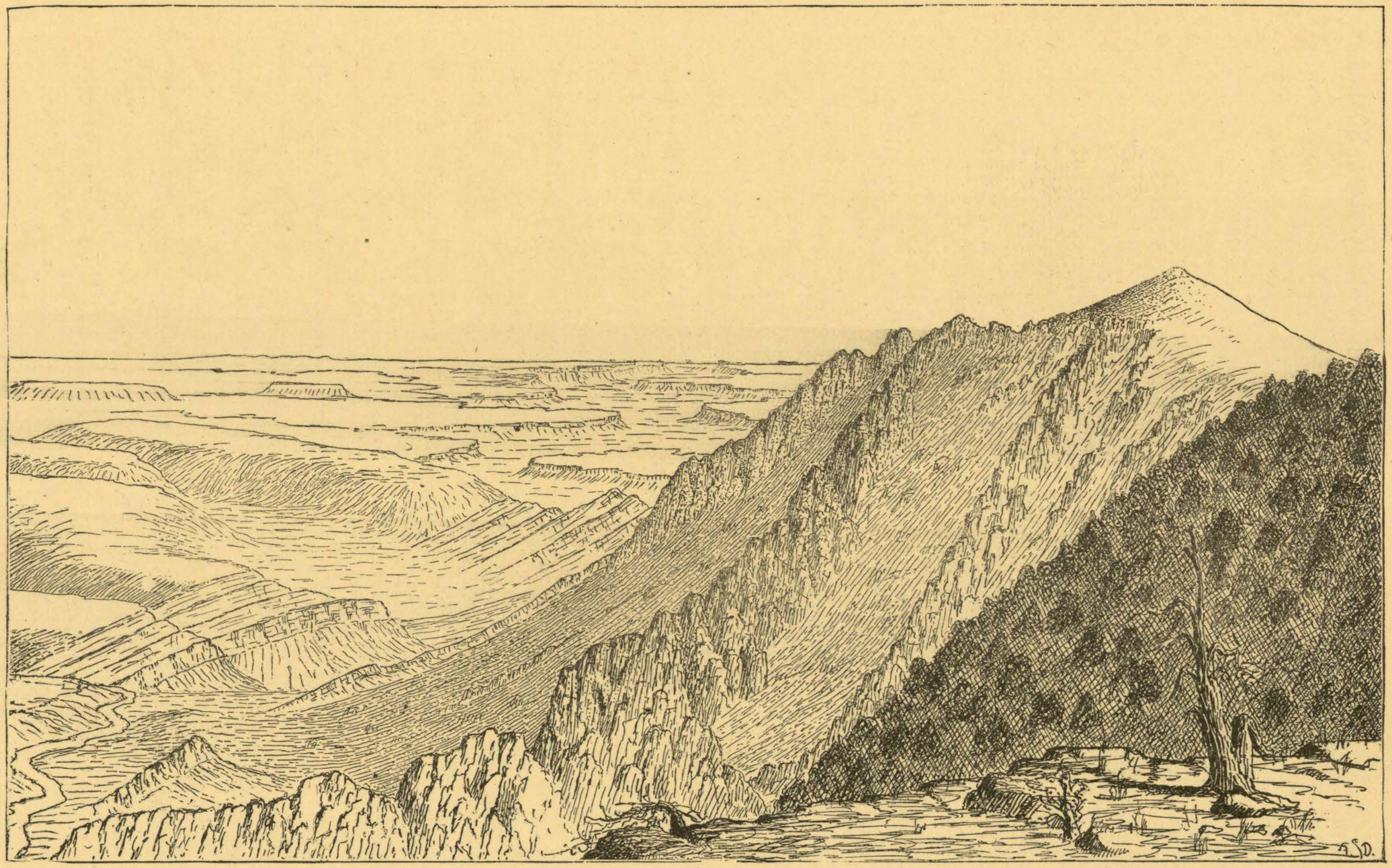


FIG. 11c.—View from the west spur of Mount Ellsworth, showing the trachyte dikes of the north spur and revetments of sandstone and trachyte.

The line of maximum dip, which separates the convex upper portion of the dome from the concave periphery, is easily traced out in nature, and runs at the foot of the steep part of the mountain. It surrounds an area two miles in width and two and two-thirds miles in length.

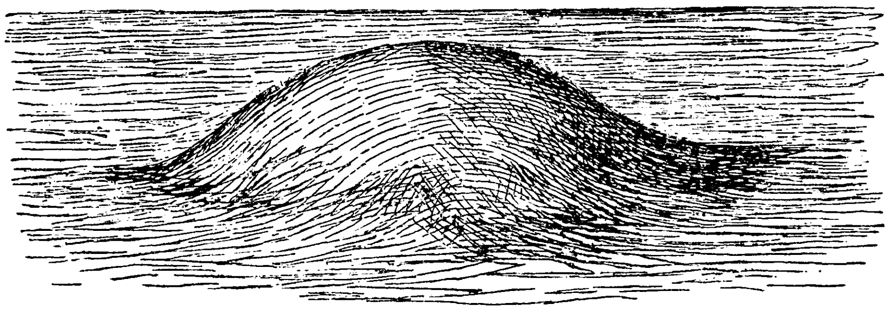


FIG. 11.—Stereogram of Mount Ellsworth; an ideal restoration of the form of the overarching strata.

The Ellsworth arch is almost but not completely isolated. The Holmes arch, upon the east side, stands so near that the bases of the two impinge and coalesce, and the same thing happens, though less notably, with the Hillers arch at the north.

The simplicity of the arch is further impaired by faults—not great faults dividing the whole uplift, but a system of small displacements which are themselves subordinate phenomena of the uplift. They are restricted to the central portion, and never occur so low down as the line of maximum dip. The strata of the upper part of the arch are divided into a number of prismoid blocks which stand at slightly different levels but are not sufficiently deranged to destroy the general form of the arch. The greatest throw is only a few hundred feet. All or nearly all of the fault planes are occupied by dikes of trachyte.

The trachyte injections are not confined to the fault planes, nor is their area so restricted as the fault area. Dikes and sheets abound from the crest of the dome down to what might be called its springing line—the line of maximum dip. At the center, dikes are more numerous; near the limit, sheets. The central area is crowded so full of dikes, and the weathering brings them so conspicuously to the surface, that the softer sedimentaries are half concealed, and from some points of view the trachyte appears to make the entire mass. The accompanying plat (Figure 12) shows the arrangement of the dikes in one of the outer amphitheaters of the mountain, where they are less complicated than in the central region. The trends of two spurs (*a b* and *c d*) are indicated by the hatchings. They join the main crest of the mountain at *e*, and inclose between them a deep amphitheater which opens to the west. Upon the steep walls of the amphitheater the dikes outcrop in lines of crags, dividing rough slopes of yellow and purple and brown sandstone. The profile of one of the walls of the amphitheater (from *a* to *b*, Figure 12) is drawn in Figure 13 for the sake of exhibiting the relation of the dikes to faulted blocks of sandstone. It will be seen that the throw of the faults is not constantly in one direction.

The zone of sheets is just inside the line of maximum dip. Usually

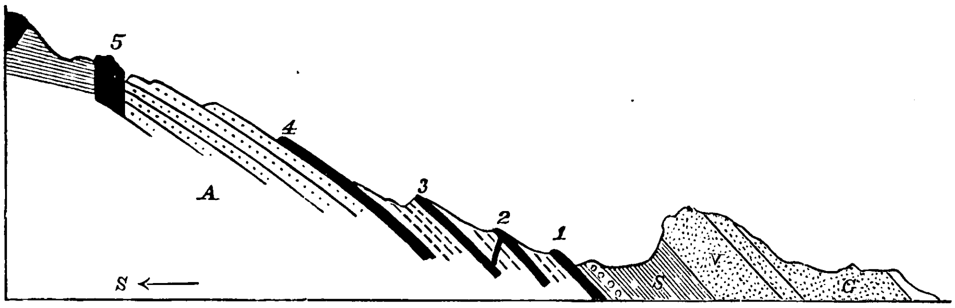


FIG. 14.—Profile of the Northern Spur of Mount Ellsworth. 1, 2, 3, 4, and 5 are Trachyte Dikes. *A*, Aubrey Sandstone. *S*, Shinarump Shale. *V*, Vermilion Cliff Sandstone. *G*, Gray Cliff Sandstone.

only one or two sheets are laid bare by the erosion, but at one point (see Figure 14) four can be counted. Toward the center of the uplift all of these are limited by the erosion and exhibit their broken edges. Downward, or toward the periphery, they dip out of sight. Laterally they can be traced along the mountain side for varying distances, but they soon wedge out and are replaced by others *en echelon*. In thickness the sheets rarely exceed 50 feet, and never 100. They are always thin as compared to the rock masses which separate them, but, by reason of their superior ability to resist erosion, monopolize a large share of the surface, and mask a still greater amount with their *débris*.

The sedimentary rocks are not altered beyond the region of trachyte intrusion. The mere flexure of the strata was not accompanied by a perceptible change of constitution. In the zone of sheets there is little change except along the surfaces of the contact. For a few feet, or perhaps only

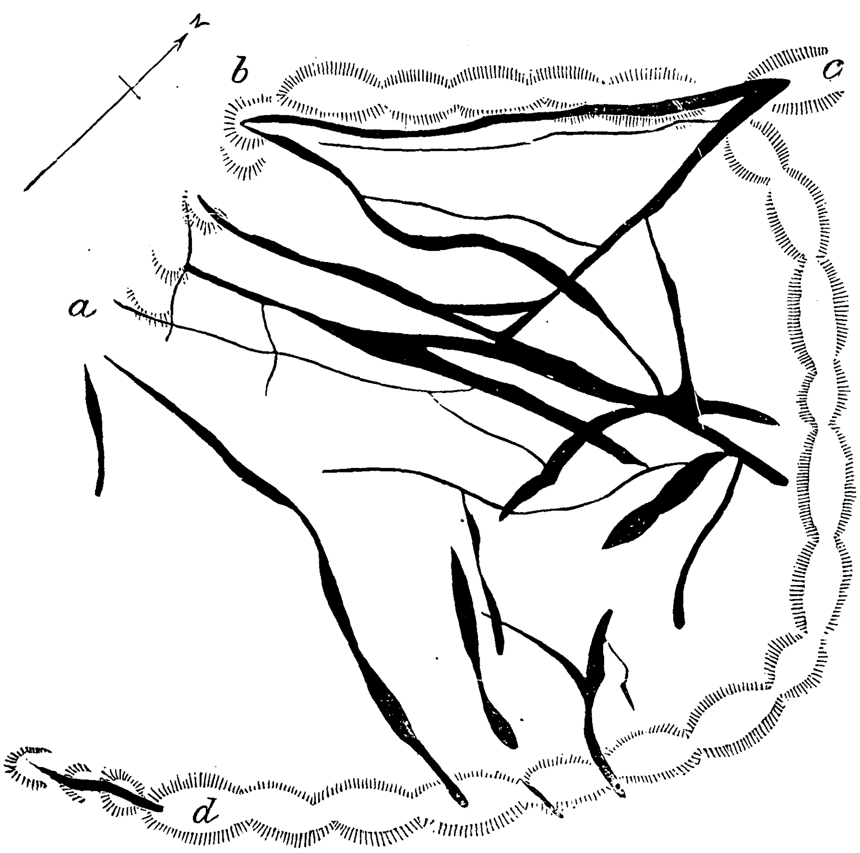


FIG. 12.—Ground plan of Trachyte Dikes on the western flank of Mount Ellsworth.

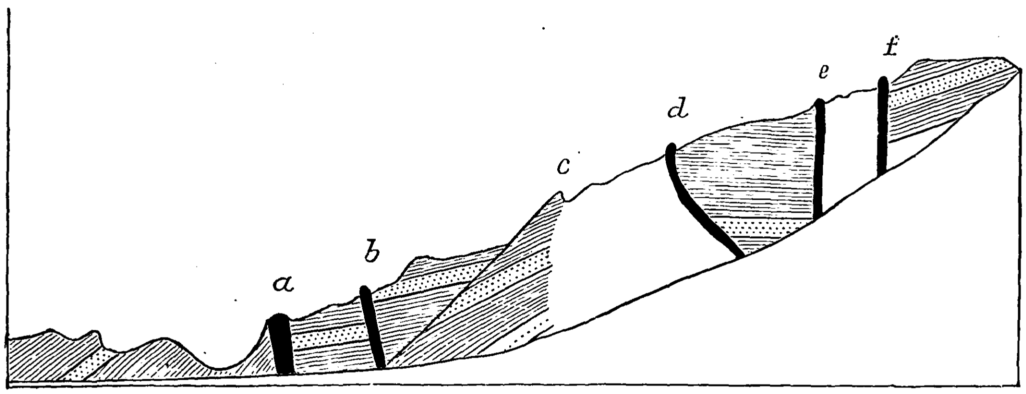


FIG. 13.—Profile of a western spur of Mount Ellsworth, showing the arrangement of Dikes and Faults. The dotted bed is the purple band at the top of the Vermilion Cliff Sandstone. The dikes of trachyte are indicated by letters.

a few inches, there is a discoloration (usually a decolorization) and a slight induration, without notable alteration of minerals. But in the region of reticulated dikes none of the sedimentaries are unchanged; crystals are developed, colors are modified, and hardness is increased, so that the physical properties of familiar strata no longer serve for their identification. Still there is no crumpling.

The trachyte masses and the altered rocks in contact with them are so much more durable than the unaltered strata about them that they have been left by the erosion in protuberences. The outcrop of every dike and sheet is a crag or a ridge, and the mountain itself survives the general degradation of the country only in virtue of its firmer rock masses. Nevertheless, the mountain, because it was higher than its surroundings, has been exposed to more rapid erosion, and has been deprived of a greater depth of strata. From the base of the arch there have been worn 3,500 feet of Cretaceous, and from 500 to 1,500 feet of the Jura-Trias series, which is here about 3,000 feet thick. From the summit of the arch more than 2,500 feet of the Jura-Trias have been removed.

The strata exposed high up on the mountain being older than those at the base, and the dip being everywhere directed away from the center, it is evident that the mountain is surrounded by concentric outcrops of beds which lift their escarpments toward it. It is usually the case, where the strata which incline against the flank of a mountain are eroded, that the softer are excavated the more rapidly, while the harder are left standing in *ridges;* and an alternation of beds suitable for the formation of a ridge occurs here. One of the upturned beds is the massive Vermilion Cliff sandstone, and beneath it are the shales of the Shinarump Group. By the yielding of the shales the sandstone is left prominent, and it circles the base of the mountain in a monoclinal ridge. But the ridge is of a peculiar character, and has really no title to the name except in the homology of its structure with that of the typical monoclinal ridge. It lacks the continuity which is implied by the word "ridge". The drainage of Mount Ellsworth is from the center of the dome outward. A half dozen drainage-lines originate in the high crests and pass outward through the zone of upturned strata. Lower down their interspaces are divided by others, and when they reach the circling escarpment of the Vermilion sandstone their number is fifteen. Each of these cuts the ridge to its base, and the effect of the whole is to reduce it to a row of sandstone points circling about the mountain. Each point of sandstone lies against the foot of a mountain spur, as though it had been built for a *retaining wall* to resist the out-thrust of the spur. Borrowing a name from the analogy, I shall call these elementary ridges *revet-crags*, and speak of the spurs which bear them as being *revetted*. The accompanying sketch is designed to illustrate the structure, but is not drawn from nature. In the view of Mount Hillers (Figure 27) the revetments may be seen, and in the bird's-eye view of the Henry Mountains (Plate V), as well as in the Frontispiece, the revet-crags of Mount Ellsworth also are portrayed. The diagram of the north spur of Mount Ellsworth (Figure 14) shows the revet-crag of that spur at *V.*

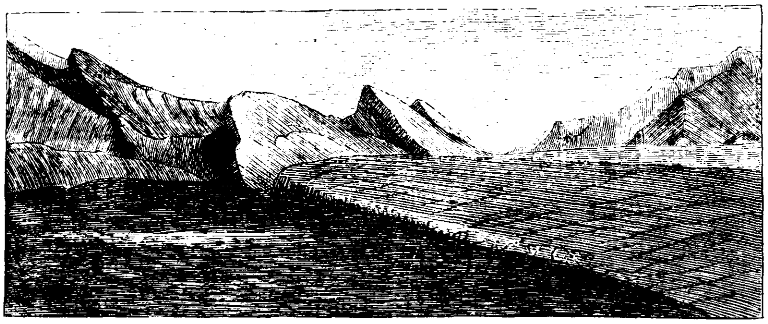


FIG. 15.—Revet-Crags.

The revet-crags of Vermilion sandstone follow, in a general way, the line of maximum dip about the base of Mount Ellsworth; but a few of them rise higher, and one—that which joins the northwest spur—climbs until it is but little lower than the summit of the mountain. Outside the circle of Vermilion Cliff sandstone lies the Gray Cliff sandstone, and in a few places it takes the form of a revetment. Inside the same circle there are many revetments, constituted by trachyte sheets bedded in Shinarump shales (Figure 14). Conforming perfectly with the strata, the sheets yield by erosion forms which are identical with those afforded by hard sedimentary beds, and to the distant eye the impression of the arching structure of Mount Ellsworth is conveyed less by what can be seen of the strata than by ascending revetments of trachyte sheets, which simulate and interpret the strata.

FIG 16.—Mount Holmes, from the north.

The laccolite of Mount Ellsworth is not exposed to view, but I am nevertheless confident of its existence—that the visible arching strata envelop it, that the visible forest of dikes join it, and that the visible faulted blocks of the upper mountain achieved their displacement while floated by the still liquid lava. The proof, however, is not in the mountain itself, but depends on the association of the phenomena of curvature and dike and sheet with laccolites, in other mountains of the same group. In the sequel these will be described, but it chances that the mountain next to be considered is even less developed by erosion than Mount Ellsworth.

MOUNT HOLMES.

The order of sequence which places Mount Ellsworth before Mount Holmes is the order of complexity. The former contains one laccolite, the latter two. Neither of the two is visible, but the strata which envelop them shadow forth their forms and leave no question of their duality. They are so closely combined that the lesser seems a mere appendage of the greater. From the center of the greater there is a descent of strata in all directions, but from the center of the lesser the rocks incline toward one-half only of the horizon. Where the two convex arches join there is a curved groin—a zone of concave curvature uniting the two convexities. About the compound figure can be obscurely seen a line of maximum dip, and beyond that the fading of the curves. The curves throughout are so gentle that it was found exceedingly difficult to establish their limits. In a general way it may be said that each of the Holmes arches is as broad as the Ellsworth arch, but the vertical displacement is less. In the formation of the greater Holmes arch the amount of uplift was 3,000 feet; for the lesser arch, 1,500 feet.

There is no evidence in the forms of the arches which proves one to be older than the other. Studying the curves in the field, I could not discover that either arch asserted itself more strongly than the other in their common ground. They seem to meet upon equal terms. Still it is probable, *a priori*, that they were formed successively and not simultaneously. The coincidence in time of two eruptions of lava from neighboring vents is no more unlikely than the coincidence of the two irruptions, and the same principle of least resistance which causes individual laccolitic arches to assume spheroidal forms, would have given to the compound arch of two laccolites, coincident in time, a simple instead of a compound form.

Assuming that the arches were successive in origin I shall in another and more appropriate chapter discuss the problem of their chronological order in the light of their somewhat peculiar drainage system.

The lesser arch betrays no dikes nor sheets. The Vermilion Cliff sandstone covers it to the top. The greater is crowned by a few grand dikes which govern its topography. From the center a long dike runs to the south, a short one to the north, two to the east, and one to the west. The course of each is a mountain spur, and between them are amphitheaters and gorges. Clinging to the dikes are bodies of altered sandstone, but the great sandstone masses of the summit were unaltered and from them have been excavated the gorges. Along the dike-filled fissures there has been some faulting, but there is no reason to believe that the displacement is great in amount. Toward the flanks of the mountain there are a few sheets, the outermost of which is far within the line of maximum flexure. Their escarpments instead of facing upward like the revetting sheets of Mount Ellsworth, face downward; their buried and unknown edges are the edges toward the mountain. Their thinning toward the periphery of the arch is conspicuous to the eye in many instances, as is also the thinning of the dikes.

Another peculiarity of dike form, one which has since been noted in a number of localities, was first detected in Mount Holmes. It consists in a definite upper limit. The dike so marked is often as even upon its upper surface as an artificial stone wall. The upper surface may be level or may incline toward one end of the dike, but in either case it is sure to be found parallel to the bedding of the strata which inclose the dike. This fact led to the suspicion, afterward confirmed by more direct evidence, that the flat top of the dike was molded by an unbroken stratum of rock bridging across the fissure which the lava filled (Figure 20). The converse phenemenon can be observed in the ridge which joins Mounts Ellsworth and Holmes. A great dike there forms the crest of the ridge for half

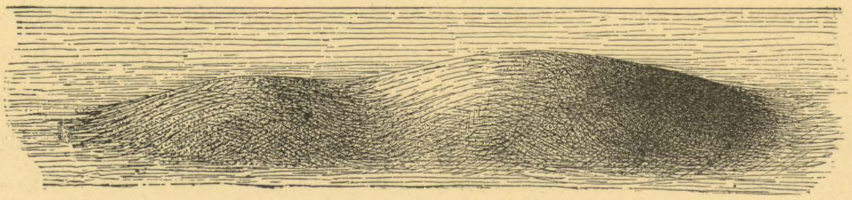


FIG. 17.—Stereogram of the Holmes Arches; an ideal restoration of the form of the over-arching strata.

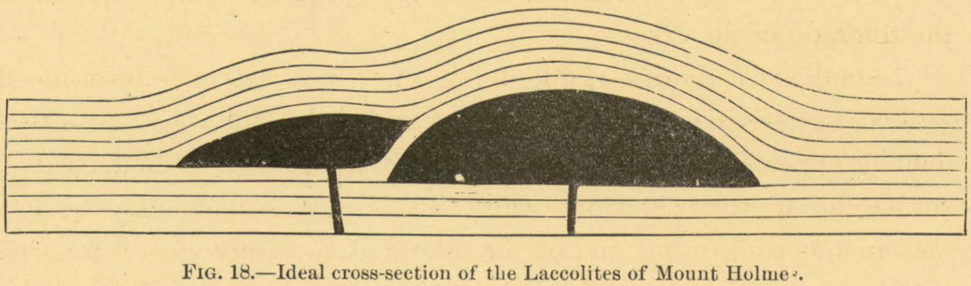


FIG. 18.—Ideal cross-section of the Laccolites of Mount Holmes.

FIG. 19.—A flat-topped dike.

a mile, its base being buried in sandstone; but at the end of the ridge the strata are seen to be continuous beneath it (Figure 21).

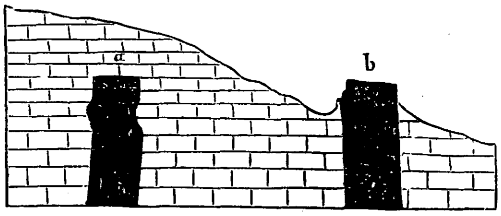


FIG. 20.—Ideal Cross-section of Flat-topped Dikes; *a*, before denudation; *b*, after denudation.

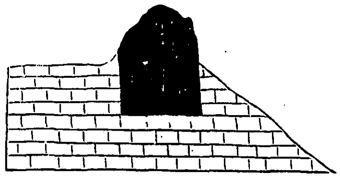


FIG. 21.—Ideal Cross-section of a Flat-bottomed Dike.

That a fissure several feet or several scores of feet in width should end thus abruptly, demands explanation, and the phenomena immediately concerned offer none. Nevertheless it is easy to make an assumption which if true renders both cases clear. If we assume that the fissure instead of ending at the cross-head is merely offset, and resumes its course beyond, and that the dike contained in it has two bodies connected by a thin sheet (Figure 22), we shall have no difficulty in conceiving the erosion which will produce either of the natural appearances described.

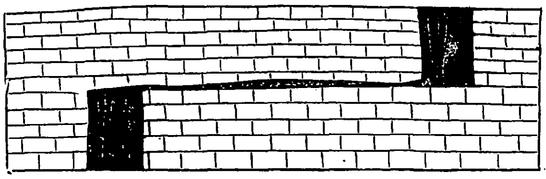


FIG. 22.—Diagram to illustrate a hypothetical explanation of Flat-edged Dikes.

The rocks which constitute Mount Holmes are the same as those about its base. The Vermilion Cliff and Gray Cliff Sandstones alone appear in the crests. The underlying Shinarump shales are cut by the erosion at a few points only, and those are near the base. For this reason the Vermilion Sandstone is not undermined about the base, and the circle of revet-crags which surrounds Mount Ellsworth finds no counterpart. There are, indeed, a few revetments of Gray Cliff sandstone, but they are scattered and for the most part inconspicuous.

In the general view of Mount Holmes (Figure 16), one of the main dikes crowns the nearest spur, and another the spur leading to the right. At the left are minor dikes, and high up is a trap sheet notched on its lower edge. At the left base of the mountain lies the lesser arch.

Figure 23 gives a section exhibited by one of the northward cañons. It shows one of the faults of the upper part of the arch and illustrates the thinning of the sheets as they descend.

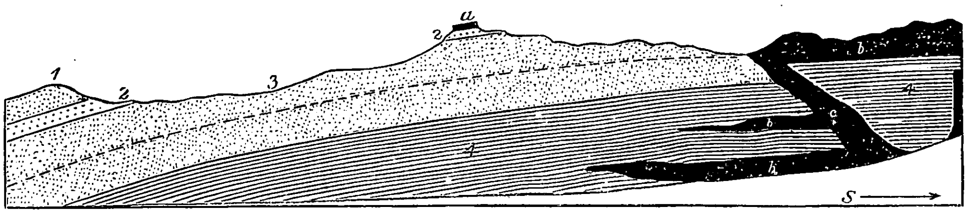


FIG. 23.—Section shown in a northward cañon of Mount Holmes. *a*, Vestige of Trachyte sheet. *b b b*, Trachyte sheets. *c*, Trachyte dike. 1, Gray Cliff Sandstone. 2 2, Purple Sandstone. 3, Vermilion Cliff Sandstone. 4, Shinarump Shale.

MOUNT HILLERS.

Next in order to the north is Mount Hillers. Let it not be supposed, however, that there is discernible system in the geographic arrangement of the mountains or of the laccolites. A chart of the mountain peaks and a chart of the laccolites would alike prove intractable in the hands of those geologists who draw parallel lines through groups of volcanic vents by way of showing their trend. They are as perfectly heterotactous as they could be made by an artificial arrangement.

The diagram (Figure 24) shows the relation of the laccolite groups to each other and to the meridian. The principal mountain summits are indicated by triangles, and the curved lines inclose areas of disturbance.

Mount Hillers and its foot-hills are constituted by a group of no less than eight laccolites, and a ninth, the Howell laccolite, is conveniently classed with them, although not contiguous.

The Hillers laccolite is the largest in the Henry Mountains. Its depth is about 7,000 feet, and its diameters are four miles and three and three-quarter miles. Its volume is about ten cubic miles. The upper half constitutes the mountain, the lower half the mountain's deep-laid foundation. Of the portion which is above ground, so to speak, and exposed to atmospheric degradation, less than one-half has been stripped of its cover of arch-arching strata. The remainder is still mantled and shielded by sedimentary beds and by many interleaved sheets of trachyte. The portion which has been uncovered is not left in its original shape, but is sculptured into alpine

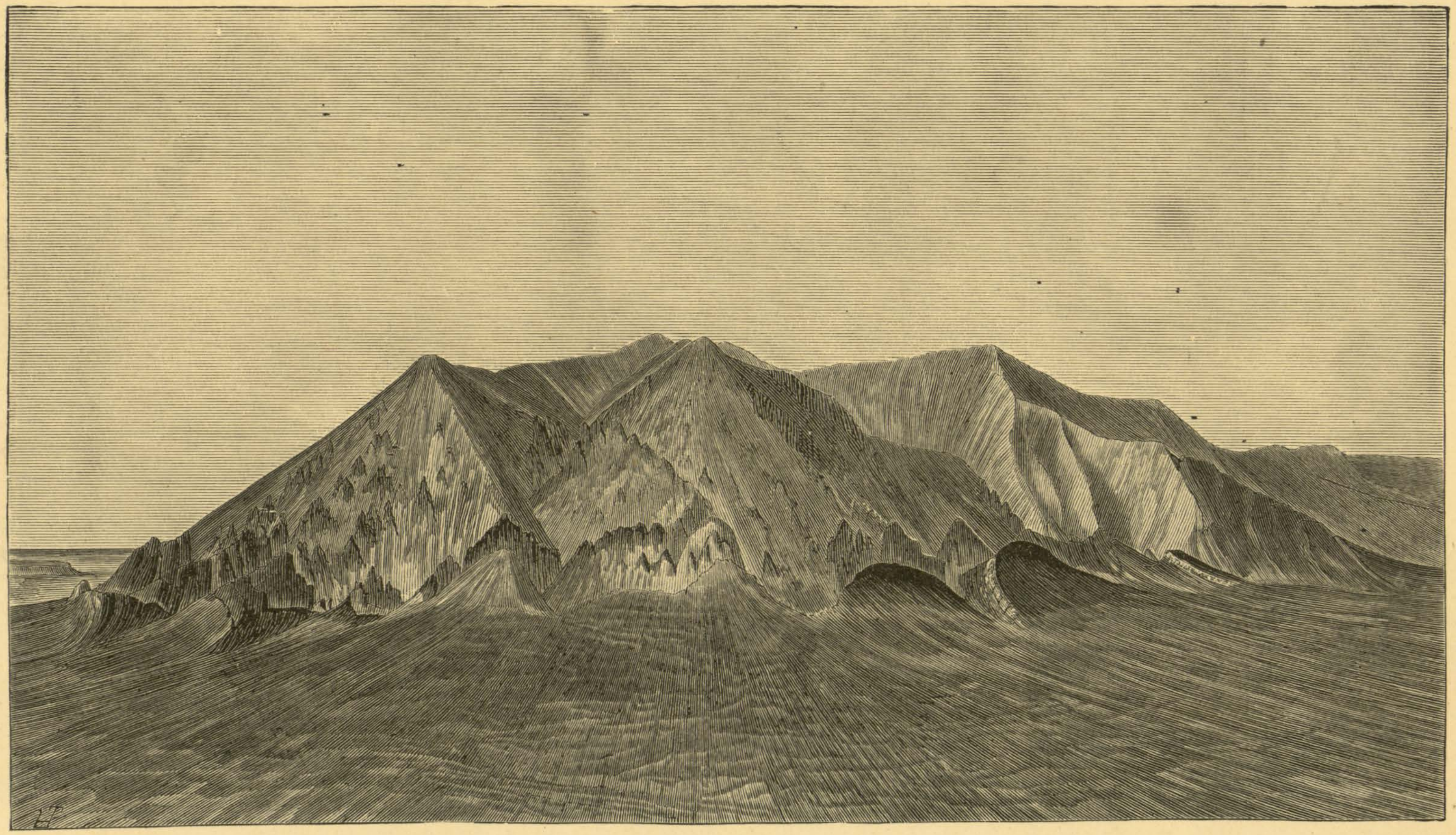


FIG. 27.—Mount Hillers, from the south.

forms and scored so deeply that not less than 1,000 feet of its mass are shown in section. All about the eroded (south) face of the mountain the base is revetted by walls of Vermilion and Gray Cliff sandstone, strengthened by trachyte sheets. At the extreme south these stand nearly vertical (80°), and their inclination diminishes gradually in each direction, until at the east and west bases of the mountain it is not more than 60°. On the north side there are no revet-crags, and the inclination is comparatively slight. It would appear that the laccolite was asymmetric, and was so much steeper-sided on the south that that side suffered most rapid degradation.

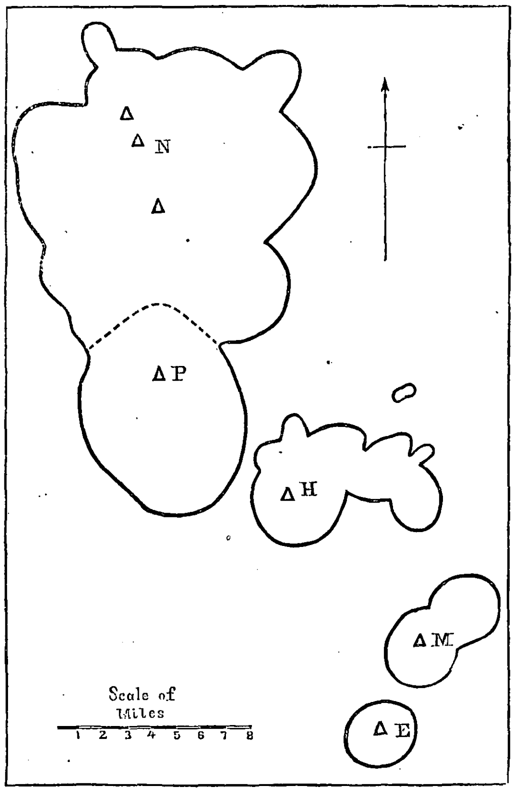


FIG. 24.—Ground Plan of the Henry Mountains. The curved lines show the limits of the principal displacements; the triangles, the positions of the main peaks. N, Mount Ellen. P, Mount Pennell. H, Mount Hillers. M, Mount Holmes. E, Mount Ellsworth.

By reference to the section (Figure 25) it will be seen that the sedimentary strata of the north flank stretch quite to the summit of the mountain. The same beds which form the revet-crags on the southern base constitute also some of the highest peaks. Since these rest directly upon the laccolite, it is assumed that the next lower beds of the stratigraphic series form its floor; and the base of the laccolite is drawn in the ideal section on the level which the Shinarump Group holds where it is unaffected by the displacements of the mountain.

It is noteworthy that wherever the sedimentaries appear upon the mountain top they are highly metamorphic. But in the revet-crags there is very little alteration. Massive sandstone, divided by sheets and dikes several hundred feet in thickness, is discolored and indurated at the contact surface only, and ten feet away betrays no change.

The engraving of Mount Hillers (Figure 27) exhibits the south face with its revet-crags and bold spurs of trap. In nature the effect is heightened by the contrast of color, the bright red revetments being strongly relieved against the dark gray of the laccolite. The strata of the summits cannot be discriminated at a distance. They are too near the laccolite in hardness to differ from it in the style of their sculpture.

Of the minor laccolites of the cluster there are three so closely joined to the chief that they merge topographically with the mountain. They are not well exposed for study. The smallest, which overlooks the pass between Mount Hillers and Mount Pennell (A, Figure 28) has probably lost the whole of its cover and with it so much of its substance that the original form and surface cannot be seen. Its floor is probably the Tununk sandstone. East of it and lying a little deeper in the Cretaceous series is a second laccolite (B), broader, lower, and less eroded. The third (C) joins the great one on the northeast, and is so closely united that it was at first supposed to be the same body. Later examinations have shown, however, that its immediate roof is the Henry's Fork conglomerate, and its horizon is thus established as more than two thousand feet above that of its great companion.

The Steward laccolite (Figure 30) is better exposed for study. It was

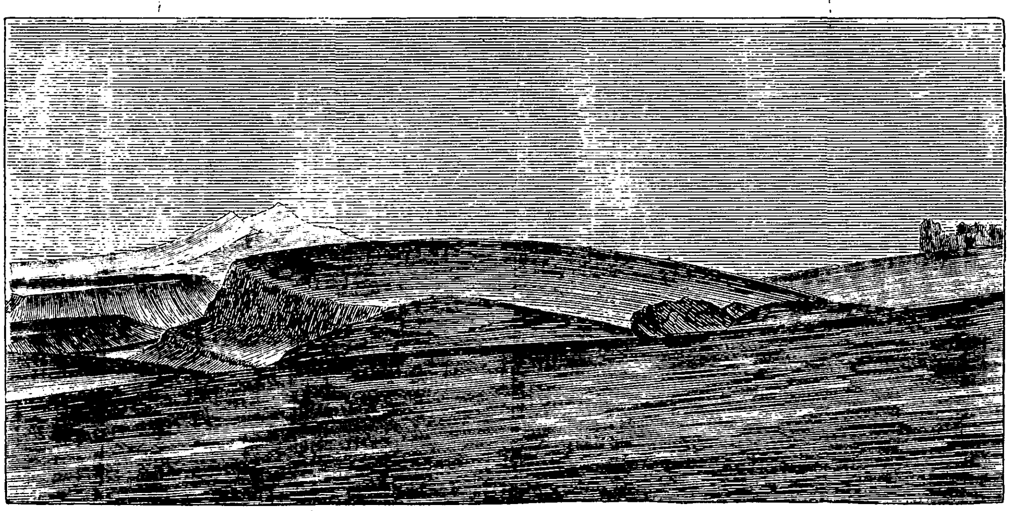


FIG. 30.—The Steward Laccolite.

buried in the soft bad-land sandstone of the Flaming Gorge Group, and its matrix has been so far washed away that nearly the whole body of trap is

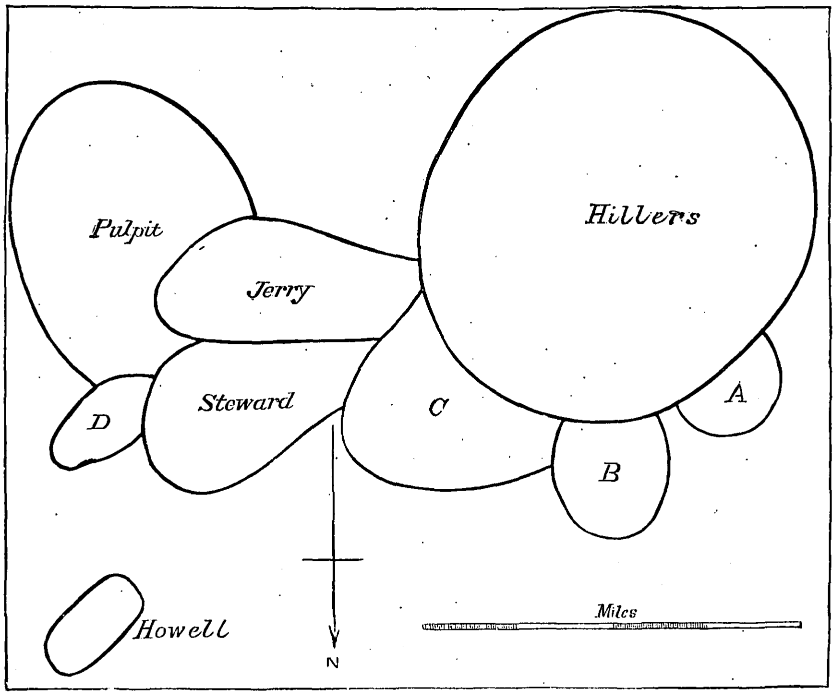


FIG. 28.—Diagram of the Hillers Cluster of Laccolites; Ground plan.

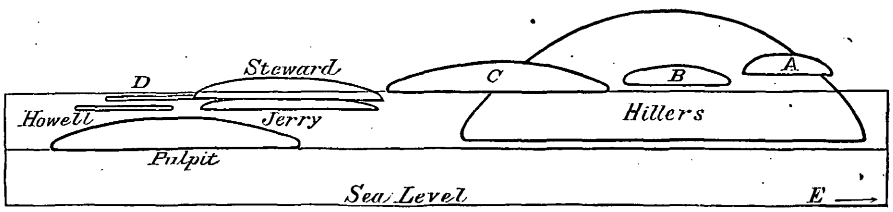


FIG. 29.—Diagram of the Hillers Cluster of Laccolites; Elevation.

The upper horizontal line marks the base of the Cretaceous; the middle, the base of the Jura-Trias; the lower, the level of the sea.

revealed. It is weathered out, like a chert-nodule on the face of a block of limestone. At one end it is bared quite to the base, and the sandstone floor on which it rests is brought in sight. The waste of the sandstone has undermined its edge, and a small portion of the laccolite has fallen away. Near the opposite end a fragment of its cover of arching sandstone survives—just enough to indicate that the sedimentaries were once bent over it, and that the smooth low-arching surface which now crowns it portrays the original form which the molten lava assumed. The laccolite is about two and a half miles long and one and one-half broad. The height of its eastward face, where it is sapped by the erosion of the bad-land rock, is six hundred feet, and the central depth must be more than eight hundred feet.

Pulpit arch is as high and as broad as the lesser arch of Mount Holmes, but its place is not marked in the topography by an eminence for the reason that the degradation of the land has not yet progressed so far as to unearth its core of trachyte. The drainage from Mount Hillers crosses it from west to east and has given it an oblique truncation, as illustrated in the diagram. At the upper end of the slope the Henry's Fork conglom-

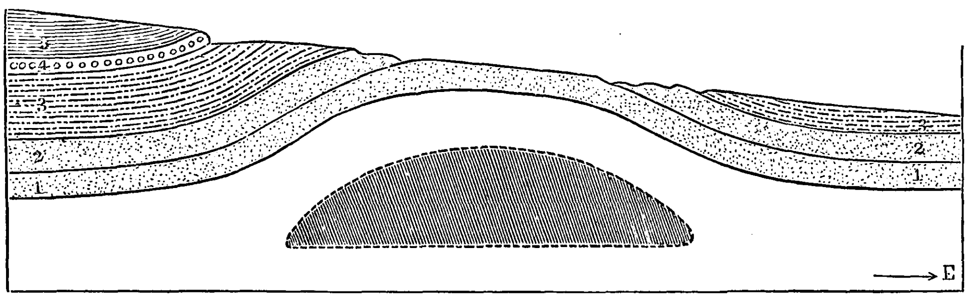


FIG. 31.—Cross-section of the Pulpit arch, with ideal representation of the Pulpit Laccolite. Scale, 1 inch = 3,500 feet. 1, Vermilion Cliff Sandstone. 2, 2, Gray Cliff Sandstone. 3, 3, Flaming Gorge Shale. 4, Henry's Fork Conglomerate. 5, Tununk Shale.

erate outcrops; at the lower end the base of the Flaming Gorge series, and in the interval the Gray Cliff sandstone is lifted to the surface. The same streams which planed away the crown of the arch have now cut themselves deeper channels and divide the massive sandstone by picturesque cañons, between which it is grotesquely carved into pinnacles and ridges. A curious salient of the sandstone has given its name to the arch. How deeply the

Pulpit laccolite lies buried is not known, no sheet nor dike of trachyte betraying its proximity. The valley of the Colorado may have to be deepened thousands of feet before it will be laid bare.

The Jerry Butte is the most conspicuous adjunct to Mount Hillers and topographically is more important and striking than the features which have just been described, but its structure is less clear. Its crest is formed by a great dike several hundred feet in width and two miles in length, and with an even top like those observed on Mount Holmes. The western end of the dike is the higher and forms the culminating point of the butte, and from it there radiate three other dikes of notable size. The inclosing strata, preserved from erosion only by the shelter of the dikes, are the lower portion of the Cretaceous series, and they are so little lifted above their normal level that there is room for no considerable laccolite beneath them. The inclination of the beds is so complicated by the dips of the Pulpit, Steward, and Hillers arches, all of which are contiguous, that nothing can be made out of the form of the laccolite, if it exists.

The Howell laccolite lies apart from the cluster and is well exposed. It differs from all that have been enumerated in its extreme thinness. With a breadth of more than two thousand feet, it has a depth of only fifty. Seen from the east, it might readily be mistaken for a *coulée*, for on that side it is the thin, hard, black cap of a table carved out of soft, sandy shale (Flaming Gorge Group) by circumdenudation. But followed westward, the table is found gradually to lose its height by the rising of the adjacent land, and at last the lava-bed runs into the slope and disappears beneath the upper layers of the same sandy shale on which it rests. How far it extends under ground can only be conjectured. How far it originally stretched in the opposite direction cannot be known because it is broken away. The original edge is concealed at one end and has been undermined and destroyed at the other, so that the only place where it can be seen is the point at which it emerges from the shale. At this point, where erosion has bared but has not yet attacked the lava, the form and character of the edge are exhibited. In place of the tapering wedge which usually terminates intrusive sheets, there is a blunt, rounded margin, and the lava scarcely diminishes in depth in approaching it. The underlying strata, locally hardened to sandstones, lie

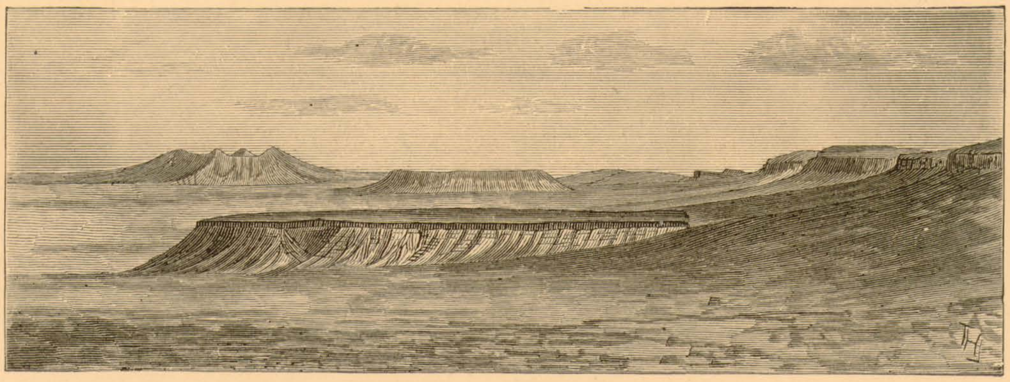


FIG. 32.—The Howell Laccolite, as seen from the north.

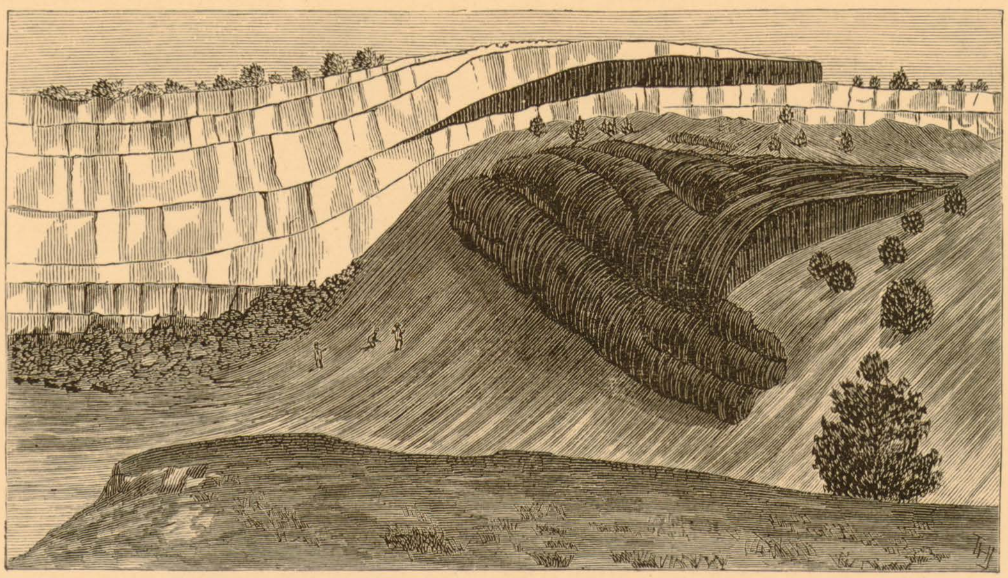


FIG. 33.—The Edge of the Howell Laccolite.

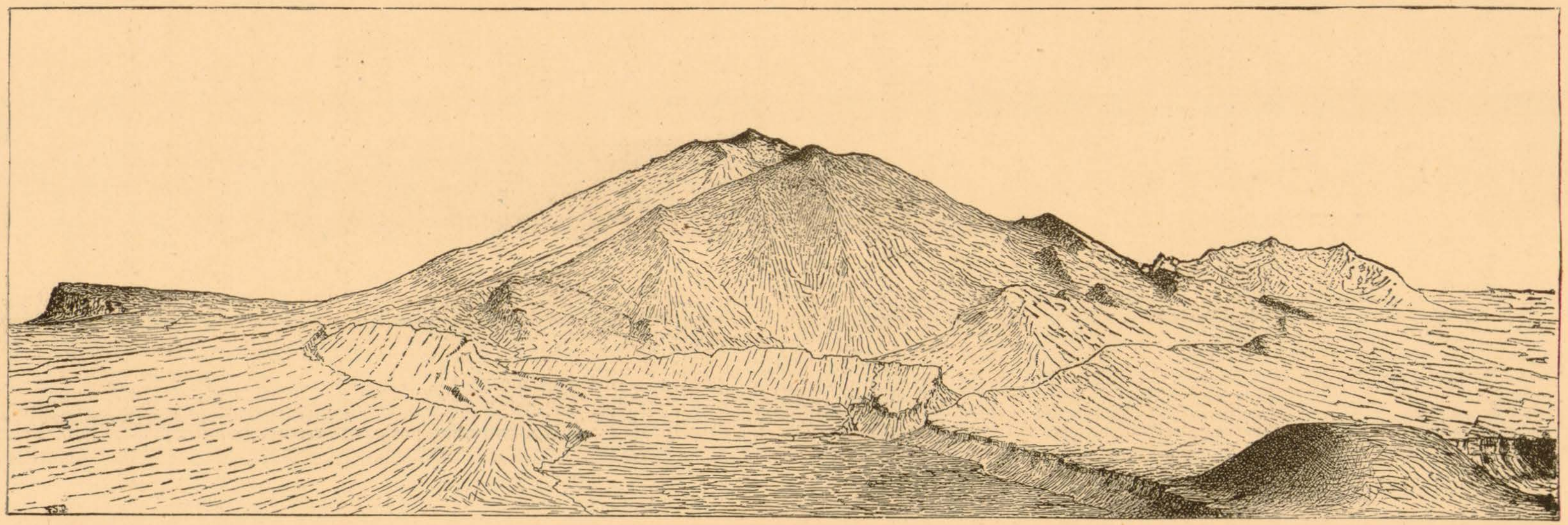


FIG. 34.—Mount Pennell, from the west.

level; the overlying curve downward to join them, and between the curved strata is interleaved a curved lava-sheet. In all these characters the intrusive body is affiliated with the typical laccolites, and distinguished from the typical sheets.

The laccolite which is marked "D" on the diagrams of the Hillers cluster is identical in nearly all its characters with the Howell; it is thin and broad. One margin is wasting as its foundation is sapped; the other is hidden from view. Its depth does not diminish toward the edge. Moreover, a few dikes issue from its margin, or from beneath its margin. It was intruded within the same formation as the Howell (the Flaming Gorge shale), but at a horizon several hundred feet higher; and, what is specially noteworthy, the rock of which it is composed is identical in *facies* with that of the Howell laccolite, and notably different from all others which were observed in the Hillers cluster.

Thus there are grouped in this one cluster laccolites of the most varied character, differing in form, in magnitude, in the stratigraphic depth at which they were intruded, in the extent to which they have been uncovered or demolished in the progress of erosion, and also, but very slightly, in their lithologic characters. The greatest is one thousand times as bulky as the least. The length of the most obese is three times its depth; the length of the most attenuated is more than one hundred times its depth. The one highest in the strata lies a thousand feet above the base of the Cretaceous rock series; the lowest is not higher than the summit of the Carboniferous. The latter has not yet been touched by erosion, others have been completely denuded, and some have been partially demolished and removed.

MOUNT PENNELL.

Mount Pennell and Mount Ellen are distinct mountain masses separated by a low pass, but there is no interval between the clusters of laccolites by which they are constituted.

Whether the site of a laccolite shall be marked by a mountain depends in great measure on the relation of the laccolite to the progress of erosion. In the Henry Mountains the laccolites which have not been reached by the denudation scarcely affect the topography. The arched sedimentaries above them are no harder than the same strata in the surrounding plain, and they are brought substantially to the same level. It is to those which the downward progress of erosion has reached and passed that the mountains are due. In virtue of their hardness they survive the general degradation, and conserve with them broad foundations of more perishable material. Mounts Ellen and Pennell mark the positions of the highest of a great cluster of laccolites, and the pass between them marks a part of the cluster where all the laccolites lie low in the strata.

Mount Pennell is not so easily studied as the lower mountains at the south. Its summits are timbered and are carved into alpine forms which

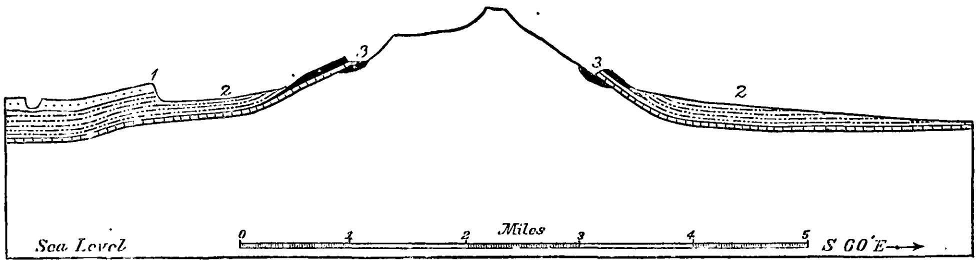


FIG. 35.—Cross-section of Mount Pennell. 1, Blue Gate Sandstone. 2, 2, Blue Gate Shale. 3, 3, Tununk Sandstone. The full black lines represent Trachyte.

do not portray the structure but rather mask it. Upon its flanks however the topography and the structure are in so close sympathy that the latter is easily read; and by their study some of the general features of the mountain have been made out. From the east and south and west the strata can be seen to rise toward it. The uprising strata on the west are the Tununk sandstone and the shales above and below it. The sandstone forms no revetments, but accords so closely in its dips with the slopes of the mountain that it is the surface rock over a broad area, outcropping wherever there is rock exposure. At the head of the foot-slope trachyte sheets are associated with it, some overlying and others underlying it; and at one point a gorge reveals a laccolite not far below it—a laccolite that may or may not be the great nucleus of the mountain. On the west and south flanks the uprising strata are the Blue Gate and Tununk sandstones, with their shales. The Gate sandstone has been worn away nearly to the foot of the slope, and forms a monoclinal ridge circling about the base. The ridge is interrupted by a number of waterways, and it sends salients well up upon the flank,

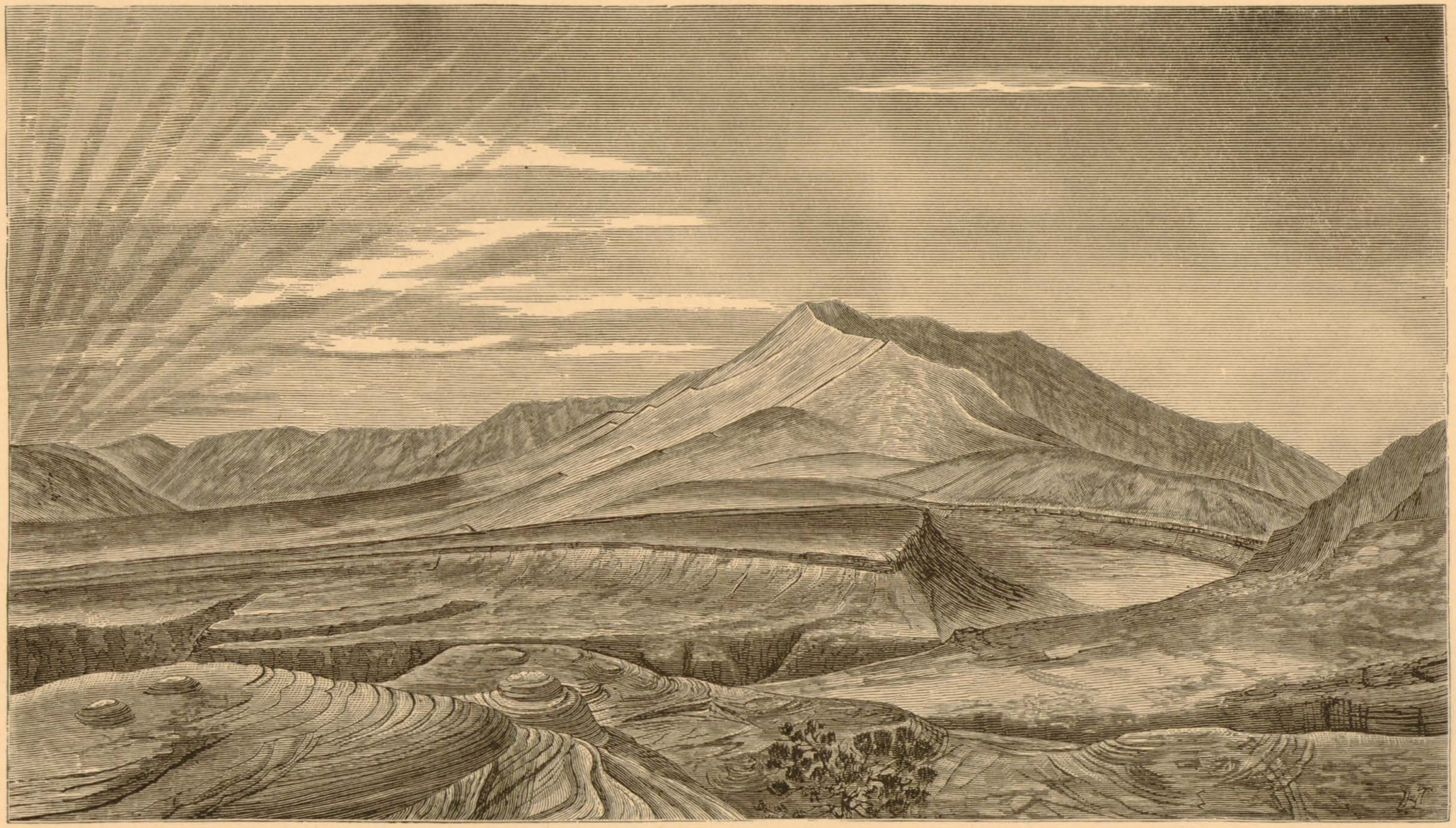


FIG. 36.—Mount Pennell, from the north.

but it is too continuous to be regarded as a mere line of revetments. The Tununk sandstone is not to be seen without search, being covered by heavy trachyte sheets. Trachyte sheets also underlie it, and the whole are carved into a conspicuous series of revet-crags.

The association of overarching strata with sheets of trachyte leaves no doubt in my mind that the core of Mount Pennell is laccolitic, but whether it is simple or compound is not so clear. The collation of all the observed dips shows that if there be but one laccolite it has not the simplicity of form which usually characterizes them.

There are low arches of the strata at the southern, northern, and northeastern bases, which reveal no trachyte and give the impression that there may be a foundation of low-lying laccolites upon which the main trachyte mass or masses of the mountain are based. One of these low arches, that

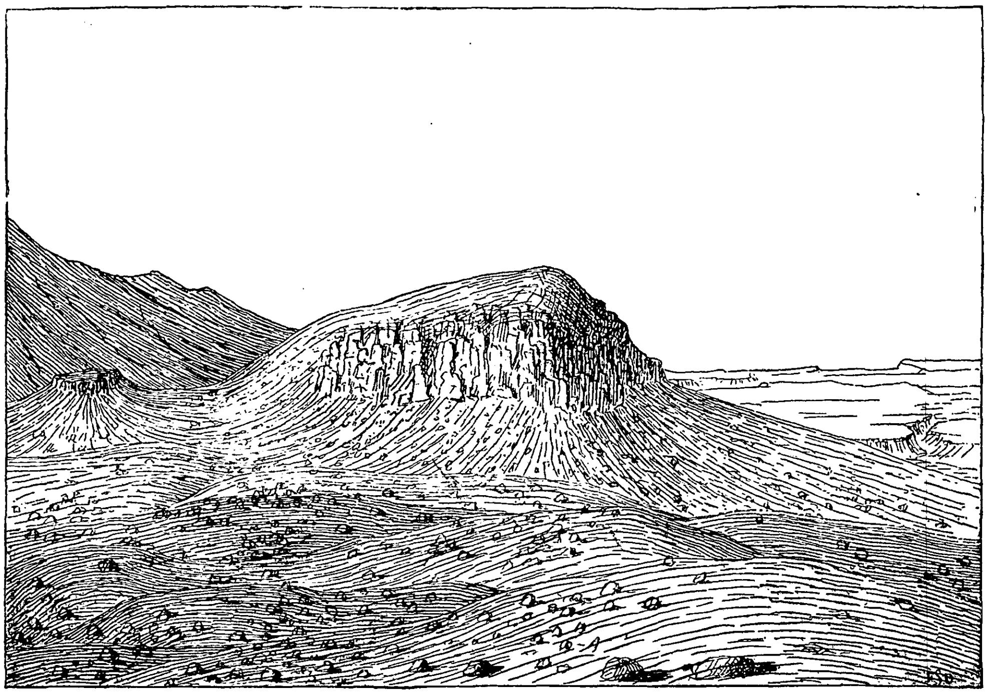


FIG. 37.—Sentinel Butte.

at the northeast, is shown in the foreground of Figure 36. The strata which portray it are of the Henry's Fork conglomerate, and the laccolite which they cover is of necessity distinct from that which is revealed on the east flank of the mountain.

In addition to the laccolites of the foundation and of the main body, there is a series which jut forth from the northern flank like so many dormer windows. They are comparatively small but are rendered conspicuous by the removal of the soft rocks which originally inclosed them. They are higher in the strata than any other observed laccolites, their position being above the Tununk sandstone and in the Blue Gate shale. The core of the main body of the mountain is probably inclosed in the Tununk shale, and the laccolites under the low arches (at the north at least) are entirely below the Cretaceous. The higher series stand on top of the low arches, and are just outside of the sheets which inclose the central body. The largest of them constitutes Sentinel Butte, and stands guard over Penellen Pass. Sapped by the yielding of its soft foundation it is rapidly wasting, and on three sides its faces are precipitous. The huge blocks which cleave from it as they are undermined strew the surrounding slopes for a great distance. Its depth of 400 feet is made up of two layers, of which the lower is the deeper, and between which there is a slight lithologic difference. The upper surface of the butte is smooth and plane with an inclination to the south. It is probably a portion of the original surface of the laccolite.

Thus we have in Mount Pennell a great central body consisting of a single laccolite or of a number closely massed together; an inferior group of three or more, evidenced by low broad arches; and a superior group of not less than four, all of which are partially destroyed.

MOUNT ELLEN.

The crest of Mount Ellen is as lofty as that of Mount Pennell and it is more extended. It stretches for two miles from north to south and is buttressed by many spurs.

The sculpture of the crest is alpine, and the structure is consequently obscured. There are dikes of trachyte and perhaps the remnants of laccolites; there are Cretaceous sandstones greatly indurated; and there are Cretaceous shales baked to clinking slate; but they are all carved into smooth, pyramidal forms, and each is half hidden by the *débris* from the rest so that their order and meaning cannot be seen.

The flanks however are full of interest to the geologist. The Ellen cluster of laccolites is a broad one, and all but the central portion is well exposed for study. In the spurs and foot-slopes and marginal buttes no less than sixteen individual laccolites have been discriminated, a number of them most beautifully displayed. They will be enumerated in the order of their position, beginning at the west of Penellen Pass and passing along the western, northern, and eastern flanks to the Scrope Butte, east of the pass.

In the chart of the Ellen cluster, Figure 38, an attempt is made to show

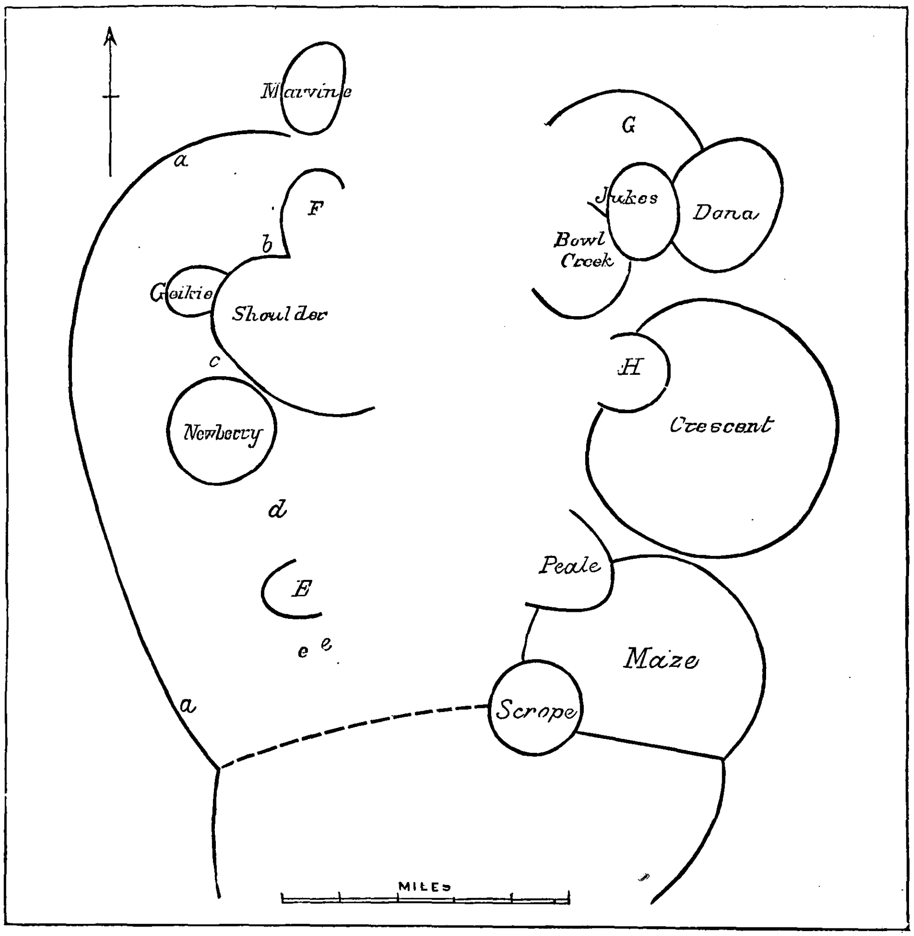


FIG. 38.—Ground Plan of the Ellen Cluster of Laccolites.

the horizontal grouping of the laccolites and the order of their superposition wherever they overlap. It will be observed that where the limits are imperfectly known the outlines are left incomplete, and that the central area remains blank, not because it contains no trachyte masses, but because its alpine sculpture has prevented their study. Where it is not evident which of two encroaching laccolites is the superior, they are separated by a straight line.

The line *a a* in the chart is the springing line of a broad, flat arch which underlies all the other arches of the western flank. If it covers but one laccolite, that one is the rival in magnitude of the Hillers nucleus, although widely different in proportions; but it is more probable that it contains a greater number. The upper surface is rolling and uneven, and has not the degree of symmetry which laccolites usually display. At the points *b*, *c*, *d*, and *e* the altitude of the arch is 3,800, 3,500, 2,000 (estimated) and 2,500 feet. Nevertheless there is nothing in its simple outline to indicate a compound structure; the monoclinal ridges by which it is margined do not exhibit the flexuous curves which are commonly seen about the bases of confluent arches. Whether the nucleus is simple or compound it sends no branches to the surface; the only outcrops of trachyte belong to the overlying arches. The upper parts of the arch have been so carried away that the steepness of the mountain flank is not in-

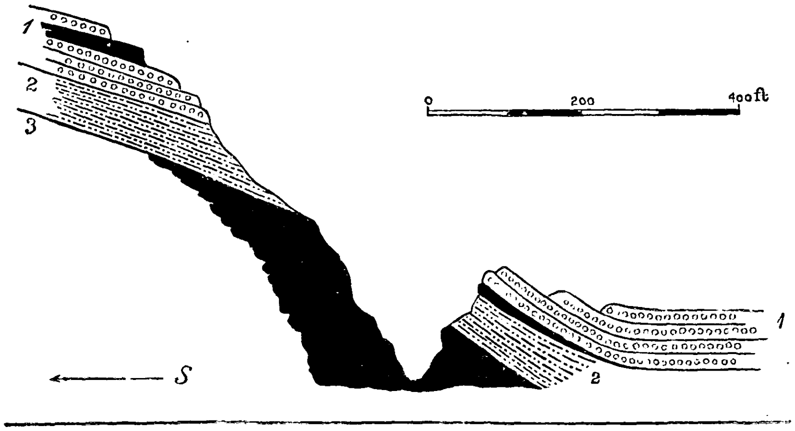


FIG. 40.—Section of the Lewis Creek Cañon through the Newberry Arch. 1, Henry's Fork Conglomerate. 2, Upper portion of Flaming Gorge Shale. 3, Newberry Laccolite.

creased by it, and inferior strata are brought to the surface. At the north the crown of the arch bears the Henry's Fork conglomerate, while beyond its base the plateau is built of Blue Gate sandstone. At the south the arch bears the Tununk sandstone, and the Masuk lies outside

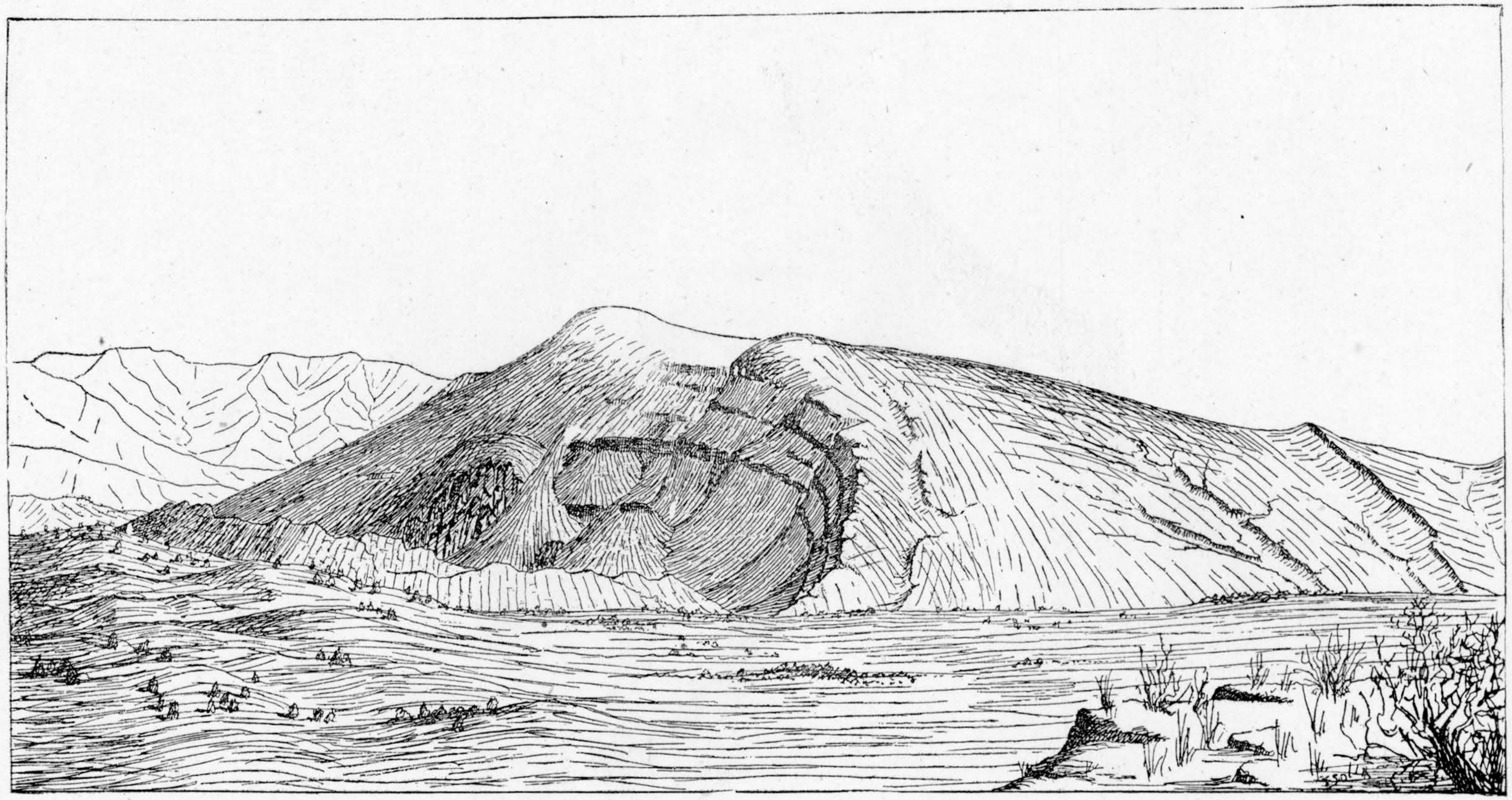


FIG. 39.—The Newberry Arch and Laccolite.

The laccolite marked "E" on the chart rests upon the Tununk sandstone. The Blue Gate shale which once buried it has been all washed away except some metamorphosed remnants upon the top, and the trachyte itself has wasted to such an extent that its original form cannot be traced. The laccolite has no near neighbor, and the erosion has left it prominent upon the mountain flank. A continuous and solitary spur joins it to the central ridge.

The Newberry laccolite makes a knob 1,700 feet high, and stands by itself. Its cover of Henry's Fork conglomerate is re-enforced by a number of trachyte sheets, and is broken through at one point only. At that point Lewis Creek cuts with a straight course across a flank of the arch, and exposes a portion of the nucleus in section (Figures 39 and 40). The conglomerate

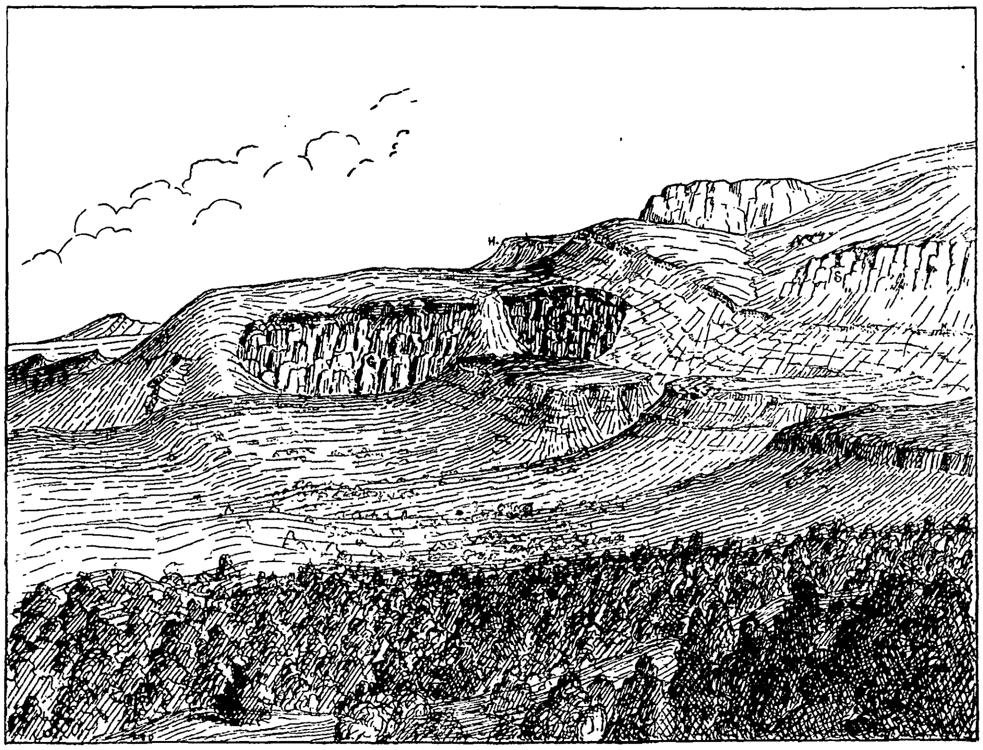


FIG. 41.—The Geikie Laccolite (*G*), overlapped by the Henry's Fork Conglomerate (*H H*), and the Shoulder Laccolite (*S*).

does not rest directly upon the trachyte, but is separated by one or two hundred feet of shale of the Flaming Gorge Group.

Two miles to the northward is the *Geikie laccolite*, smaller than the rest but similar in character. It lies close to the top of the Flaming Gorge shale, and is enwrapped by the Henry's Fork conglomerate. Upon three sides the conglomerate can be seen to curve over its margin from top to bottom, and upon two of these sides the curves are so broken through by erosion that the trachyte is visible within. On the north two cañons cut down to the nucleus, and on the south there is a broad face of trachyte framed all about by the cut edges of the conglomerate beds.

The Shoulder laccolite overlaps the Geikie, and the two are exposed in such manner as to show their relation in section. The conglomerate runs under the one and over the other and separates them. The upper laccolite is a broad and deep one, and takes its name from the fact that it makes a great shoulder or terrace on the mountain side. Toward the mountain it is buried; toward the valley it is uncovered, and in part bounded by a cliff. It is deeply cleft by cañons. It has not been subjected to measurement, but its depth is not overestimated at fifteen hundred feet nor its area at five square miles.

In the sketch (Figure 42) many of these features can be traced—the Geikie laccolite at the left and the Shoulder in the center, with an outcrop of the conglomerate curving down from the roof of the one to the floor of the other, and the Newberry arch in the foreground with its cleft side. At the rear is the pyramidal Ellen Peak and the *F* laccolite, overlooking the Shoulder. In the distance at the left is the Marvine laccolite.

Little more can be said of the *F laccolite* than that it exists and is the nucleus of a lofty spur. Its summit rises too nearly to the crest of the mountain to be well defined, and at its base the sedimentaries are hidden by talus.

Not so the *Marvine laccolite.* Lying at the foot of the mountain where erosion is so conditioned as to discriminate between hard and soft, and surrounded by nothing firmer than the Tununk shale and Tununk sandstone, it has suffered a rapid denudation, in which nearly the whole of its cover has been carried away without seriously impairing its form. It stands forth on a pedestal, devoid of talus, naked and alone. The upper surface undulates in low waves preserving the original form as it was impressed on the molten mass. Over a portion there is a thin coating of sandstone,

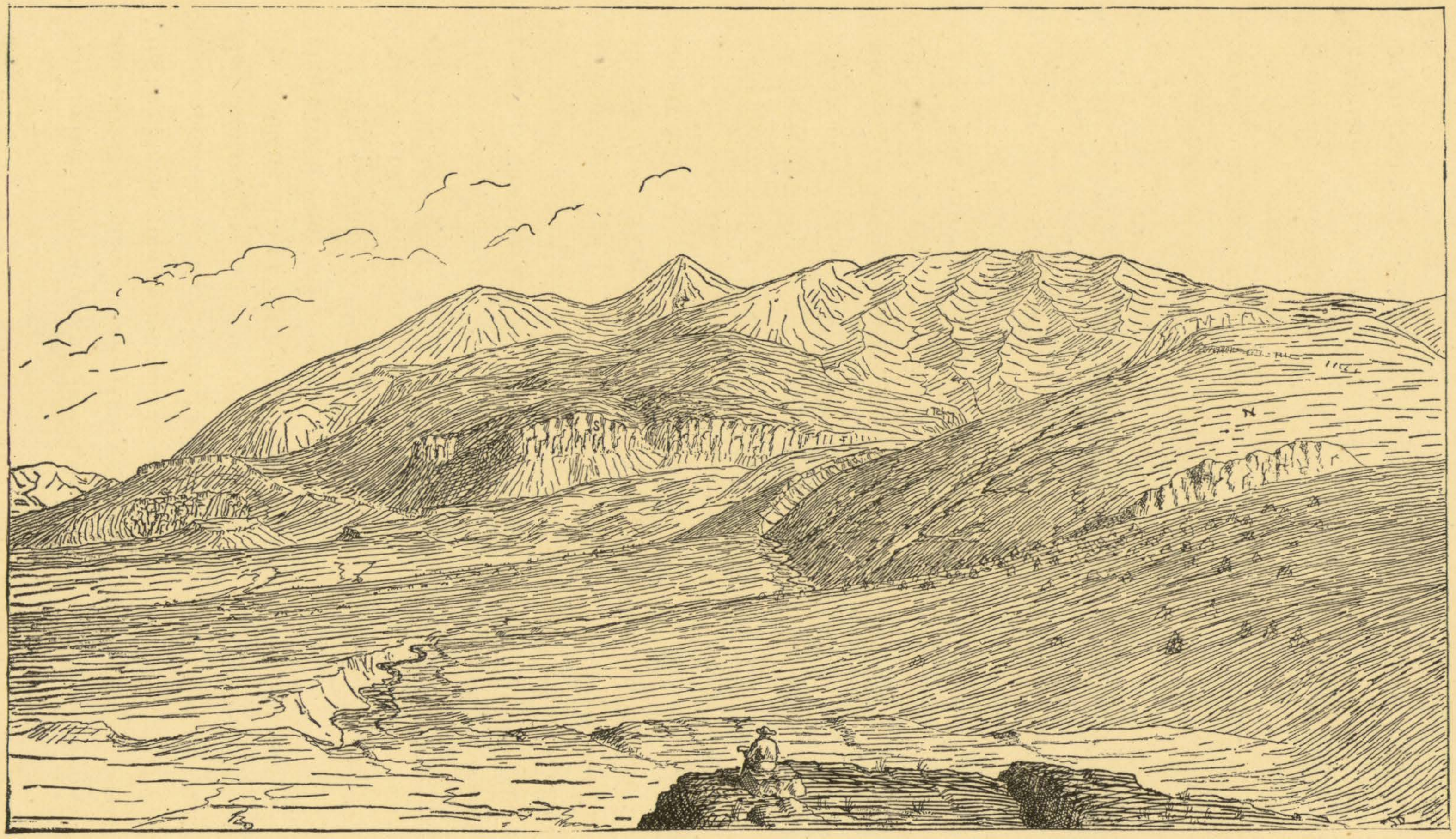


FIG. 42.—The Western Flank of Mount Ellen. *N*, Newberry Arch; *S*, Shoulder Laccolite; *G*, Geikie Laccolite.

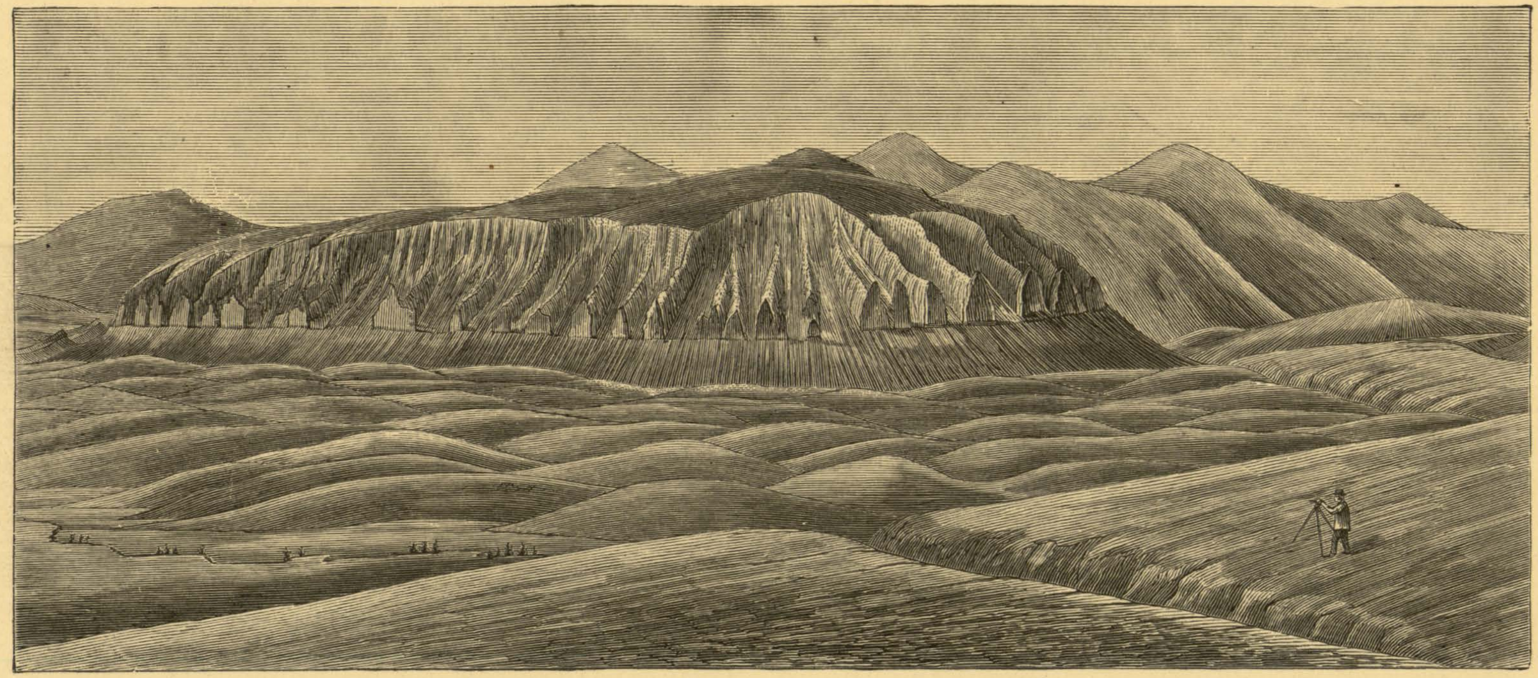


Fig. 43.—The Northern face of the Marvine Laccolite.

FIG. 44.—The Western face of the Marvine Laccolite.

the layer next to the trachyte being saved from destruction by the induration acquired during the hot contact. From the remainder this also has disappeared, and the contact face of the trachyte is bare. For some reason the exterior portion of the laccolite disintegrates more slowly than the interior. It may be that there was some reaction from the surrounding sedimentaries during the cooling, which modified the crystallization. Or it may be that at a later epoch a reciprocal metamorphism was induced along the contact of the diverse rocks. At all events there is a crust a few feet in thickness which is specially qualified to resist destructive agents, and which by this peculiarity can be distinguished from the trachyte of the interior. All about the northern and western faces, which are steep, this crust has been broken through and the interior excavated; but it is only along the upper edge of the face that the crust is completely destroyed. Along the lower edge it is preserved in remnants sufficiently numerous to fully define the outline of the base. Each remnant is a sort of revet-crag standing nearly vertical and joined by a buttress to the cliff behind it. In the accompanying sketches (Figures 43 and 44) the most of these features find better expression than words can give them. The solemn order of the tombstone-like revetments is not exaggerated, nor is the contrast between the ruggedness of the cliff and the smoothness of the upper crust. At the left in the upper view, and at the right in the lower, there can be seen inclined strata, the remnants of the arch which once covered the whole.

The extreme depth of the laccolite is 1,200 feet, and its diameters are 6,000 and 4,000 feet.

The G arch, the Dana, the Crescent, and the Maze agree in having no visible laccolites. They are mere dome-like uplifts, by which inferior beds are brought to light. In the middle of the Crescent arch, and there only, is a small dike. They differ in their dimensions and in their erosion and topography. The G arch is low and broad, and lifts the Henry's Fork conglomerate a few hundred feet only. It is covered by that bed except where Bowl Creek and one or two others cross it in shallow cañons.

The Dana arch bears the same relation to Mount Ellen and Jukes Butte that the Pulpit arch bears to Mount Hillers. The streams which flow down have truncated it, and afterward carved a system of cañons below the plane of truncation. The Henry's Fork conglomerate overlooks it from the base of the Jukes laccolite on one side, and on the other margins it with a monoclinal ridge; and in the interval the Flaming Gorge and Gray Cliff rocks come to the surface.

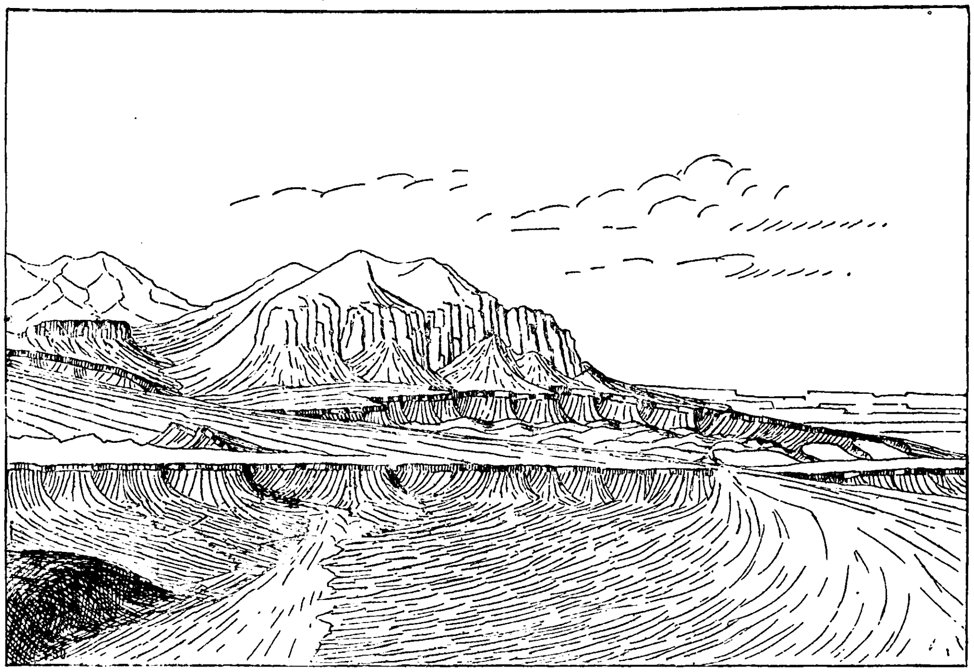


FIG. 45.—The Jukes Butte, as seen from the southeast, showing the Jukes Laccolite, resting upon the Dana Arch.

The Crescent arch is so perfectly truncated by the existing mountain streams that their flood-plains unite above it in a single broad slope. On the side toward the mountain there are a few insular hills of the conglomerate, and on the side toward the plateau the same rock lifts a low monoclinal ridge which circles about the base of the arch in a crescent. Within the crescent there are few outcrops, but it is probable that the Gray Cliff Sandstone is brought to the surface. Near the center a solitary thin dike juts forth, like a buoy set to mark the place where a laccolite is sunk. Judging the magnitude of the laccolite by the proportions of the uplift, it has a diameter of nearly four miles and a depth of 2,500 feet; and these dimensions indicate a volume of three and a half cubic miles.

The Maze arch covers a smaller area than the Crescent, but its height is greater. The drainage from the mountain crosses it on a number of lines, but there is no indication that at any recent stage of the degradation they have produced an even truncation. At present they divide the Gray and Vermilion Sandstones by so intricate a labyrinth of deep cañons that the whole area of the uplift is almost impassable. The monotony of red sandstone, for here all members of the Jura-Trias are brick-red, the variety of dip, complicated to the eye by oblique lamination, the multiplicity of cañons and ridges, conspire to give an impression of chaos from whatever point the tract is viewed; and even from the most commanding stations I was unable to make out completely the arrangement of the drainage lines. Still no faults were discerned, and it is probable that the Maze arch, intricate as it seems, is a simple circular dome. On the north it adjoins the Crescent arch, and the monoclinal ridges of conglomerate which margin the two at the east are confluent. On the south it adjoins rather more closely one of the low arches which have been referred to the Pennell cluster. On the west, or toward the mountain, it is probably met by other arches at its own level; but these if they exist cannot be fully known until the progressing degradation of the country shall have removed certain laccolites which lie above them and slightly overlap the Maze arch.

The four arches just described are of the foundation series of the eastern base, and cover laccolites of unknown depths. Higher in the strata, and at the same time absolutely higher, is a second series, which to a certain extent overlap them. The Bowl Creek encroaches on the G laccolite; the Jukes, on the Dana and on the Bowl Creek; the H laccolite, on the Crescent; the Peale and Scrope, on the Maze.

The Bowl Creek arch is so masked by the overlapping Jukes laccolite, and by the encroachment of certain large dikes, that its general form and

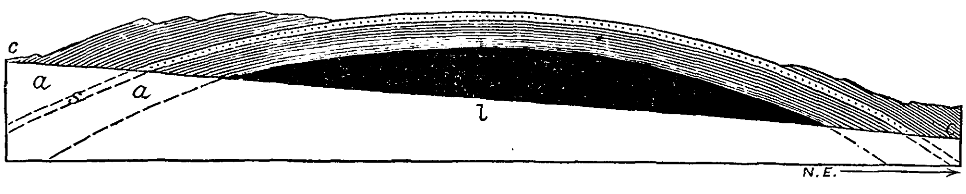


FIG. 46.—Cross-section of the Bowl Creek Arch. *c*, *c* marks the water-level of Bowl Creek; *l*, the Bowl Creek Laccolite; *a*, *a*, Shales; and *s*, the Gryphea Sandstone. Scale, 1 inch = 1,000 feet.

proportions are not known; but it is laid bare at one point in a fine natural section. Bowl Creek crosses it near the center, and in the walls of the cañon are exhibited two hundred feet of the laccolite, together with two hundred and fifty feet of superjacent beds. The curve of the strata is unbroken by faults or dikes, and carries them below the level of the creek at each end of the cañon. Next above the trachyte lies a clay shale which has been baked to the hardness of limestone. It is one hundred feet thick, and is more or less altered throughout, as is also the sandstone which overlies it. The extent of the metamorphism indicates that the trachyte mass by which it was produced is not a mere sheet, but is the body of the laccolite itself.

The Jukes laccolite encroaches upon the G, the Dana, and the Bowl Creek arches, and is superior to them all; it may be said to stand upon them. The trachyte has a depth of only one thousand feet, but it lies so high with reference to the general degradation that it is a conspicuous feature of the topography. The edges of the laccolite are all eaten away, and only the central portion survives. All of its faces are precipitous. The cover of shale or sandstone has completely disappeared, and the upper sur-

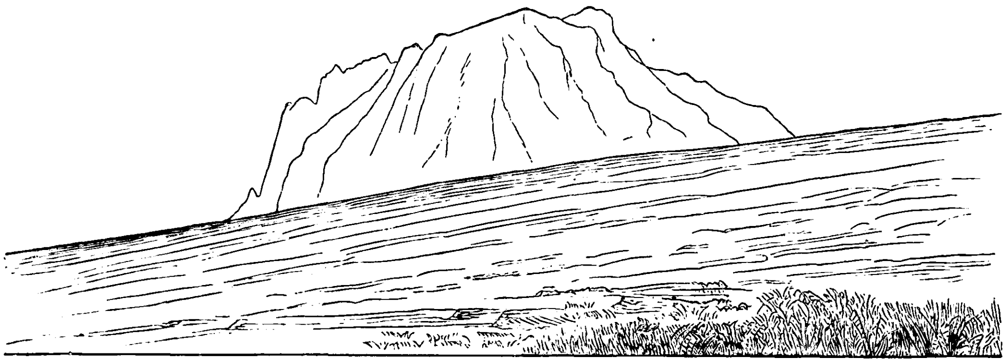


FIG. 47.—Profile of the Jukes Butte, as seen from the northwest.

face seems uneven and worn; but a distant view (Figure 47) shows that its wasting has not progressed so far as to destroy all trace of an original even surface. The eminences of the present surface combine to give to the eye which is aligned with their plane the impression of a straight line. The hill is loftier than the laccolite, for under the one thousand feet of trachyte are five hundred feet of softer rock which constitute its pedestal, and by their yielding undermine the laccolite and perpetuate its cliffs.

The H laccolite is not well exposed. It lies on one edge of the Crescent arch and is covered by the Henry's Fork conglomerate.

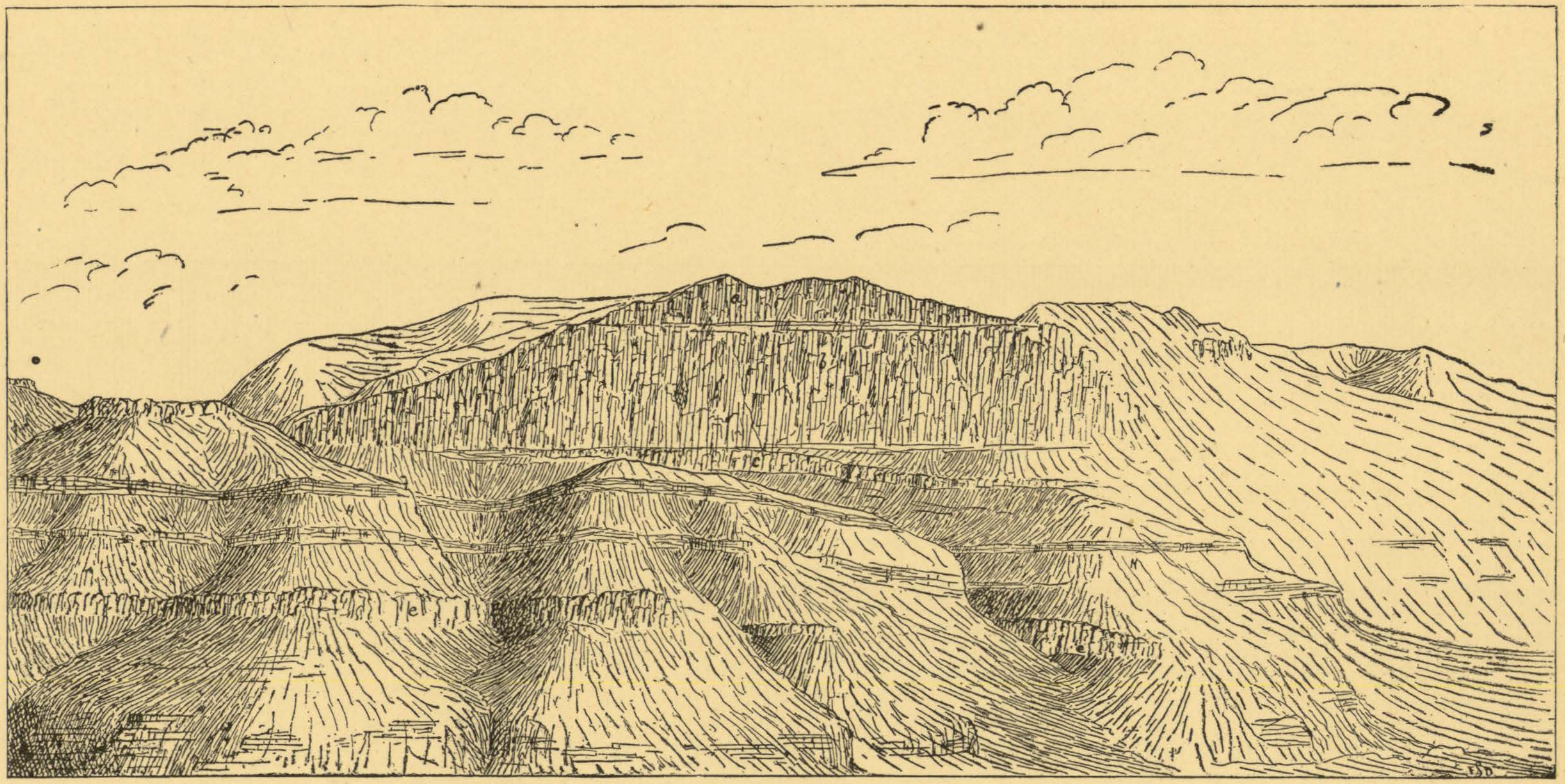


FIG. 48.—The Peale Laccolite exposed in natural cross-section. *a*, *b*, *c*, *d*, and *e* are intrusive masses of trachyte.
H is the Henry's Fork Conglomerate.

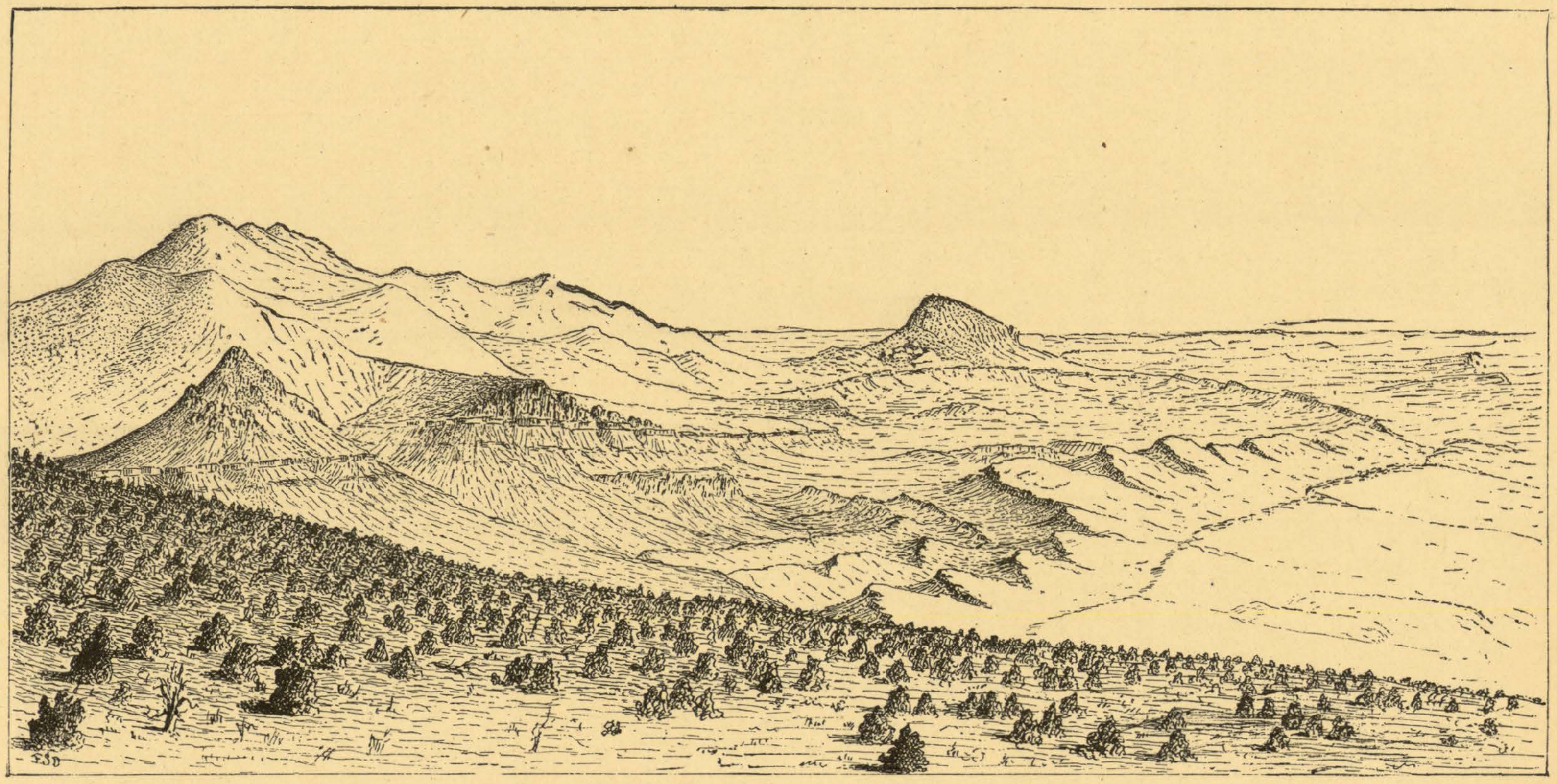


Fig. 49.—The East Flank of Mount Ellen, showing the Scrope, Peale, and Jukes Laccolites, and the Maze and Crescent Arches.

Little is known of the form of the *Peale laccolite.* One edge is lost in the obscurity of the alpine sculpture, and the other has been removed along with the crest of the Maze arch, on which it rested. But by this removal a section has been opened across the laccolite, revealing its internal structure from top to bottom. It is shown to be composite, attaining its height of 850 feet by the compilation of three distinct beds of trachyte, separated by partings and wedges of shale. The lowest bed is thin and of small extent. Next is the main bed, six hundred feet thick and a mile or more broad; and on top is a bed two hundred feet thick and proportionately narrow. Each of the beds is lenticular in section, and the piling of the less upon the greater produces a quasi-pyramidal form. The interleaved shale bands are metamorphosed to the condition of slate. Under the laccolite are one or two hundred feet of shale, apparently unaltered except at the contact. Then come the Henry's Fork conglomerate, 350 feet thick, and the Flaming Gorge shale, several times thicker. Within the upper shale is a restricted trachyte sheet and near the top of the lower shale is a broader one. The latter is double throughout, its two layers having been intruded at different times.

The top of the escarpment is at the top of the laccolite, and only a short distance back from the brow are shale and sandstone resting upon the trachyte and conforming to its uneven surface.

The Scrope laccolite resembles the Jukes in everything except that its erosion has progressed so far as to obliterate every trace of the original upper surface. Its position in the strata is about the same, and the erosion of its matrix has left it a conspicuous crag. It rests on the flank of the Maze arch, just as the Jukes laccolite rests on the Dana arch. The remnant of trachyte is less than one thousand feet high, and has been carved into a subconical form in which no hint of the original size and proportions of the trachyte body is conveyed.

Figure 49 is a view of the east flank of Mount Ellen, as seen from Mount Hillers. It groups together many of the details that have been enumerated. The conical hill at the left is the Scrope laccolite. The spur from the mountain which ends just at the right of it is the Peale laccolite. The bold butte which terminates the last spur of the mountain in the distance is the Jukes laccolite. Across the base of the latter one can trace the outcrop of a hard bed. This is the Henry's Fork conglomerate, and the upward curve which it shows belongs (probably) to the Crescent arch. Nearer than the Jukes Butte and in the same direction is a low hill, marking the dike within the Crescent. Just to the left of it is an insular outcrop of the conglomerate, and nearer by is another outcrop in the form of a cliff, which is continuous to the base of the Peale laccolite. Between the Peale and Scrope laccolites the conglomerate is hidden by an embayment of the cliff, and it reappears in the base of the Scrope Butte. In all these outcrops the escarpments of conglomerate face toward the east and at the same time toward the Maze and Crescent arches. On the opposite side of the arches the same conglomerate outcrops in a monoclinal ridge with its escarpment facing to the west. The ridge can be traced in the sketch from a point in the foreground under the Jukes Butte nearly to the eastern base of the butte, the course at first being almost directly toward the butte and then curving far to the right and forming the Crescent. Between the Scrope and Peale laccolites on one side and the monoclinal ridge on the other, lie the Maze and the Maze arch. Beyond the Maze arch and limited at the right by the Crescent, is the Crescent arch. The Scrope, the Peale, and the Jukes are visible laccolites; the Maze and Crescent arches cover invisible laccolites.

The determinate laccolites and arches which compose the lower slopes of Mount Ellen, while they are of prime importance for purposes of investigation, must not be considered superior in number and magnitude to those of the central region. That region is known to abound in trachyte masses, and it far exceeds the marginal district in the extent and degree of its metamorphism. There is every reason to believe that the mountain crest marks the zone of greatest igneous activity, and that the foot-hills are as truly subsidiary from a geological point of view as they are from a topographic. There is no evidence of a great central laccolite, such as the Hillers and Pennell clusters possess, and I am disposed to regard the mountain as a great congeries of trachyte masses of moderate size, separated and in the main covered by shales and sandstones. The sedimentary strata of the summits are all of the Cretaceous series, but they are too greatly altered to permit the discrimination of the Masuk, Gate, and Tununk groups. The Henry's Fork conglomerate, which might have been recognized even in a metamorphic condition, was not seen.

STEREOGRAM OF THE HENRY MOUNTAINS.

For the double purpose of mapping and studying the mountains a model in relief was constructed, in which great pains was taken to give all the principal features their proper altitudes and proportions. This model was photographed, and has been reproduced by the heliotype process in Plate III, at the end of the volume. After it had been completed, a second model was constructed by adding to the surface of the first. Wherever the Blue Gate sandstone appeared in the original model no addition was made. Where the Tununk sandstone appeared there was added an amount equivalent to the combined thickness of the Blue Gate sandstone and the Blue Gate shale; and in general, enough was added in every part to bring the surface up to the summit of the Blue Gate sandstone. In this way a restoration was made of the form of that sandstone previous to its erosion. It is not to be understood that the mountains ever possessed this form; for when the surface of the Blue Gate sandstone was unbroken by erosion it was unbroken only because it was covered by other strata, which while they shielded it were themselves eroded. If the sandstone had been indestructible, this is the form which would have been developed by the washing away of all the overlying beds; and in this form are embodied the arches and domes which were impressed upon the sandstone by the upswelling of the laccolites. The model became a stereogram of the displacements of the Henry Mountains, and a photograph from the stereogram appears in Plate IV.

It will be observed that over the central district of Mount Ellen, where by reason of the peculiar sculpture of the rock its structure was concealed, the restoration of the sandstone was not carried; it seemed better to represent our lack of knowledge by a blank than to bridge over the interval by the aid of the imagination.

If the reader will study the plate, he will find that it expresses a great body of the phenomena which have been described in this chapter. The simplicity of the Ellsworth and Holmes arches is contrasted with the complexity of the others; the greatness of the Hillers and Pennell domes with the smallness of those which lie upon their flanks. One point that is especially striking is the relation between the upper and lower domes of the Ellen cluster. The upper, which give rise to all the conspicuous features of the mountain flanks, are comparatively small, while the lower, which might almost be overlooked in a rapid examination of the mountain, are comparatively large and constitute the great mass of the uplift. The smaller laccolites, because they are the upper, have been denuded of their covers, and in virtue of their hardness stand forth salient. The larger, because they are the lower, have not been laid bare, and the comparatively feeble resistance which their covers have opposed to erosion has impressed their forms but slightly on the topography.

CHAPTER IV.

THE LACCOLITE.

The principal facts in regard to the laccolites of the Henry Mountains having been set forth in the preceding chapter, an attempt will now be made to deduce from them the natural history of the Laccolite.

There is a question which the critical geologist will be likely to propound, and which should be answered at the outset. "What evidence", he may demand, "is there that the origin of the laccolite was subsequent to the formation of the inclosing strata rather than contemporaneous with it? May it not have been buried instead of intruded? May not the successive sheets and masses of trachyte have been spread or heaped by eruption upon the bottoms of Mesozoic seas, and successively covered by the accumulating sediments?" The answer is not difficult.

1st. No fragment of the trachyte has been discovered in the associated strata. The constitution of the several members of the Mesozoic system in the Henry Mountain region does not differ from the general constitution of the same members elsewhere. This evidence is of a negative character, but if there were no other it would be sufficient. For there is indubitable proof that at the end of the Shinarump period the Henry Mountain region was lifted above the ocean, and if any of the nuclei of the mountains had then existed they could not have escaped erosion by shore waves, and must have modified the contemporaneous deposits.

2d. The trachyte is in no case vesicular, and in no case fragmental. If it had been extruded on dry land or in shallow water, where the pressure upon it was not sufficient to prevent the dilatation of its gases, it would have been more or less inflated, after the manner of recent lavas. If it had issued at the bottom of an ocean, the rapidity of cooling would have cracked the surface of the flow while the interior was yet molten and in motion, and breccias of trachyte *débris* would have resulted. The absence of inflation and of brecciation are of course of the nature of negative evidence, but they derive weight from the fact that a great number of distinct bodies of trachyte have been examined in the course of the investigation.

3d. The inclination of the arched strata proves that they have been disturbed. If the laccolites were formed in each case before the sediments which cover them, the strata must have been deposited with substantially the dips which they now possess. This is incredible. The steepest declivity of earth-slopes upon the land is 34° from the horizontal, and they have not been found to equal this under water. Prof. J. D. Whitney noted 23° as the original slope of a deposit on the Pacific Coast, and regarded it as an extreme case. The writer has made many measurements of the inclination of oblique lamination in massive sandstones, and found the maximum to be 24°. But the strata which cover the laccolites dip in many places 45° to 60°, and in the revetments of the south base of Mount Hillers they attain 80°.

4th. It occasionally happens that a sheet, which for a certain distance has continued between two strata, breaks through one of them and strikes across the bedding to some new horizon, resuming its course between other strata. Every such sheet is unquestionably *subsequent* to the bedding.

5th. The strata which overlie as well as those which underlie laccolites and sheets, are metamorphosed in the vicinity of the trachyte, and the greatest alteration is found in the strata which are in direct contact with it. The alteration of superior strata has the same character as the alteration of inferior. This could never be the case if the trap masses were contemporaneous with the sediments; the strata on which they were imposed would be subjected to the heat of the lava, but the superior strata would accumulate after the heat had been dissipated. In the Henry Mountains a large number of observations were made of the phenomena at and near the contacts of sedimentary and igneous rocks, and in every instance some alteration was found.

In fine, all the phenomena of the mountains are phenomena of intrusion. There is no evidence whatever of extrusion. It is not indeed inconceivable that during the period in which the subterranean chambers were opened and filled, a portion of the lava found its way to the top of the earth's crust and there built mountains of eruption; but if such ever existed, they have been obliterated.

The Henry Mountains are similar among themselves in constitution. They all exhibit dome-like uplifts; they all contain intrusive rocks; and their intrusive rocks are all of one lithologic type. They are moreover quite by themselves; the surrounding country is dissimilar in structure, and there is no gradation nor mingling of character. Thus similar and thus isolated it is natural to regard the mountains as closely related in origin, to refer their trachytes to a common source, and to look for homology in all their parts. It was the search for such homology which led to the hypothesis that the laccolite is the dominant element of their structure. It is now time to examine this hypothesis, the truth of which has been assumed in the preceding pages, and see how far it accords with the facts of observation.

The facts to be correlated are the following:

1st. There are seven laccolites which lie so far above the local plane of erosion that they are specially exposed to denuding agents. They have no enveloping strata, and their only associated sheets lie in the strata under them. Their original forms have been impaired or destroyed by erosion. They are the Scrope, the Jukes, the Sentinel and its three companions, and the A laccolites.

2d. There are two laccolites so nearly bared that their forms are unmistakable, but which are still partially covered by arching strata, and which have associated sheets and dikes. They are the Marvine and the Steward laccolites.

3d. There are five supposed laccolites situated where the erosion planes are inclined, which run under the slopes and are covered at one side or end, and at the other project so far above them as to have lost something by erosion. These are accompanied by overarching strata and by sheets and dikes. They are the Peale, the Howell, the Shoulder, the D, and the E.

4th. There are seven or eight supposed laccolites, of which only a small part is in each case visible, but which are outlined in form by domes of overarching strata. Their bases are not exposed. Associated with them are dikes and sheets. They are the Hillers, the Pennell, the Geikie, the Newberry, the Bowl Creek, the C, the H, and perhaps the F.

5th. There are five domes of strata accompanied by dikes and (with one exception) by sheets, but showing no laccolite. They are the Ellsworth, the Greater Holmes, the Crescent, the Jerry, and the B arches.

6th. There are nine or more domes of strata with no visible accompaniment of trachyte. They are the Lesser Holmes, the Pulpit, the G, the Dana, and the Maze arches, and those of the foundation of Mount Pennell and of the west base of Mount Ellen.

Upon the hypothesis that all these phenomena are examples of the laccolitic structure, they have the following explanation: Each individual case comprised originally a laccolite, covered by a great depth of uplifted and arching strata, and accompanied by dikes and sheets which penetrated the strata to a limited distance. Lying at different depths from the surface, they have borne and still bear different relations to the progressive degradation of the country, and have been developed by erosion in different degrees. In nine of the instances cited the arch of strata has been truncated, but at so high a level that no dikes nor sheets were unearthed. In five instances the plane of truncation was so low that dikes and sheets were brought to light, but not the main body of trachyte. The truncation was in most of these cases less perfect because of the resistance to erosion by the hard dikes and sheets and by the strata which their heat had hardened. In eight other instances the erosion has left prominent the dome of hardened strata with its sheets and dikes, but has somewhere broken through it so as to reveal a massive core of trachyte. In five instances one side of the dome of strata has been washed away, exposing the core of trachyte to its base and showing undisturbed strata beneath it. In two instances the soft matrix has been so far washed away from the laccolite as to expose its form fully; and seven laccolites have not only lost all cover but have themselves been partially demolished.

Certainly, the hypothesis accords with all the facts that have been observed and unites them into a consistent whole. It explains fourteen domelike arches of sedimentary rock which are imperfectly exposed, by classing them with seven other arches of the same region which have been opened in section *to the base* and found to contain laccolites; and it strengthens the case by pointing to a connected series of intermediate phenomena. Until some strata-dome of the Henry Mountains, or of a closely allied mountain, shall be found to display some different internal structure, it will be safe to regard the whole phenomena of the group as laccolitic.

Form of laccolites.—As a rule laccolites are compact in form. The base, which in eleven localities was seen in section, was found flat, except where it copied the curvature of some inferior arch. Wherever the ground plan could be observed it was found to be a short oval, the ratio of the two diameters not exceeding that of three to two. Where the profile could be observed it was usually found to be a simple curve, convex upward, but in a few cases and especially in that of the Marvine laccolite the upper surface undulates. The height is never more than one-third of the width, but is frequently much less, and the average ratio of all the measurements I am able to combine is one to seven.

The ground plan approximates a circle, and the type form is probably a solid of revolution—such as the half of an oblate spheroid.

Internal Structure.—Of the laccolites which are best exhibited in section, there are a number which appear to be built up of distinct layers. The Peale exhibits three layers with uneven partings of shale. The Sentinel shows two without visible interval. The Howell shows two. The Pennell has a banded appearance but was not closely examined. The Marvine shows at a distance a faint banding, which near by eludes the eye. No division nor horizontal structure was seen in the Hillers, Jukes, Scrope, or Steward laccolites, but observation was not sufficiently thorough to satisfy me of its absence. It is probable that all the larger laccolites are composite, having been built up by the accession of a number of distinct intrusions.

There is little or no prismatic structure in the trachytes. It is sometimes simulated by a vertical cleavage induced in sheets and laccolites which are undergoing disintegration by sapping, but I did not observe the peculiar prismatic cleavage which is produced by rapid cooling in dikes, sheets, and *coulées* of basalt. The two structures are not often discriminated, but they are really quite distinct, and their peculiar characters are easily recognized. The cleavage planes produced by cooling are as a rule perpendicular to the cooling surface, and the systems of prisms which are based on the opposite walls of a dike or sheet, do not correspond with each other, and do not run across, but meet midway in a confused manner. The cleavage planes which are produced by the shearing force when a massive bed of trap or other rock is undermined or sapped and yields under its own weight, extend from base to top, and are perpendicular to the plane of the horizon instead of the plane of the bed.*

Vertical Distribution.—The range of altitudes at which laccolites have been formed is not less than 4,500 feet, and neither the upper nor the lower limit is known.

The highest that are known—those which were intruded at the highest geological horizon—are near the base of the Blue Gate shale (Middle Cretaceous), but it is quite possible that higher ones have been obliterated by erosion. The lowest that is known was intruded in the Shinarump shale, but it is known of the invisible Ellsworth laccolite that upper Carboniferous strata lie above it, so that its horizon of intrusion must be still lower. The plexus of dikes and sheets on the Ellsworth arch indicates that the laccolite is not deeply buried; but in the series of arches there are nine which show no trachyte, and we have no data from which to infer their depth.

How the laccolites are distributed within these limits is more readily comprehended by the aid of a diagram. In Figure 50 the triangles mark the horizons of determined laccolites, and the crosses the horizons which the invisible laccolites cannot exceed. For example, the base of the Scrope laccolite is visible and is seen to lie on the Tununk shale 400 feet above the Henry's Fork conglomerate; to represent it a triangle is placed at about the middle of the space representing the Tununk shale, and in the column devoted to the Ellen cluster. The upper surface of the Geikie laccolite is visible and upon it rest, first a few feet of Flaming Gorge shale, and then the Henry's Fork conglomerate; to represent it a triangle is placed near the top of the Flaming Gorge space. The crown of the Pulpit arch has

* See page 172 of the "Exploration of the Colorado River", by J. W. Powell.

been so far eroded that half of the Vermilion Cliff sandstone is shown in section, but no laccolite is revealed. It is evident that the Pulpit laccolite is lower than the middle of that sandstone; and to represent it a cross is placed below the middle of the Vermilion Cliff space and in the column devoted to the Hillers cluster.

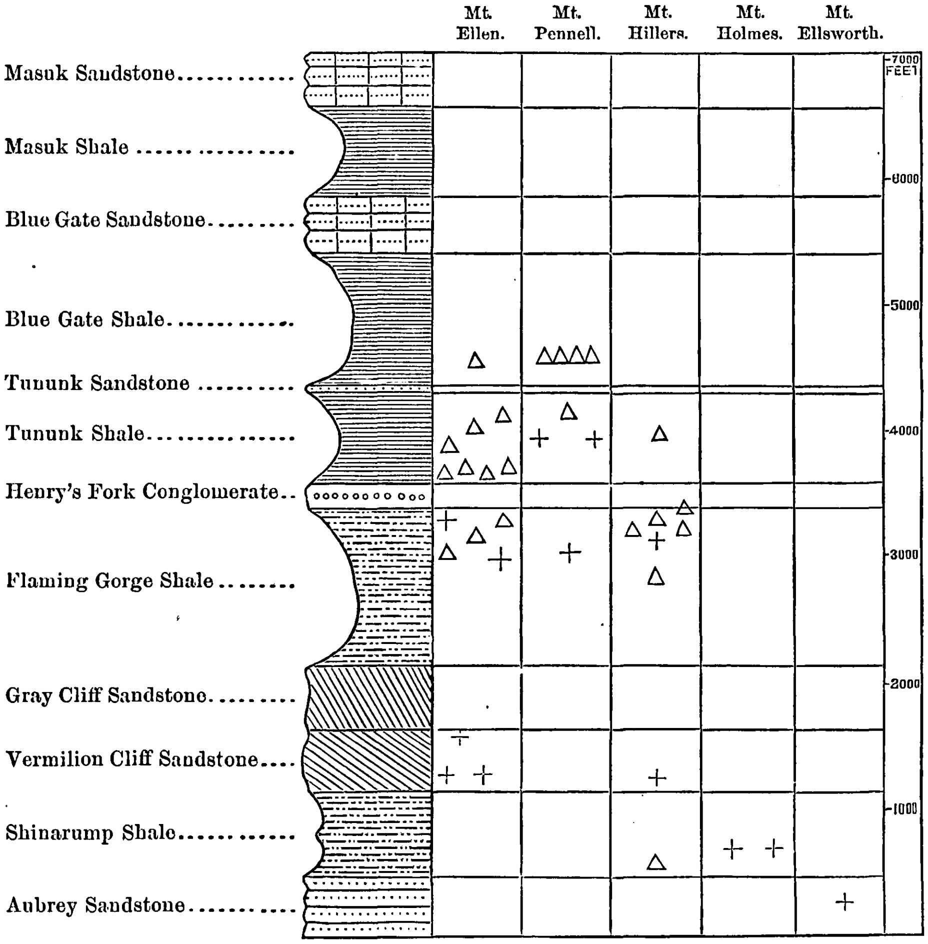


FIG. 50.—Diagram of the Vertical Distribution of the Laccolites of the Henry Mountains.

The first feature which this graphic assemblage yields to the eye is that there are at least two zones of laccolites. The upper ranges from the lower part of the Blue Gate Group, through the Tununk and Henry's Fork, to the upper part of the Flaming Gorge Group. The lower has not yet been fully developed by erosion, but its proximity is indicated. The Hillers laccolite is uncovered at top, and the dikes of the Ellsworth, the Greater Holmes, and the Crescent have been reached. All of the invisible laccolites indicated in the Vermilion Cliff and Shinarump spaces must be referred to this zone; and there is reason to suspect that all but one of the invisible laccolites whose indication falls in the Tununk and Flaming Gorge spaces belong also to the lower zone. However this may be, it is not probable that the determination of the depths of the invisible laccolites would vitiate the conclusion that there is an upper zone of laccolitic frequency which is separated from a lower zone by an interspace of laccolitic infrequency.

Another feature illustrated by the diagram is that all the determined laccolites are inclosed by soft beds. They have been intruded into the shales, but not the sandstones. They cluster about the Henry's Fork conglomerate, but none of them divide it. This selection of matrix is confined however to the laccolites and is not exercised by sheets and dikes. Trachyte sheets were seen within the Henry's Fork, the Gray Cliff, the Vermilion Cliff, and the Aubrey sandstones.

A third feature of the diagram is the restriction of the upper zone of laccolites to the northward clusters; Mounts Ellsworth and Holmes contain laccolites of the lower zone only. This fact of distribution is correlated with a fact of denudation—namely, that in the general degradation of the country, the region about the southern mountains has lost two thousand feet more than the northern. One fact is probably the cause of the other. The absence of laccolites of the upper zone at the south may have permitted the greater degradation; or the greater degradation may have caused the destruction of several of the upper laccolites. The fact that the difference in degradation can be independently accounted for is favorable to the latter supposition. The Colorado River which is the main artery of drainage for the whole region, flows close to the bases of the southern mountains, and the rapid declivity from the mountain summits to the river has given and still gives exceptionally great power to the agents of erosion. No other cause is needed to explain the difference of degradation, and the absence of laccolites of the upper zone is explicable without assuming that they were never present.

The negative objection to the idea that the southern mountains originally possessed laccolites of the upper zone being thus disposed of, it is worth while to inquire whether there is any evidence in its favor. If superior laccolites existed, they would be sure to leave behind them a record of the conduits through which their lava was injected. A dike or a chimney must always connect a laccolite with the source of its material; and the removal of the laccolite necessarily exposes a cross-section of its stem. The discovery of such a dike can be regarded, not indeed as a proof of the former existence of a superior laccolite, but as demonstrating its possibility. The summits and flanks of Mounts Holmes and Ellsworth bear many dikes, which have been regarded as subsidiary features of the laccolites beneath them, but it is quite possible that any one of them formerly led to another laccolite above. The upper laccolite may have been first formed and then have been lifted, dike and all, when the lower was intruded; or it may have been last formed, and been fed through a fissure which traversed the lower after its congelation. The only dike which was discovered in the vicinity of these mountains, without being upon them, stands midway between them. It is the only observed dike of the Henry Mountains (excepting always the alpine district of Mount Ellen), which is not so closely associated with some laccolite as to seem an accessory feature, and its exceptional position has led to the suspicion that it belonged to an overlying laccolite.

Upon such uncertain evidence no positive conclusion can be based, and it is vain to build laccolites in the air. The most that can be said is that the southern mountains need not be distinguished from the northern, because at the present stage of degradation they contain laccolites of the lower zone only.

The Material of the Laccolites.

The intrusive rocks of the Henry Mountains were sampled with care. Specimens were selected which had undergone little decomposition and which represented all the prominent lithologic varieties. They were chosen from the trachytes of both zones and of each of the mountain masses; and they represent dikes and sheets, as well as laccolites. From about thirty specimens thin slices were cut for microscopic examination.

Captain C. E. Dutton, of Omaha, Nebraska, was so kind as to undertake the study of the collection, and the letter which embodies his conclusions is given below. In accordance with his diagnosis I shall call the intrusive rocks *porphyritic trachyte;* and I am glad to have the weight of his authority in support of my belief that all the rocks of the series are of one type, their resemblances far outweighing their differences.

NOTE.—Persons desiring to examine the Henry Mountain trachytes under the microscope can obtain mounted thin sections from Mr. Alexis A. Julien, School of Mines, Columbia College, New York.

REPORT ON THE LITHOLOGIC CHARACTERS OF THE HENRY MOUNTAIN INTRUSIVES.

BY CAPTAIN C. E. DUTTON.

"I have examined with great interest and attention the Henry Mountain rocks you sent me, and proceed to acquaint you with such results as my limited facilities have permitted me to derive from the examination. It is a very well defined series, having some marked characters which distinguish it from the nearest allied group with which I am acquainted. This is all the more interesting, because I am inclined to think that these peculiarities may have a definable association with or relation to the manner in which the intrusive rocks occur in those "laccolites", as you term them.

"The hand-specimens show in most cases large and unusually perfect crystals of orthoclase imbedded in a very compact uniform paste through which hornblende is also disseminated rather more abundantly than is usually the case where the dominant felspar is monoclinic. Micaceous crystals appear to be wholly wanting and this is a notable circumstance, since the trachytes of the Plateau country, to which these rocks are most nearly allied, are seldom without one or more of them. The only other mineral which is of frequent occurrence in the specimens is magnetite (or possibly titanic iron), which is diffused in the usual form of minute granules in many of them, but is scarce in several of them. In general there is a great scarcity of mineral species and any others than those mentioned are of the greatest rarity.

"The dominant felspar is orthoclase, but a portion of it is triclinic, and I presume this portion is albite, with an occasional occurrence of oligoclase. The groundmass in which the crystals are included is in most cases decidedly compact and without distinguishable crystals, but shows between the crossed Nicols closely aggregated luminous points, which with a $\frac{1}{4}$-inch objective are resolved indistinctly into felspar. In some cases the crystals of the groundmass are quite apparent with an inch objective, and their species determinable. But the greater portion of the groundmass is quite amorphous, and does not polarize light at all. The proportion of crystalline to amorphous matter in the paste is highly variable—in some cases it is quite bright between crossed Nicols, in others far less so, and in none is it entirely dark. Those specimens which have the finer and more amorphous groundmass have the larger and more perfect crystals of felspar—an association of properties which is not wholly without qualification, but still sufficiently decided.

"Turning to the included felspars, their mode of occurrence is quite an uncommon one, I believe, so far as the eruptive rocks of the Rocky Mountain region are concerned, and give rise to some hesitation before assigning them definitely to the trachytic group. In a great many cases the felspathic crystals are well developed, and so large and so nearly perfect that their aspect is decidedly porphyritic. This is especially the case with the dikes of Mounts Ellsworth and Holmes (Nos. 56, 61, 68, and 69). The orthoclase is invariably of the white "milky" variety, with the exception of a single specimen from a Mount Ellsworth dike (No. 57), where it is present as sanidin. (This is an exceptional rock in all respects, and will be spoken of hereafter.) Nearly all of them appear to have been subject to alteration by chemical action since their formation as is indicated by their diminished power to polarize light. Whether this is due to atmospheric weathering or to changes *en masse* it is of course impossible to distinguish with certainty, though I incline to the latter view since it is manifested as decidedly in specimens which show no external indications of weathering as in those which do show them. It is not uncommon to find crystals which have almost entirely ceased to polarize. The zonal arrangement is very common in the crystals, and some of the zones contain numberless minute fluid cavities in the largest crystals. The foreign substances included in the crystals present no novelty, being the ordinary films of hornblende, minute needles of felspar, granules of magnetite, and those dust-like points of brownish yellow color which are the proper inclusives of the groundmass.

"The orthoclase occasionally presents the adular variety, but this never becomes a marked feature. I have observed the same in many of the trachytes of the High Plateaus and of the Great Basin. Another phenomenon is the occurrence of crystals which are quite typically monoclinic at one end (orthoclase), and at the other end have the arrangement of plagioclase. This is well known elsewhere, and described by Zirkel. (Mik. Beschaff der Mineralien u. Gesteine).

"In classifying these rocks therefore, we may observe that they present a blending of the characteristics which are common to trachyte and felsitic porphyry. Those who regard porphyry as a distinct class of eruptive rocks would have no hesitation in calling Nos. 18, 56, 61, 68, and 69 undebatable felsitic porphyries, and to the same series might with propriety be added No. 33. With equal confidence Nos. 16, 20, 35, and 43 may be called unqualified trachytes. The other rocks are intermediate in character between these two extremes, and the whole may be regarded as a series in which the individuals form a graduated scale.

"You will recall the fact that many lithologists object to the terms porphyry or porphyritic being used to designate a distinct class or group of rocks, holding that they merely characterize a single feature which is more or less frequently presented by all igneous rocks and having no necessary relation to any of them, and that this is no more adequate to such an important distinction than the color or relative degree of fineness or coarseness of texture. Although this latter view seems to me to underrate the distinctive value of the porphyritic character in general, I incline very decidedly to the belief that it is true as applied to these Henry Mountain rocks. Here at least the porphyritic character has but little significance. In some varieties the crystals are larger and more perfect and the groundmass more homogeneous; in others the crystals are smaller and imperfect, and the groundmass more coarse and irregular; while still others are 'betwixt and between'. The most careful scrutiny fails to show any fundamental differences in the groundmass or in the included minerals. Hence I think these rocks would be accurately designated *as a group* by calling them porphyritic trachytes. Such varieties as Nos. 16, 20, and 35 may by themselves be called simply trachyte, the porphyritic character being insufficiently distinct in them to warrant any qualification of the name.

"There is one specimen (No. 57, from dike in Shinarump shale, Mount Ellsworth) which constitutes an exception to the foregoing. By inspection of a hand-specimen it might hastily pass for a very compact andesite, but the observer will be instantly undeceived by applying the miscroscope. It consists of imperfect crystals, which must be sanidin, imbedded in a very close groundmass composed of a material which differs from the foregoing trachytes in being wholly amorphous. Between crossed Nicols the paste transmits no light whatever, though between the parallel Nicols it closely resembles the others. The hand specimen is very dark colored (gray), but the slide is sufficiently translucent. The felspar crystals are either fragmental or very imperfectly developed as to their edges and angles, but polarize very sharply. The amount of twinning is very small, but it appears occasionally. The rock is undoubtedly a trachyte, but an unusual one. Its dark color is not due to hornblende nor to magnetite, both of which occur in it very sparingly, especially the former.

"I have already remarked that the only frequent minerals besides felspar are hornblende and magnetite. Apatite occurs and is tolerably plentiful in a few of the specimens, but absent from most of them. The crystals are all small, requiring a low power for the determination of the larger and a high power for the smaller. They present no peculiarities. Of very rare occurrence is nepheline. This mineral is usually associated with the more basic volcanic rocks and seldom penetrates the trachytic group. Quartz is almost equally rare. The absence of any great variety in the mineral species is quite normal, except possibly the total absence of mica, which is usually present and frequently the only associate of felspar in the western trachytes. The Henry Mountain rocks do not so far as I can discover contain a trace of it.

"In answer to your particular inquiries—

"1st. 'Is the paste vesicular, or is there any evidence in the crystals to indicate the pressure under which they were formed?' I can only say that the paste is extremely compact and contains no vesicles even in those specimens of which the aspect is most decidedly trachytic. Some of the larger crystals of felspar contain an abundance of pores or vesicles which may have contained liquids, but with a $\frac{1}{4}$-inch objective they are too small for treatment by the method you refer to. A few large cavities, usually of irregular shape, occur, but I am quite unfamiliar with the practical treatment of this subject and cannot advise you. I do not find any cavities still containing fluids, and I presume that even if they existed they would be difficult if not impossible to gauge on account of the impellucidity of the felspar. I presume quartz is the most favorable mineral for this investigation on account of its transparency and the greater frequency of its large cavities. Quartz however is almost the scarcest of the contents of these rocks.

"2d. 'Do any mineralogic differences correlate with the superficial or geographic distribution of the rocks?' and

"3d. 'Do any mineralogic differences correlate with the vertical distribution of the trachytes?' As it appears from your account of the distribution of the masses that the upper zone belongs (with one exception) to Mounts Ellen and Pennell and the lower to the other mountains, the answer to one is the answer to both, and this is in the negative. The mineralogical differences are exceedingly small, considering the number of distinct masses, and this covers the inquiry entirely. Regarding the texture or habitus, on the contrary, it appears to me that the true trachytes predominate in the upper zone and the porphyries in the lower, but not without exceptions.

"4th. 'Do any mineralogic differences correlate with the size of the intrusive masses?' No mineralogical differences thus correlate, but I find a preponderance of the porphyritic texture in the smaller masses and of the trachytic texture in the larger. It is not without exception, and the preponderance is small."

Metamorphism and Contact Phenomena.—Wherever the trachytes came in contact with the sedimentaries the latter were more or less altered. Large bodies of trachyte produced greater changes than small. The laccolites both metamorphosed their walls more completely, and carried their influence to a greater distance than the sheets and dikes. The summits of the laccolites had a greater influence than the edges; a phenomenon to which I shall have occasion to revert. The sandstones were less affected than the shales, at least in such characters as readily catch the eye. Clay shales were indurated so as to clink under the hammer, and Captain Dutton discovered with the microscope that minute crystals of felspar had been developed. Sandstones were usually modified in color, and their iron was segregated so as to give a mottled or speckled appearance to the fracture. They were indurated, but the granular texture was always retained.

The trachyte carries numerous small fragments of sedimentary rock broken apparently from its walls, and these are as thoroughly crystalline as their matrix.

The altered rocks are usually jointed, but nothing approaching to slaty cleavage was seen, nor has there been any crumpling.

The reciprocal influence of the sandstone and shale upon the trachyte was small. Specimens broken from the contact surface of a laccolite and from its interior cannot be distinguished. In the Marvine laccolite however there is a difference between the exterior and interior portions in their ability to withstand erosion.

Historical.—Before leaving the subject of the structure of the mountains it is proper to place on record certain observations by others which antedated my own but have never been published.

While Professor Powell's boat party was exploring the cañons of the Colorado, Mr. John F. Steward a geologist and member of the party climbed the cliff near the mouth of the Dirty Devil River and approached the eastern base of the mountains. He reported that the strata had in the mountains a quaquaversal dip, rising upon the flanks from all sides.

The following year Prof. A. H. Thompson then as now in charge of the geographic work of Professor Powell's survey crossed the mountains by the Penellen Pass and ascended some of the principal peaks. He noted the uprising of the strata about the bases and the presence of igneous rocks.

In 1873 Mr. E. E. Howell at that time the geologist of a division of the Wheeler Survey traveled within twelve miles of the western base of the mountains, and observed the uprising of the strata.

My own observations were begun in 1875, at which time a week was spent among the mountains. They proved so attractive a field for investigation that in the following year a period of nearly two months was devoted to their study.

Other Igneous Mountains.—The Henry Mountains are not the only igneous group which the Plateau province comprises. They are scattered here and there throughout its whole extent. From the summits of the Henry Mountains one can see the Sierra La Sal ninety miles to the northeastward, and the Sierra Abajo seventy miles to the eastward. Beyond them and two hundred miles away are the Elk Mountains of Colorado. Fifty miles to the southwestward stands the Navajo Mountain on the brink of the Colorado; and one hundred and twenty miles to the southeast the Sierra La Lata and the Sierra Carriso are outlined against the horizon. Westward it is less than thirty miles to the Aquarius Plateau, the nearest member of the great system of volcanic tables among which the Sevier and Dirty Devil Rivers rise.

Beyond the horizon at the south and southwest and southeast are a series of extinct volcanoes; Mount Taylor and the Marcou Buttes in New Mexico; the Sierra Blanca, the Sierra Mogollon, the San Francisco Group and the Uinkarets in Arizona; and the Panguitch Lake Buttes in Utah.

Of the groups which are visible, all but that of the Aquarius Plateau are allied in character to the Henry Mountains.

The Sierra Abajo was studied in 1859 by Dr. J. S. Newberry, geologist of the Macomb Expedition, who writes: "Within the last few weeks we have been on three sides of this sierra, and have learned its structure quite definitely. It is a mountain group of no great elevation, its highest point rising some 2,000 feet above the Sage-plain, or perhaps 9,000 feet above the sea. It is composed of several distinct ranges, of which the most westerly one is quite detached from the others. All these ranges, of which there are apparently four, have a trend of about 25° east of north, but being arranged somewhat *en echelon*, the most westerly range reaching farthest north, the principal axis of the group has a northwest and southeast direction. The sierra is composed geologically of an erupted nucleus, mainly a gray or bluish-white trachyte, sometimes becoming a porphyry, surrounded by the upheaved, partially eroded, sedimentary rocks. The Lower Cretaceous sandstones and Middle Cretaceous shales are cut and exposed in all the ravines leading down from it, while nearly the entire thickness of the Cretaceous series is shown in spurs which, in some localities, project from its sides; apparently the remnants of a plateau corresponding to, and once connected with, the Mesa Verde. Whether the Paleozoic rocks are anywhere exposed upon the flanks of the Sierra Abajo I cannot certainly say, though we discovered no traces of them. It is, however, probable that they will be found in some of the deeper ravines, where, as in most of these isolated mountains composed mainly of erupted material, they are doubtless but little disturbed, but are buried beneath the ejected matter which has been thrown up through them.

"The relations of the Cretaceous rocks to the igneous nucleus of the Sierra Abajo are very peculiar, for, although we did not make the entire circuit of the mountain mass, and I can, therefore, not speak definitely in regard to the western side, as far as our observations extended we found the sedimentary strata rising on to the trachyte core, as though it had been pushed up through them." (Geology of the Macomb Expedition, page 100.)

Of another group Dr. Newberry says in the same report (page 93): "Of the composition of the Sierra La Sal we know nothing except what was taught by the drifted materials brought down in the cañons through which the drainage from it flows. Of this transported material we saw but little, but that consisted mainly of trachytes and porphyry, indicating that it is composed of erupted rocks similar to those which form the Sierra Abajo, of which it is in fact almost an exact counterpart. From the cliffs over Ojo Verde we could see the strata composing both the upper and second plateaus, rising from the east, south, and southwest on to the base of the Sierra La Sal, each conspicuous stratum being distinctly traceable in the walls of the cañons and valleys which head in the sierra. It is evident, therefore, that the rocks composing the Colorado Plateau are there locally upheaved, precisely as around the Sierra Abajo * * *."

These mountain groups have been since visited by the geologists of Dr. Hayden's survey, Dr. A. C. Peale ascending the Sierra La Sal and Mr. W. H. Holmes the Sierra Abajo. Mr. Holmes has also examined the La Lata and Carriso Mountains and found in them the same upbending of Cretaceous strata and the same association of igneous material.

The Navajo Mountain has been viewed by Mr. Howell and by the writer from a commanding position on the opposite side of the Colorado River, and fragments of its trachyte have been gathered on the river bank by Professor Powell, but no geologist has yet climbed it. Still there can be no question of its general structure. It is a simple dome of Jura-Triassic sandstone, springing abruptly from a plateau of the same material, and veined at the surface by sheets and dikes of trachyte—the counterpart in fine of Mount Ellsworth, only of more imposing proportions.

The La Sal, the Abajo, the La Lata, the Carriso, the Navajo, and the Henry Mountains agree in their essential features. Structurally they have no trends. Their phenomena are grouped about centers and not axes. In all of them the strata are lifted into dome-like arches, and associated with these arches are bodies of trachyte. The trachytes are all of one lithologic type, and are so closely related that a collection of rock specimens representing all the groups would show scarcely more variety than a collection representing the Henry Mountain laccolites. With so many characters in common they can hardly fail to agree in the possession of laccolitic nuclei.*

The Elk Mountains are at the very margin of the plateau, and geographically might be connected with the Sawatch Range which bounds

* While these pages are passing through the press a paper by Dr. A. C. Peale "On a peculiar type of eruptive mountains in Colorado" (Bulletin U. S. Geol. Sur., Vol. III, No. 3) comes to hand. He groups together as of one type not only the Elk, La Sal, Abajo, La Lata, and Carriso Mountains, but also the Spanish Peaks, Park View Mountain, Mount Guyot, Silverheels Mountain, the San Miguel Mountains, the La Plata Mountains, and certain smaller masses in Middle Park and near the Huerfano River. He says, "Although modified in several instances, the general plan appears to be the same. The igneous material came up through fissures in the sedimentaries, sometimes tipping up their ends, and sometimes passing through without disturbing them. On reaching the Cretaceous shales, it generally spread out in them, and pushed into and across them dikes and intrusive sheets of the same igneous rock. The elevation in some cases appears to be due to actual upheaval caused by the eruptive force. The mountains as they now exist are doubtless largely the result of erosion, the hard igneous rock opposing greater resistance to erosive influences than do the surrounding soft sedimentary beds."

the plateau province on that side. But structurally they are a group instead of a range, and affiliate with the groups which are insulated by an environment of tables. Thanks to the labors of Mr. Holmes and Dr. Peale their general structure is known. The Eastern Elk Mountains consist of four great bodies of "eruptive granite", over which are arched not only Mesozoic but Paleozoic strata. Their foundation must be a floor of Archæan metamorphics. Two of them, the Snow Mass and White Rock laccolites, are joined by a continuous line of disturbance, in the description of which by pen and pencil Mr. Holmes has made an important contribution, not only to dynamical geology, but to the methods of geological illustration. The others are more symmetric and are complementary illustrations of the common structure. One, the Sopris, is half truncated by erosion so that the core is exposed at top with an encircling fringe of upturned sedimentaries; and the other, the Treasury, retains a complete arch of Paleozoic strata. The Western Elk Mountains are a cluster of smaller laccolites which are inserted between strata of Cretaceous age. Their traps include porphyritic trachytes undistinguishable from those of the Henry Mountains, and eruptive granites identical with those of the Eastern Elk Mountains; and they exhibit a gradation from one to the other. Indeed the two rocks are nearly related, and their assignment to classes so diverse as trachyte and granite is merely an illustration of the imperfection of our classification of rocks. The description of the Elk Mountains will be found on pages 61 to 71 and 163 to 168 of the Annual Report for 1874 of the "Geological and Geographical Survey of the Territories."

If we turn now to the distinctively volcanic mountains of the Plateau province—to those which are built by eruption at the surface—we leave at once the porphyritic trachytes. Mount San Francisco, Mount Bill Williams, Mount Sitgreaves, Mount Kendrick, Mount Floyd and the Sierra Blanca (of Arizona) are all composed of basic trachytes, and so are the Aquarius Plateau and the many tables that lie beyond it.

The Mogollon group, the Marcou Buttes, the minor cones about Mount San Francisco, the Uinkarets, and the Panguitch Lake group are basaltic. In each of these instances the igneous rock issued above the surface and there is no evidence by displacement that any portion of it was deposited below.

Mount Taylor may be an exception. In the character of its lava and its general features it resembles Mount San Francisco, but there are disturbed strata on its southern flank, and it is possible the mountain is both extrusive and intrusive. Extrusion and intrusion are probably combined in some small tables lying fifty miles north of the Henry Mountains. They are built of Flaming Gorge shale, preserved from erosion by dikes, sheets, and (probably) outflows of basalt.

Combining all these facts we attain to a simple relation between two types of igneous rock on the one hand, and two types of mountain structure on the other. One type of rock is acidic, including "porphyritic trachyte" and "eruptive granite", and its occurrence is without exception intrusive. The other type of rock is basic, including basic trachyte and basalt, and its occurrence is almost uniformly extrusive.

It is not possible to combine the two groups of phenomena by saying that in one case the eruptive cones cover laccolites, and in the other the laccolites have been covered by eruptive cones which have disappeared; first, because many of the eruptive cones are too well exposed to admit of the concealment of laccolitic arches beneath them; second, because the two types of lava are essentially different. The acidic type if extruded at the surface would be an ordinary trachyte; the basic type if crystallized under pressure would be classed with the greenstones.

The basis for the generalization is exceedingly broad. I have enumerated only seven groups of laccolitic mountains and ten groups of eruptive; but with few exceptions each group is composed of many individuals, each one of which is entitled to rank as a separate phenomenon. In the Uinkaret Mountains Professor Powell has distinguished no less than one hundred and eighteen eruptive cones, and in the Henry Mountains I have enumerated thirty-six individual laccolites. In one locality basic lava has one hundred and eighteen times risen to the surface by channels more or less distinct, instead of opening chambers for itself below. In the other locality porphyritic trachyte has thirty-six times built laccolites instead of rising to the surface.

If our attention was restricted to these two localities we might as naturally correlate the types of structure with some accidents of locality as with types of lava; but when all the localities are taken into account it is evident that there is no common mark by which either the laccolitic or the volcanic are distinguished.

THE QUESTION OF CAUSE.

We are now ready to consider the question: Why is it that in some cases igneous rocks form volcanoes and in other cases laccolites?

It is not necessary to broach the more difficult problem of the source of volcanic energy. We may assume that molten rock is being forced upward through the upper portion of the earth's crust, and disregarding its source and its propelling force may restrict our inquiry to the circumstances which determine its stopping place.

Let us further assume, but for a moment only, that the cohesion of the solid rocks of the crust does not impede the upward progress of the fluid rock, nor prevent it from spreading laterally at any level. The lava will then obey strictly the general law of hydrostatics, and assume the station which will give the lowest possible position to the center of gravity of the strata and lava combined.

(1) If the fluid rock is less dense than the solid, it will pass through it to the surface and build a subaërial mountain.

(2) If the upper portion of the solid rock is less dense than the fluid, while the lower portion is more dense, the fluid will not rise to the surface but will pass between the heavy and light solids and lift or float the latter.

(3) If the crust be composed of many horizontal beds of diverse and alternating density, the fluid will select for its resting place a level so conditioned that no superior group of successive beds, including the bed immediately above it, shall have a greater mean specific gravity than its (the fluid's) own; and that no inferior group of successive beds, including the bed immediately beneath, shall have a less mean specific gravity than its own.

[In the diagram, a series of light and heavy beds are represented in section by open and shaded spaces. A lava stream free to move upward or laterally will intrude itself at some point (*c*) so placed that every combination of superior beds (*a*), which includes the lowest, shall have a less average density; and every combination of inferior strata (*b*), which includes the highest, shall have a greater average density than that of the lava.]

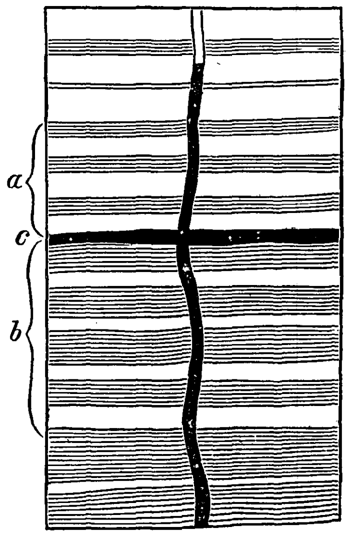


FIG. 51.—Diagram to illustrate the application of the law of Hydrostatic Equilibrium to the movements of lavas. The shaded bands represent heavy strata; the open, light.

The first case is that of a volcano; the second is that of a laccolite; and the third is the general case, including the others and applying to all volcanoes and laccolites.

Conversely we may say that, given a series of strata of diverse and alternating density, a very light lava will traverse it to the top and be extruded; a heavier will intrude itself at some lower level; and a series of dissimilar lavas may select an equal number of distinct levels.

It is easy to imagine such a balancing of conditions that a slight change in a lava will determine a great change in its level of intrusion.

Having seen the general application of the hydrostatic law, it is time to recall the condition which we laid aside at the start. Cohesion, or rigidity, is never absent and must affect every phase of vulcanism. It certainly opposes the free circulation of lavas, and it cannot but modify their obedience to the hydrostatic law.

But granting this, and believing that a full comprehension of the subject must include this condition, I am at a loss to tell in what way it influences the selection by a lava flood of a subaërial or a subterranean bourne. Whether it will on the whole oppose upward progress more than lateral, or *vice versa*, is not clear. If it resists lateral intrusion the more strongly, it favors the formation of volcanoes; if it resists upward penetration the more strongly, it favors the formation of laccolites; and in either case the working of the hydrostatic law is modified.

But in neither case is the working of the law more than modified. The law is not abrogated, and in obedience to it light lavas still *tend* to rise higher than heavy however much the rising of all lavas may be hindered or favored.

In brief, since lavas are fluids they are subject to the law of fluid equilibrium, and their behavior is conditioned by the relations of their densities to the densities of the solids which they penetrate; and since the latter solids are rigid and coherent, it is further conditioned by the resistance which is opposed to their penetration. When the resistance to penetration is the same in all directions, the relation of densities determines the stopping place of the rising lava; but when the vertical and lateral resistances are unequal, *their* relation may be the determining condition.

If we can decide whether the determinative condition in the Plateau region was that of densities or that of penetrability, we shall have solved our problem.

Assuming, first, that the essential condition is that of penetrability, we should expect that some particular stratum or that a few particular strata, being less penetrable than others, would check the rising lavas and accumulate them in a system of laccolites, which would occupy one, or a few definite horizons. Volcanoes would occur in districts from which such impenetrable strata either were originally absent or had been removed before the igneous epoch; and we should expect to find the same variety of material in laccolites and in volcanoes.

Assuming, second, that the essential condition is that of densities, we should expect as before to find certain stratigraphic horizons more favorable than others to the accumulation of laccolites, and we should also expect to find certain lavas usually volcanic and certain others usually laccolitic.

That is to say—since the condition of impenetrability resides in the solid rock only, and the condition of density pertains to both solid and fluid, either condition might determine laccolites at certain stratigraphic horizons, while the latter only could discriminate certain lavas as intrusive and others as extrusive.

The vertical distribution of laccolites is not inconsistent with either assumption. In the Henry Mountains there are two zones of occurrence; in the Eastern Elk Mountains there is a third; and it is probable in the present state of our knowledge that all other laccolites of the Plateaus can be assigned to one or another of these. The fact that the laccolites of the upper zone have a vertical range of two thousand feet is rather favorable to the idea that their stations were determined by relations of density, but is not decisive.

When however we turn to the relation between the constitutions and the behaviors of lavas, we find the entire weight of the evidence in favor of the assumption that conditions of density determine the structure. The coincidence of the laccolitic structure with a certain type of igneous rock is so persistent that we cannot doubt that the rock contained in itself a condition which determined its behavior.

We are then led to conclude that the conditions which determined the results of igneous activity were the relative densities of the intruding lavas and of the invaded strata; and that the fulfillment of the general law of hydrostatics was not materially modified by the rigidity and cohesion of the strata.

Having reached this conclusion it is natural to seek for confirmation by the investigation of the densities of the rocks concerned in the phenomena. As will appear by a table given further on, the density of the Henry Mountain trachyte has been determined to be 2.61; but the densities of the erupted lavas of the Plateaus are not yet known. There can be no doubt however that the latter are heavier. Von Cotta in his Lithology gives 2.9 to 3.1 as the density of basalt, and 2.6 to 2.9 as the density of the more basic trachytes. And in general, it is well established that where the state of aggregation is the same, basic igneous rocks are always heavier than acidic. But in order that the laccolitic structure should have been determined by density, the acidic rock of the laccolites must have been heavier in its *molten* condition than the more basic rocks of the neighboring volcanoes; and since in the *crystalline* condition the acidic is the lighter, it follows that it has gained less density in cooling than the basic.

If the amount of contraction of the several rocks in passing from their natural molten condition to the crystalline condition could be determined experimentally, a crucial test would be applied to our conclusions as to the origin of laccolites. The matter is however beset with difficulties. Bischof attempted by melting eruptive rocks in clay crucibles to obtain their ratios of expansion and contraction, but his method involved so many sources of error that his results have been generally distrusted. He concluded that the contraction in passing from the molten to the crystalline state is greater in acidic than in basic rocks. Delesse by an extended series of experiments in which crystalline rocks were melted and afterward cooled to glasses, showed that acidic rocks increase in volume from 9 to 11 per cent. in passing from the crystalline state to the vitreous, while basic increase only 6 to 9 per cent. Mallet concluded from some experiments of his own that the contraction of rocks in cooling from the molten condition is never more than 6 per cent., and that it is greater with basic than with acidic rocks; but considering that the substances which he treated were artificial and not natural products, that his methods were not uniform, and that he ignored the distinction between the vitreous and the crystalline, of which Delesse had demonstrated the importance, no weight can be given to his results.

If however all of these experiments were trustworthy and their results were concordant, their bearing upon the problem of the laccolites would still be slight. It is generally conceded that the fusion of lavas is hydrothermal, while in all the experiments recourse was had to dry fusion; and the densities attained in the two ways are necessarily different. The practical difficulty in the way of restoring the natural molten condition is great and may be insuperable, but unless it shall be overcome we cannot learn experimentally the changes of density which igneous rocks undergo in congelation.

There is a fact of observation which tends to sustain the view that the laccolitic rocks contracted less in cooling than the volcanic. The prismatic structure is produced by the contraction of cooling rocks during and after solidification. That it does not occur in the Henry Mountain trachytes indicates that their contraction was small. That it does occur at numerous localities in Utah in basalts, indicates that their contraction was relatively great. Mr. Jukes, in his Manual of Geology, says that it is most frequently exhibited in "doleritic lavas and traps, being especially characteristic of basalt, but occurs almost as perfectly in some greenstones and felstones";

and in the range of my own observation I can recall no instance of its occurrence in other than basic rocks.

For the sake of comparing the densities of the intrusive rocks with those of the strata which contain them, a number of determinations were made of the specific gravities of specimens representative of the trachytes and of the several sedimentary groups of the Henry Mountains.

Trachytes were selected to represent as great a variety of locality and relation as possible, and at the same time exclude all specimens which showed traces of decomposition. Hand specimens weighing from one hundred to four hundred grains were used, and these were weighed first dry, and then suspended in water. By using such large quantities averages were obtained of a rock which, minutely considered, is heterogeneous; and by using the blocks entire instead of pulverized or granulated, the state of aggregation of its minerals was included as an element of the specific gravity of the rock.

It will be observed that the range, 2.54 to 2.66, is very small.

Table of Specific Gravities of Trachytes of the Henry Mountains.

Locality.	Specific gravity.
East flank of Mount Pennell; sheet	2.66
Marvine Laccolite; north base of Mount Ellen	2.65
Peale Laccolite; east flank of Mount Ellen	2.64
Dike on Mount Ellsworth	2.64
South base of Mount Hillers; sheet	2.63
Sheet under the Peale Laccolite	2.62
Scrope Laccolite; southeast base of Mount Ellen	2.60
Bowl Creek Laccolite; northeast base of Mount Ellen	2.58
North spur of Mount Pennell; dike	2.58
Sentinel Laccolite; north base of Mount Pennell	2.54
Mean	2.61

Specimens to represent the stratigraphic series were selected at the *margins* of the disturbed region so far as possible, to avoid the effect of metamorphism. But as it was not practicable to eliminate this source of error in every case, the densities of highly metamorphic specimens were also measured for the purpose of indicating the effect of the metamorphism. In order to restore so far as practicable the condition of the rocks at the time of the lavic intrusion, the specimens were saturated with water, and in this condition were weighed in air as well as in water. The results for the porous sandstones are from one-seventh to one-fourteenth lower than would have been obtained by the usual method. Hand specimens were used as before.

Table of Specific Gravities of Sedimentary Rocks of the Henry Mountains.

	Rock.	Condition.	Specific gravity.
1	Masuk Sandstone	Unaltered	2.16
2	Blue Gate Sandstone	Unaltered	2.14
3	Blue Gate Shale	Unaltered	2.45
4	Flaming Gorge Shale	Unaltered	2.42
5	Gray Cliff Sandstone	Unaltered	2.13
6	Vermilion Cliff Sandstone, (top)	Unaltered (?)	2.21
7	Vermilion Cliff Sandstone, (base)	Unaltered (?)	2.28
8	Henry's Fork Conglomerate	Slightly altered	2.25
9	Vermilion Cliff Sandstone	Altered	2.48
10	Aubrey Sandstone	Altered	2.55
11	Tununk Shale	Altered	2.69

It is plain from this table that the effect of the metamorphism was to increase the densities of the rocks affected. The Blue Gate shale which *unaltered* gave 2.45, is lithologically identical with the Tununk shale which *altered* gave 2.69. The Aubrey sandstone cannot be observed unaltered in the vicinity of the mountains, but at a distance of forty miles where it again comes to the surface it closely resembles the Gray Cliff sandstone. If it has the same normal weight as the latter, then it has increased from 2.13 to 2.55.

The specimens of the Vermilion Cliff sandstone numbered 6 and 7 were not visibly changed, but as they were obtained from the flank of the Holmes arch there was reason to suspect that their condition was not normal, and the determined densities strengthen the suspicion. Judged by other localities, the normal density of the Vermilion Cliff rock is not far from that of the Gray Cliff rock, namely 2.13; and it is easy to believe that the upper portion of the bed where it lay on the side of the Holmes arch was changed in density to 2.21; while the lower portion lying nearer the laccolite was changed to 2.28; and while the same bed among the Ellsworth dikes acquired the density of 2.48.

Taking into account both these considerations and certain others which need not be enumerated, I derive the following:

Table of the Specific Gravities of the Henry Mountain Sedimentary series in the Order of Superposition.

Bed.	Specific gravity.
Masuk Sandstone	2.16
Masuk Shale .... estimated	2.40
Blue Gate Sandstone	2.14
Blue Gate Shale	2.45
Tununk Sandstone	2.15
Tununk Shale .... estimated	2.45
Henry's Fork Conglomerate	2.25
Flaming Gorge Shale	2.42
Gray Cliff Sandstone	2.13
Vermilion Cliff Sandstone .... estimated	2.15
Shinarump Shale .... estimated	2.40
Aubrey Sandstone .... estimated	2.15

Taking into account the thicknesses of the several beds enumerated in the foregoing table, it is easy to obtain the mean specific gravity of all which lie above a given horizon; and by making this determination for the horizon of the base of each of the indicated beds, the following table has been derived. The figures are based on the assumption that the rock series included nothing above the Masuk sandstone. If (as is probable) there were Tertiary beds also, the estimates are too low, for the Tertiaries of the vicinity are calcareous and argillaceous and consequently dense.

Table showing the Mean Specific Gravities of the Rock Series contained between certain horizons and the summit of the Masuk Sandstone.

Horizons.	Specific gravities.
Base of Masuk Sandstone	2.16
Base of Masuk Shale	2.28
Base of Blue Gate Sandstone	2.23
Base of Blue Gate Shale	2.32
Base of Tununk Sandstone	2.31
Base of Tununk Shale	2.34
Base of Henry's Fork Conglomerate	2.33
Base of Flaming Gorge Shale	2.36
Base of Gray Cliff Sandstone	2.33
Base of Vermilion Cliff Sandstone	2.32
Base of Shinarump Shale	2.33

From this it appears that the laccolites of the upper zone, extending from the lower part of the Blue Gate Shale to the upper part of the Flaming Gorge Shale, bore loads of which the mean densities were from 2.31 to 2.34, and that laccolites of the lower zone, which has its upper limit in the Shinarump Shale, bore loads of which the mean densities were 2.32 and upward. If the positions of the laccolites were determined purely by the law of hydrostatic equilibrium, then these figures define the density of the molten trachyte, and show that its contraction in cooling—from the density 2.34 to the density 2.61—was about one-tenth of its volume.

THE STRETCHING OF STRATA.

It has been the opinion, not only of the writer but of other students of the displacements of the West, that the ordinary sedimentary rocks, sandstone, limestone, and shale, are frequently *elongated* as well as compressed by orographic movements, and that this takes place without any appreciable metamorphism; but it is difficult to find opportunity for the demonstration of the phenomenon by measurement. When a fold is made in a level stratum, either of two things may take place; the portions of the stratum which remain level at the sides may approach each other; or the stratum may be stretched. But when a circular portion of a continuous level stratum is lifted into a quaquaversal arch (as illustrated in Figure 11), an approach of the level portions is out of the question, and there must be a stretching or a fracture. Of the unfractured quaquaversals of the Henry Mountains there is one which combines all the essentials of a crucial case. The Lesser Holmes arch is nearly isolated; on three sides it rises from the undisturbed plateau, and on the fourth it joins a similar but fractured dome.

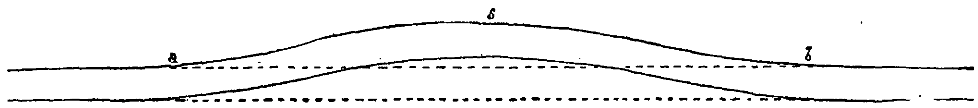


FIG. 52.—Cross-section of an uplifted dome. The dotted lines show the original position of a bed; the curved lines, the imposed.

The major part of its surface is composed of one bed, the Vermilion Cliff sandstone, broken only by erosion. Comparing the length of this bed in its present curved form with the space it must have occupied before it was upbent, I find that in a distance of three miles it has been elongated three hundred feet. Moreover there is every reason to suppose that the elongation was produced quickly, or at least by a succession of finite rather than infinitesimal increments; for the lifting of the arch was caused by the intrusion of a laccolite, and though the latter may have been built by the addition of many separate lava flows, it could not have risen with secular and continuous slowness. The molten trachyte, rising through a passage and into a reservoir that were comparatively cool, would have clogged itself by congelation had it not moved with a certain degree of rapidity.

The condition which rendered possible the elongation and the sudden bending of so rigid and brittle a rock as a massive sandstone, was PRESSURE. At the time of the uplift the sandstone was buried by other sediments to a depth of from five thousand to eight thousand feet, and sustained a pressure of from five thousand to eight thousand pounds to the square inch. Now the experiments which have been made upon building stones show that the weight required to crush similar sandstones in a dry condition, is three thousand to five thousand pounds to the inch; and it is a fact familiar to quarrymen that sandstone and limestone which are quarried below the water level are both softer and weaker while they are still saturated than they are after drying. So we may fairly assume that the Vermilion sandstone was loaded at the time of its displacement with a crushing weight. No part could yield to the pressure while it was sustained by the surrounding parts; but every part was ready to yield whenever its support was withdrawn. It was in a quasi-plastic state and abhorred a fissure as strongly as "nature abhors a vacuum", and for the same reason. A fissure could not be opened in it unless it was coincidently filled by something—such as lava—which would resist the tendency of its walls to flow together. The formation of a gaping fissure being thus prevented, and the uplifting of the dome requiring that the sandstone should cover a greater area, an extension of the bed was the necessary result. It was not *stretched* into the dome form; it was *compressed.* The efficient force did not act in the direction of the extension, but vertically. The sandstone was pushed, not pulled.

If this explanation is the true one, then it is true in general that just as for each rock there is a crushing weight, so there is for each rock a certain depth at which it cannot be fissured and can be flexed. The softer rocks are plastic at small depths. Fire-clays under coal-seams exude, or "creep", even with the pressure of a few feet of superincumbent strata. Springs of water rise at the outcroppings of soft strata because the joints which intersect most rocks near the surface of the ground cannot cross those which are soft enough to yield under the pressure incident to them. If the soft beds were jointed they would not intercept percolating water, and the distribution of springs would be very different.

The phenomena of fissure veins are in point. When a fault takes place, and one rock mass is slidden past another to which it had been joined it is usually the case that the opposed surfaces no longer fit together as they did before the movement, and interspaces are left. These become filled, at first by water, and afterward by minerals deposited from the water, and the mineral masses thus deposited are called fissure veins. But the preservation of the interspaces depends upon the rigidity of the rocks which inclose them; and it frequently happens that where a system of rocks is traversed by a fault, the harder will keep somewhat apart and maintain a fissure, while the softer will be crushed together without an interspace. If the mineral vein which forms in such a fissure is afterward explored in mining, it is found to be traceable and continuous so far as it is walled by the hard rock upon both sides, but when the hard is replaced by the soft in one or both walls, the vein is either reduced to a mere fillet or disappears completely. If the fault extends to a great depth, it will finally reach a region where the hardest rocks which it separates are coerced by so great a pressure that they cannot hold themselves asunder, but are forced together before the fissure can be filled by mineral deposits. Thus there is a definable inferior limit to the region of vein formation; and even while it is impossible to assign a downward limit to the fault which made place for a vein, it may be possible to assign a downward limit to the vein itself.

Accordant with this view is the absence of fissure veins from the Henry Mountains. Displacement and thermal disturbance are usually regarded as the conditions of mineral concentration; and here were displacement and lavic intrusion coincident in time and place. The heat which metamorphosed great bodies of shale and sandstone was surely competent to excite the currents and reactions which concentrate minerals in veins; but the displacements did not open fissures, and the heated water could circulate only through the pores of rocks. Fissure veins were impossible, and the sluggish currents which were engendered in continuous rock masses did not effect a great change in the distribution of minerals.

THE CONDITIONS OF ROCK FLEXURE.

There are three known conditions under which strata of the most rigid character may be bent without fracture; or in other words there are three ways in which flexibility may be either induced or demonstrated. At ordinary temperatures and at the surface of the earth a hard stratum cannot be quickly flexed. But no rigidity is absolute, and a constant strain, even though slight, will in the course of time produce deformation. The same result may be accomplished quickly if the temperature of the stratum is raised to near the point of fusion. Or it may be accomplished with neither great heat nor great time if only the stratum is so deeply buried that the weight of its cover keeps it from opening fissures. The three conditions of flexure are time, heat, and pressure; and whenever the circumstances of a displacement include none of these, the rocks are broken. A fourth condition, moisture, is of great importance as an accessory, but alone it is not sufficient to prevent fracture. The whole body of strata of the earth's crust is saturated with water, except a very little at the surface, and all rock movements are thereby facilitated. If the strata were dry, their flexure would require much more time, or heat, or pressure, than is necessary in their moist condition.

Often the three conditions complement each other; but not always.

We may say, the greater the load which strata bear the more rapidly they can be flexed; and conversely, the more slowly strata are displaced the less the pressure necessary to prevent fracture.

And we may say, the higher the temperature of strata the more rapidly they can be flexed; and conversely, the more slowly strata are displaced the lower the temperature necessary to prevent fracture.

For both these statements we find support in a great series of homologies. But we cannot affirm that such a reciprocal relation exists between the effects of heat and pressure. For all rocks are believed to expand by heating, up to the point of fusion; and it is a recognized physical law that in all bodies which heat expands, the effects of heat are opposed by pressure. Hence we cannot say, "The heavier the load which strata bear the lower the temperature necessary to prevent fracture", nor can we say, "The higher the temperature of strata the less the load necessary to prevent fracture".

THE QUESTION OF COVER AND THE QUESTION OF AGE.

It is evident that the laccolites of the Henry Mountains were formed beneath the surface of the earth's crust, but at what depth is not so evident. The problem is involved with the problem of the age of the laccolites, and the two are connected with the general history of the Basin of the Colorado. Neither problem can be called, for the present at least, determinate, but it is possible to narrow them down by the indication of limits which their solutions will not exceed.

So much of the Colorado Plateau region as lies within Colorado and Utah was covered during a geological age which it is convenient to call

Cretaceous, by a sea, the waters of which appear to have become fresh toward the last. Then came elevation both general and differential. A great part of the sea bed became dry land, and the accumulated sediments together with many which underlay them were bent into great waves thousands of feet in altitude. The crests of the waves were subjected to erosion and truncated. Then came a second submergence which was purely lacustrine. In some way that has not been ascertained a lake basin was formed, and the region received a new system of sediments which it is convenient to call Tertiary, and which not merely filled the troughs between the great rock-waves but covered the truncated summits of the waves themselves. Then followed the desiccation of the basin by the cutting down of its rim where the water overflowed. The overflowing river as it deepened its channel and gradually lowered the lake, steadily extended its upper course to follow the receding shore; and finally when the basin was completely drained the river remained, its channel leading through what had been the deepest part of the Tertiary sea. That river is the Colorado. As portions of the lake bottom were successively drained they began at once to be eroded, and from that time to this there has been progressive degradation. The regions nearest to the central river were reduced most rapidly and have been completely stripped of their Tertiary strata, but broad areas of the latter remain at the west, and north, and east.

(The reader will understand that this succinct history is shorn for the sake of clearness of all details and qualifications. There have been complicating eruptions and displacements or oscillations at every stage, and if the full story could be told, it would not be by a single paragraph nor by a single chapter.)

When the Cretaceous strata were thrown into waves the site of the Henry Mountains remained in a trough, and it probably was not dried, but continued the scene of sedimentation while the crests of the surrounding rock-waves were worn away. Certainly it was not greatly eroded at that time; and when the Tertiary lake beds were thrown down it was favorably disposed for a heavy deposit. It is not extravagant to assume that four thousand feet of lake beds rested on the Masuk sandstone at the beginning of the final desiccation.

In brief there may be distinguished—

1. The deposition of the Cretaceous.
2. The folding and erosion of the Cretaceous.
3. The deposition of the Tertiary.
4. The desiccation of the Tertiary lake basin.
5. The erosion which is still in progress.

It is evident that the laccolites were not formed until the Cretaceous strata had been deposited; for their uplifts have bent and tilted all Cretaceous rocks up to and including the Masuk sandstone.

They were not formed at any late stage of the final erosion, for they conserve tables along their western base, which but for their shelter would long since have disappeared. From the end of the Cretaceous period to the end of the desiccation of the basin there is no event with which the laccolites can be directly connected. There is however a consideration which in an indirect way sanctions the opinion that the epoch of igneous activity was after the deposition of the Tertiaries and before their erosion.

The Masuk Sandstone is at once the summit of the Cretaceous and the highest bed in the present Henry Mountain section. If it were restored over the entire range, the laccolites of the upper zone would have on the average thirty-five hundred feet of cover, and those of the lower zone nearly seven thousand feet. This was the depth of their original cover, if they were intruded at the close of the Cretaceous age. During the epoch of Tertiary deposition and the subsequent epoch of erosion, the cover first increased in depth and then diminished, having its maximum at the end of the Tertiary deposition. If it can be shown that the original cover of the upper laccolites exceeded thirty-five hundred feet, the question of age will be reduced to comparatively narrow limits. In order to discuss the problem of the original depth of cover it will be necessary to consider another matter, of which the connection will not at first be apparent.

The size of laccolites.—It is a matter worthy of note that no laccolite of inconsiderable extent is known in the Henry Mountains. The smallest which has been measured is more than half a mile in diameter, and the largest about four miles. The phenomenon does not occur upon a small scale, but has a definite inferior limit to its magnitude. Let us seek an explanation of this limit.

The dome of strata which covers a laccolite has for its profile on every side a monoclinal curve. In Figure 52 the section of a dome exhibits a monoclinal flexure in *s a* and again in *s b;* and the dome being approximately circular this flexure completely surrounds it. We may even describe or define the dome as a monoclinal flexure encircling a point or a space. Considering now that when the laccolite was injected the overlying strata were lifted, and that this disturbance was communicated upward to the then existing surface of the earth, we may properly speak of the lifted body of rock as a cylinder bounded on every side by a monoclinal flexure. Furthermore, since the monoclinal flexure is the structural equivalent of the fault*, we may render our conception still simpler by replacing in imagination the encircling flexure by an encircling fault, and picturing to ourselves the uplifted rock mass as a simple cylinder, perfectly divided from the surrounding rock and slidden upward so as to project above the surface an amount equal to the depth of the laccolite.

It is possible to give a mathematical expression to the force necessary to produce such a circular fault. Disregarding lithologic differences, the resistance to the rupture is measured by the area of the faulted surface, or what is the same thing, the area of the convex surface of the cylinder. Representing the resistance to be overcome by r, the height of the cylinder (equal to the depth of the cover of the laccolite) by d, and its circumference by c, we have

$$r = d\,c\,C \qquad (1),$$

in which C is a function of the cohesion of the material and is constant.

The force by which the cylinder is lifted and by which it is assumed that the faulting is accomplished, is communicated through the molten lava of the forming laccolite. Being thus communicated it is applied equally to all parts of the base of the cylinder, and its efficient total is measured

* Exploration of the Colorado, pp. 182–184. Explorations West of the 100th Meridian, Vol. III, p. 48. American Journal of Science, July, 1876, p. 21.

by the area of that base. A part of it is devoted to lifting the weight of the cylinder, and the remainder is devoted to the making of the fault. Each of these parts is proportioned, like the whole, to the area of the base of the cylinder, or to the area of the laccolite. Representing the portion applied to the faulting by f, and the area of the laccolite by a, we have

$$f = a\, C_{\prime}$$

in which $C_{\prime}$ is a constant, and a function of the pressure under which the lava is injected.

Substituting for a its equivalent, $\frac{c^2}{4\pi}$

$$f = \frac{c^2\, C_{\prime}}{4\pi}$$

and substituting $C_{\prime\prime}$ for the constant term $\frac{C_{\prime}}{4\pi}$

$$f = c^2\, C_{\prime\prime} \qquad (2)$$

Equation 1 gives an expression for the resistance which cohesion can oppose to the uplift of the cylinder. Equation 2 gives an expression for the force exerted by the fluid laccolite toward overcoming the resistance of cohesion. It is evident that for a given value of d it is possible to assign a value of C so large that f will be greater than r, or so small that f will be less than r. That is to say, at a given depth beneath the surface a laccolite of a certain circumference will be able to force upward the superjacent cylinder of rock, while a laccolite of a certain smaller circumference will be unable to lift its cover. Or in other words, there is a limit in size beneath which a laccolite cannot be formed.

When a lava forced upward through the strata reaches the level at which under the law of hydrostatic equilibrium it must stop, we may conceive that it expands along some plane of bedding in a thin sheet, until its horizontal extent becomes so great that it overcomes the resistance offered by the rigidity of its cover, and it begins to uplift it. The direction of least resistance is now upward, and the reservoir of lava increases in depth instead of width. The area of a laccolite thus tends to remain at its minimum limit, and may be regarded as more or less perfectly an index of that limit.

In equations 1 and 2, if $f = r$, then

$$c^2 C_{,,} = d\, c\, C$$

or

$$c = d \frac{C}{C_{,,}} \qquad (3)$$

That is to say, if the force exerted by the lava is barely sufficient to overcome the resistance to uplift, then the circumference of the laccolite is proportional to the depth of its cover. Or in other words, the (linear) size of a laccolite is proportioned to its depth beneath the surface.

If now we return from the faulted cylinder which for simplicity's sake has been hypothecated, to the actual cylinder which is surrounded by a flexure instead of a fault, can we retain our conclusions? With certain modifications I think we can. The strains developed in deformation by flexure are less easy of analysis than those which arise in faulting, but the two cases are in some degree analogous.

The expression (equation 2) for the force which the lava applies to deformation is unaffected by the manner in which the strata yield.

The expression (equation 1) for the resistance to deformation by faulting involves two terms, each in its simplest relations; the resistance varies directly as the circumference of the laccolite, and it varies directly as the depth of the cover. In order to pass to an expression for the resistance to deformation by flexure, only one of these terms need be changed. The resistance bears the same relation to the circumference of the laccolite; but it is no longer simply proportional to the depth of the cover. It varies more rapidly.

If the covering strata were all of a given thickness, were identical in kind, and were free to slide upon each other without friction, their total resistance to deformation would be equal to the resistance of a single stratum multiplied by the number of strata. But since they are not free to slide one upon another, they sustain each other, and the resistance offered by the combination is greater than that product.

I am led by the analogy of allied problems in mechanics to assume that the resistance of the body of strata varies with some power of its depth, but I am unable to say *what* power. So far as I am aware, neither mathematical analysis nor experimentation has been directed to the problem in question. According to Rankine "the resistances of flexure of similar cross-sections [of elastic beams] are as their breadths and as the *squares* of their depths" ("Applied Mechanics", page 316), and it is possible that the same law applies to the resistances which continuous strata oppose to the uplifts of domes. But it appears more probable that the greater complexity of the strains developed in the formation of domes causes the depth to enter into the formula with a higher power than the second.

On the other hand, some allowance should be made for the fact that the elasticity of the resisting strata is imperfect.

If we call the power with which the depth enters the formula a, equation 1 becomes

$$r = d^a \, c \, C_{\prime\prime\prime} \qquad (4).$$

and equation 3 becomes

$$c = d^a \frac{C_{\prime\prime\prime}}{C_{\prime\prime}} \qquad (5).$$

It is probable that the true value of a is not less than 2, nor more than 3.

Interpreting these equations in the same manner as those applying to deformation by faulting, we reach the following conclusions:

1st. At a given depth beneath the surface, lava injected under a given pressure cannot form a laccolite of less than a certain area. This may be called its *limital area.*

2d. The pressure of injection remaining constant, the limital area of a laccolite is a direct function of its depth beneath the surface. The limital area is greater when the depth is greater, and less when the depth is less.

3d. A laccolite of small volume will not exceed the limital area, but will grow by lifting its cover. If however the volume of intruded lava be great, its own weight becomes a factor in the equilibrium of forces and modifies the distribution of the pressures. As the rock bubble rises, the weight of the contained fluid is progressively subtracted from the pressure against its top, and this proceeds until the upward and lateral pressures become proportional to the resistances which severally oppose them. Further expansion is then both upward and outward.

4th. There is a limit to upward expansion, dependent on the fact that the pressure due to the combined weight of the laccolite and cover cannot exceed the pressure of the intrusive lava. Regarding the intrusive pressure as constant, it is divisible into three parts, of which one sustains the weight of the cover, also constant; another sustains the weight of the fluid laccolite, and is measured by its thickness or depth; and the third produces deformation. When the sum of the weights of the cover and laccolite equals the total pressure of the intrusive lava, uplift ceases, and the maximum depth or thickness is attained. We may call this the *limital thickness.* With regard to simple laccolites the limit is absolute, but it applies only to the distinct layers of those which are composite; for a composite laccolite, built by successive intrusions at wide intervals of time, may be relieved of part of its load by the erosion of the mound which its expansion causes at the surface of the land.

A laccolite formed beneath the bottom of a sea has a greater limital thickness than one formed beneath a land surface; for the superjacent water being displaced and thrust aside, is to that extent subtracted from the load to be lifted.

5th. The laccolite in its formation is constantly solving a problem of "least force", and its form is the result. Below, above, and on all sides its expansion is resisted, and where the resistance is greatest its contour is least convex. The floor of its chamber is unyielding, and the bottom of the laccolite is flat. The roof and walls alike yield reluctantly to the pressure, but the weight of the lava diminishes its pressure on the roof. Hence the top of the laccolite becomes broadly convex, and its edges acutely. Local accidents excepted, the walls oppose an equal resistance on every side; and the base of the laccolite is rendered circular.

The second of the conclusions enunciated above is susceptible of test by observation. By selecting those laccolites of which the dimensions are known with the best degree of approximation, the following table has been formed:

	Formations.	Titles of Laccolites.	Diameters in miles.	Means.	
Upper Zone	Blue Gate Shale	Sentinel	.7	.7	1.2
	Tununk Shale	Geikie	.8	1.2	
		A	.9		
		Marvine	1.0		
		Jukes	1.4		
		Peale	1.8		
	Flaming Gorge Shale	Steward	1.0	1.4	
		B	1.1		
		Newberry	1.8		
		C	1.9		
Lower Zone		Dana	2.0		2.6
		Greater Holmes	2.1		
		Lesser Holmes	2.1		
		Ellsworth	2.3		
		Pulpit	2.3		
		Maze	2.8		
		Crescent	3.6		
		Hillers	3.9		

There is no laccolite of the upper zone so large as the smallest in the lower zone; and the mean diameter of those in the lower zone is double the mean of those in the upper. The measurements do not give the diameters of limital areas, but it is presumable that the actual areas bear substantially the same relation to the limital in the two zones. If we select the smallest laccolites in each group as those most likely to express the limital areas, the result is practically the same.

	Formations.	Diameters.	Means.	
Upper Zone	Tununk Shale	.8 .9 1.0	.9	1.0
	Flaming Gorge Shale	1.0 1.1	1.05	
Lower Zone		2.0 2.1 2.1		2.1

The mean for the lower zone is still double the mean for the upper.

The confirmation of the conclusion is as nearly perfect as could have been anticipated. There is no room to doubt that a relation exists between the diameters of laccolites and the depths of their intrusion.

Having determined by observation the mean size of the laccolites in the upper and lower zones, as well as the interval which separates the two zones, and knowing approximately the law which binds the size of the laccolite to its depth of intrusion, we can compute the depth of intrusion of each zone. Our result will doubtless have a large probable error, but it will not be entirely without value.

Let x represent the thickness in feet of the original cover of the laccolites of the upper zone; and $x + 3300$ the thickness of the cover of the laccolites of the lower zone. The mean circumference in feet of the upper laccolites is $1.2\,\pi \times 5280 = 6336\,\pi$. The mean circumference of the lower laccolites is $2.6\,\pi \times 5280 = 13728\,\pi$. Substituting these values in equation 5, we obtain

$$6336\,\pi = x^{a}\,\frac{C_{\prime\prime\prime}}{C_{\prime\prime}}$$

and

$$13728\,\pi = (x + 3300)^{a}\,\frac{C_{\prime\prime\prime}}{C_{\prime\prime}}$$

Dividing the second equation by the first and reducing,

$$x = \frac{3300}{\sqrt[a]{\frac{13728}{6336}} - 1} \qquad (6).$$

To obtain a minimum result, assume $a = 2$; then

$$x = \frac{3300}{\sqrt{\frac{13728}{6336}} - 1} = 7000 \text{ feet,}$$

and $$x + 3300 = 10300 \text{ feet.}$$

The summit of the Masuk sandstone is 3,500 feet above the mean level of the upper laccolites; subtracting this from the value of x gives 3,500 feet as the depth of Tertiary strata which overlay the Masuk beds during the epoch of laccolitic intrusion.

To obtain a maximum result, assume $a = 3$; then

$$x = \frac{3300}{\sqrt[3]{\frac{13728}{6336}} - 1} = 11200 \text{ feet,}$$

$$x + 3300 = 14500 \text{ feet,}$$

and the result for the depth of the Tertiary strata is 7,700 feet.

I am far from attaching great weight to this speculation in regard to the original depths of the laccolite covers. It is always hazardous to attempt the quantitative discussion of geological problems, for the reason that the conditions are apt to be both complex and imperfectly known; and in this case an uncertainty attaches to the law of relation, as well as to the quantities to which it is applied. Nevertheless after making every allowance there remains a presumption that the cover of the laccolites included some thousands of feet of Tertiary sediments.

What evidence we have then, indicates that the epoch of laccolitic intrusion was after the accumulation of deep Tertiary deposits and before the subsequent degradation had made great progress—that it was at or near the close of the epoch of local Tertiary sedimentation.

If the reader would realize the relation between the eroded material and the surviving mountains, let him turn to the Frontispiece. A perspective view is there given of a tract ten miles square, with Mount Ellsworth in the center. It is represented as cut out from all surroundings by vertical planes which descend to the level of the ocean. The southern or nearer half of the block shows the present aspect of the country; the remote half shows the form it is supposed to have had if the uplift was completed before the erosion began, or what is the same thing, the form it would have, had there been no erosion. The difference between the two represents the total amount of the material that has been washed away since the completion of the Tertiary sediments.

Partly in review, let us now sketch the

HISTORY OF THE LACCOLITE.

When lavas forced upward from lower-lying reservoirs reach the zone in which there is the least hydrostatic resistance to their accumulation, they cease to rise. If this zone is at the top of the earth's crust they build volcanoes; if it is beneath, they build laccolites. Light lavas are more apt to produce volcanoes; heavy, laccolites. The porphyritic trachytes of the Plateau Province produced laccolites.

The station of the laccolite being decided, the first step in its formation is the intrusion along a parting of strata, of a thin sheet of lava, which spreads until it has an area adequate, on the principle of the hydrostatic press, to the deformation of the covering strata. The spreading sheet always extends itself in the direction of least resistance, and if the resistances are equal on all sides, takes a circular form. So soon as the lava can uparch the strata it does so, and the sheet becomes a laccolite. With the continued addition of lava the laccolite grows in height and width, until finally the supply of material or the propelling force so far diminishes that the lava clogs by congelation in its conduit and the inflow stops. An irruption is then complete, and the progress of the laccolite is comparable with that of a volcano at the end of its first eruption. During the irruption and after its completion, there is an interchange of temperatures. The laccolite cools and solidifies; its walls are heated and metamorphosed. At the edges, where the surface of the laccolite is most convex, the heat is most rapidly dissipated, and its effect in metamorphism is least. A second irruption may take place either before or after the first is solidified. It may intrude above or it may intrude beneath it; and observation has not yet distinguished the one case from the other. In any case it carries forward the deformation of cover that was begun by the first, and combines with it in such way that the compound form is symmetric, and is substantially the same that would have been produced if the two irruptions were combined in one. Thus the laccolite grows by successive accretions until at length its cooled mass, heavier and stronger than the surrounding rocks, proves a sufficient obstacle to intrusion. The next irruption then avoids it, opens a new conduit, and builds a new laccolite at its side. By successive shiftings of the conduit a group of laccolites is formed, just as by the shifting of vents eruptive cones are grouped. Each laccolite is a subterranean volcano.

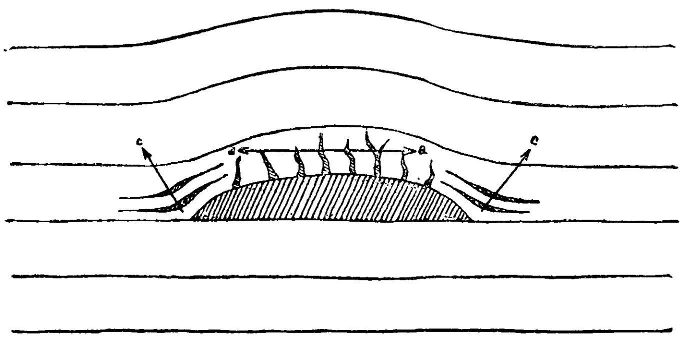


Fig. 53, Diagram to illustrate the relation of Dikes and Sheets to the Strains which are developed in the uplifting of laccolitic arches.

The strata above the laccolite are bent instead of broken, because their material is subjected to so great a pressure by superincumbent strata that it cannot hold an open fissure and is *quasi-plastic.* But although quasi-plastic it is none the less solid, and can be cracked open if the gap is instantaneously filled, the cracking and the filling being one event. This happens in the immediate walls of the laccolite, and they are injected by dikes and sheets of the lava. The directions of the cracks are normal to the directions of the extensive strains (strains tending to extend) where they occur. From the top of the laccolite dikes run upward into the roof, marking horizontal strains (*a a*). From the sides smaller vertical dikes run outward, marking horizontal, tangential strains. And parallel to the sides near the base of the laccolite, are numerous sheets, marking strains directed outward and upward (*c c*). These last especially serve to show that the rigidity of the strata is not abolished, although it is overpowered, by the pressure which warps them.

Here we are brought face to face with a great fact of dynamic geology which though well known is too often ignored. The solid crust of the earth, and the solid earth if it be solid, are as plastic *in great masses* as wax is in small. Solidity is not absolute but relative. It is only a low grade of plasticity. The rigidity or strength of a body is measured by the square of its linear dimensions, while its weight is measured by the cube. Hence with increase in magnitude, the weight increases more rapidly than the strength; and no very large body is strong enough to withstand the pressure of its own weight. However solid it may be, it must succumb and be flattened. When we speak of rock masses which are measured by feet, we may regard them as solid; but when we consider masses which are measured by miles, we should regard them as plastic.

The same principle is illustrated by the limital area of laccolites. A small laccolite cannot lift its small cover, but a large laccolite can lift its correspondingly large cover The strength or rigidity which resists deformation is overcome by magnitude.

Laccolites of Other Regions.—In many lands geologists have observed intrusive rocks occurring in great bodies, but I am not aware that such a system as that of the Henry Mountains has ever been described. Doubtless all such bodies are laccolitic, but the combination of conditions which this field presents can rarely be repeated. In the first place the strata which here contain the laccolites lay level. They had suffered no displacement before the epoch of irruption, and they have suffered none since. The laccolitic phenomena stand by themselves, with nothing to mar their symmetry or complicate their study. In the next place the laccolites are here assembled in such number and with such variety of size, form, and horizon that there is little danger of mistaking accidental features for essential. Again, the region having been recently elevated is the scene of rapid degradation. Waterways are deeply corraded, slopes are steep, and escarpments abound. And finally the climate is so arid that vegetation is exceedingly scant. The rocks are for the most part bare and their examination is unobstructed.

If the conditions of erosion and climate had been unfavorable in the Henry Mountains, they could not have yielded the key to the laccolitic structure; but the key once found, it is to be anticipated that the structure will be recognized in other laccolites of which the exposures are less perfect.

If the strata had experienced anterior displacements so as to be inclined, folded, and faulted, a symmetrical growth of laccolites would have been impossible, and the mountains would not have yielded a knowledge of the type form. But the type form being known, it is to be anticipated that in disturbed regions aberrant forms will be recognized and referred to the type.

Possible Analogues of the Laccolite.—All the arches of the Henry Mountains have been ascribed to laccolites, whether their nuclei were visible or concealed, and the evidence upon which the latter were included appears to admit of no controversy. The question arises whether the great flexures of the Plateau region may not be allied in structure. The volcano having its homologue in the laccolite, may not broad lava fields have their homologues beneath displacements of the Kaibab type?

The idea is naturally attractive to one who has made a special study of laccolites, but it is hardly tenable. There are indeed many points of resemblance between such flexures as the Waterpocket, and the uplifts of the Henry Mountains; but the points of contrast are equally conspicuous, and seem to mark a radical difference.

There is a certain symmetry of form which is characteristic of the laccolitic arches, but which is rarely seen in the great flexures. And there is a linear element which is characteristic of the latter, but not of the former. The great flexures always have direction or trend, and often exhibit parallelism; the laccolitic arches betray no trend either individually or collectively.

These features are well shown in Plate II, where the Waterpocket flexure is contrasted with the Henry Mountain arches.

CHAPTER V.

LAND SCULPTURE.

The Basin of the Colorado offers peculiar facilities for the study of the origin of topographic forms, and its marvelous sculpture has excited the interest of every observer. It has already made notable contributions to the principles of earth sculpture*, and its resources are far from exhausted. The study of the Henry Mountains has not proved entirely unfruitful, and for the sake of showing the bearing of its peculiar features upon the general subject, I shall take the liberty to restate certain principles of erosion which have been derived or enforced by the study of the Colorado Plateaus.

I.—EROSION.

The sculpture and degradation of the land are performed partly by shore-waves, partly by glaciers, partly by wind; but chiefly by rain and running water. The last mentioned agencies only will be here discussed.

The erosion which they accomplish will be considered (A) as consisting of parts, and (B) as modified by conditions.

A. PROCESSES OF EROSION.

All indurated rocks and most earths are bound together by a force of cohesion which must be overcome before they can be divided and re-

* Geology of the "Colorado Exploring Expedition", by J. S. Newberry, p. 45.

"Exploration of the Colorado River of the West", by J. W. Powell, p. 152.

"Geology of the Uinta Mountains", by J. W. Powell, p. 181.

"Explorations West of the 100th Meridian", Vol. III, Part I, by G. K. Gilbert, pp. 67 and 554.

"The Colorado Plateau Region" in American Journal of Science for August, 1876, by G. K. Gilbert.

A portion of the last paper is repeated, after modification, in the first section of this chapter.

moved. The natural processes by which the division and removal are accomplished make up erosion. They are called disintegration and transportation.

Transportation is chiefly performed by running water.

Disintegration is naturally divided into two parts. So much of it as is accomplished by running water is called corrasion, and that which is not, is called weathering.

Stated in their natural order, the three general divisions of the process of erosion are (1) *weathering*, (2) *transportation*, and (3) *corrasion*. The rocks of the general surface of the land are disintegrated by *weathering*. The material thus loosened is *transported* by streams to the ocean or other receptacle. In transit it helps to *corrade* from the channels of the streams other material, which joins with it to be transported to the same goal.

Weathering.

In weathering the chief agents of disintegration are solution, change of temperature, the beating of rain, gravity, and vegetation.

The great solvent of rocks is water, but it receives aid from some other substances of which it becomes the vehicle. These substances are chiefly products of the formation and decomposition of vegetable tissues. Some rocks are disintegrated by their complete solution, but the great majority are divided into grains by the solution of a portion; and fragmental rocks usually lose by solution the cement merely, and are thus reduced to their original incoherent condition.

The most rigid rocks are cracked by sudden changes of temperature; and the crevices thus begun are opened by the freezing of the water within them. The coherence of the more porous rocks is impaired and often destroyed by the same expansive force of freezing water.

The beating of the rain overcomes the feeble coherence of earths, and assists solution and frost by detaching the particles which they have partially loosened.

When the base of a cliff is eroded so as to remove or diminish the support of the upper part, the rock thus deprived of support is broken off in blocks by gravity. The process of which this is a part is called cliff-erosion or *sapping.*

Plants often pry apart rocks by the growth of their roots, but their chief aid to erosion is by increasing the solvent power of percolating water.

In general soft rocks weather more rapidly than hard.

Transportation.

A portion of the water of rains flows over the surface and is quickly gathered into streams. A second portion is absorbed by the earth or rock on which it falls, and after a slow underground circulation reissues in springs. Both transport the products of weathering, the latter carrying dissolved minerals and the former chiefly undissolved.

Transportation is also performed by the direct action of gravity. In sapping, the blocks which are detached by gravity are by the same agency carried to the base of the cliff.

Corrasion.

In corrasion the agents of disintegration are solution and mechanical wear. Wherever the two are combined, the superior efficiency of the latter is evident; and in all fields of rapid corrasion the part played by solution is so small that it may be disregarded.

The mechanical wear of streams is performed by the aid of hard mineral fragments which are carried along by the current. The effective force is that of the current; the tools are mud, sand, and bowlders. The most important of them is sand; it is chiefly by the impact and friction of grains of sand that the rocky beds of streams are disintegrated.

Streams of clear water corrade their beds by solution. Muddy streams act partly by solution, but chiefly by attrition.

Streams transport the combined products of corrasion and weathering. A part of the *débris* is carried in solution, and a part mechanically. The finest of the undissolved detritus is held in suspension; the coarsest is rolled along the bottom; and there is a gradation between the two modes. There is a constant comminution of all the material as it moves, and the work of transportation is thereby accelerated. Bowlders and pebbles, while they wear the stream-bed by pounding and rubbing, are worn still more rapidly themselves. Sand grains are worn and broken by the continued jostling, and their fragments join the suspended mud. Finally the detritus is all more or less dissolved by the water, the finest the most rapidly.

In brief, weathering is performed by solution; by change of temperature, including frost; by rain beating; by gravity; and by vegetation. Transportation is performed chiefly by running water. Corrasion is performed by solution, and by mechanical wear.

Corrasion is distinguished from weathering chiefly by including mechanical wear among its agencies, and the importance of the distinction will be apparent when we come to consider how greatly and peculiarly this process is affected by modifying conditions.

B. CONDITIONS CONTROLLING EROSION.

The chief conditions which affect the rapidity of erosion are (1) declivity, (2) character of rock, and (3) climate.

Rate of Erosion and Declivity.

In general *erosion is most rapid where the slope is steepest;* but weathering, transportation, and corrasion are affected in different ways and in different degrees.

With increase of slope goes increase in the velocity of running water, and with that goes increase in its power to transport undissolved detritus.

The ability of a stream to corrade by solution is not notably enhanced by great velocity; but its ability to corrade by mechanical wear keeps pace with its ability to transport, or may even increase more rapidly. For not only does the bottom receive more blows in proportion as the quantity of transient detritus increases, but the blows acquire greater force from the accelerated current, and from the greater size of the moving fragments. It is necessary however to distinguish the ability to corrade from the rate of corrasion, which will be seen further on to depend largely on other conditions.

Weathering is not directly influenced by slope, but it is reached indirectly through transportation. Solution and frost, the chief agents of rock decay, are both retarded by the excessive accumulation of disintegrated rock. Frost action ceases altogether at a few feet below the surface, and solution gradually decreases as the zone of its activity descends and the circulation on which it depends becomes more sluggish. Hence the rapid removal of the products of weathering stimulates its action, and especially that portion of its action which depends upon frost. If however the power of transportation is so great as to remove completely the products of weathering, the work of disintegration is thereby checked; for the soil which weathering tends to accumulate is a reservoir to catch rain as it reaches the earth and store it up for the work of solution and frost, instead of letting it run off at once unused.

Sapping is directly favored by great declivity.

In brief, a steep declivity favors transportation and thereby favors corrasion. The rapid, but partial, transportation of weathered rock accelerates weathering; but the complete removal of its products retards weathering.

Rate of Erosion and Rock Texture.

Other things being equal, *erosion is most rapid when the eroded rock offers least resistance;* but the rocks which are most favorable to one portion of the process of erosion do not necessarily stand in the same relation to the others. Disintegration by solution depends in large part on the solubility of the rocks, but it proceeds most rapidly with those fragmental rocks of which the cement is soluble, and of which the texture is open. Disintegration by frost is most rapid in rocks which absorb a large percentage of water and are feebly coherent. Disintegration by mechanical wear is most rapid in soft rocks.

Transportation is most favored by those rocks which yield by disintegration the most finely comminuted *débris.*

Rate of Erosion and Climate.

The influence of climate upon erosion is less easy to formulate. The direct influences of temperature and rainfall are comparatively simple, but their indirect influence through vegetation is complex, and is in part opposed to the direct.

Temperature affects erosion chiefly by its changes. Where the range of temperature includes the freezing point of water, frost contributes its powerful aid to weathering; and it is only where changes are great and sudden that rocks are cracked by their unequal expansion or contraction.

All the processes of erosion are affected directly by the amount of rainfall, and by its distribution through the year. All are accelerated by its increase and retarded by its diminution. When it is concentrated in one part of the year at the expense of the remainder, transportation and corrasion are accelerated, and weathering is retarded.

Weathering is favored by abundance of moisture. Frost accomplishes most when the rocks are saturated; and solution when there is the freest subterranean circulation. But when the annual rainfall is concentrated into a limited season, a larger share of the water fails to penetrate, and the gain from temporary flooding does not compensate for the checking of all solution by a long dry season.

Transportation is favored by increasing water supply as greatly as by increasing declivity. When the volume of a stream increases, it becomes at the same time more rapid, and its transporting capacity gains by the increment to velocity as well as by the increment to volume. Hence the increase in power of transportation is more than proportional to the increase of volume.

It is due to this fact chiefly that the transportation of a stream which is subject to floods is greater than it would be if its total water supply were evenly distributed in time.

The indirect influence of rainfall and temperature, by means of vegetation, has different laws. Vegetation is intimately related to water supply. There is little or none where the annual precipitation is small, and it is profuse where the latter is great—especially where the temperature is at the same time high. In proportion as vegetation is profuse the solvent power of percolating water is increased, and on the other hand the ground is sheltered from the mechanical action of rains and rills. The removal of disintegrated rock is greatly impeded by the conservative power of roots and fallen leaves, and a soil is thus preserved. Transportation is retarded. Weathering by solution is accelerated up to a certain point, but in the end it suffers by the clogging of transportation. The work of frost is nearly stopped as soon as the depth of soil exceeds the limit of frost action. The force of rain drops is expended on foliage. Moreover a deep soil acts as a distributing reservoir for the water of rains, and tends to equalize the flow of streams.

Hence the general effect of vegetation is to retard erosion; and since the direct effect of great rainfall is the acceleration of erosion, it results that its direct and indirect tendencies are in opposite directions.

In arid regions of which the declivities are sufficient to give thorough drainage, the absence of vegetation is accompanied by absence of soil. When a shower falls, nearly all the water runs off from the bare rock, and the little that is absorbed is rapidly reduced by evaporation. Solution becomes a slow process for lack of a continuous supply of water, and frost accomplishes its work only when it closely follows the infrequent rain. Thus weathering is retarded. Transportation has its work so concentrated by the quick gathering of showers into floods, as to compensate, in part at least, for the smallness of the total rainfall from which they derive their power.

Hence in regions of small rainfall, surface degradation is usually limited by the slow rate of disintegration; while in regions of great rainfall it is limited by the rate of transportation. There is probably an intermediate condition with moderate rainfall, in which a rate of disintegration greater than that of an arid climate is balanced by a more rapid transportation than consists with a very moist climate, and in which the rate of degradation attains its maximum.

Over nearly the whole of the earth's surface there is a soil, and wherever this exists we know that the conditions are more favorable to weathering than to transportation. Hence it is true in general that the conditions which limit transportation are those which limit the general degradation of the surface.

To understand the manner in which this limit is reached it is necessary to look at the process by which the work is accomplished.

Transportation and Comminution.

A stream of water flowing down its bed expends an amount of energy that is measured by the quantity of water and the vertical distance through which it descends. If there were no friction of the water upon its channel the velocity of the current would continually increase; but if, as is the usual case, there is no increase of velocity, then the whole of the energy is consumed in friction. The friction produces inequalities in the motion of the water, and especially induces subsidiary currents more or less oblique to the general onward movement. Some of these subsidiary currents have an upward tendency, and by them is performed the chief work of transportation. They lift small particles from the bottom and hold them in suspension while they move forward with the general current. The finest particles sink most slowly and are carried farthest before they fall. Larger ones are barely lifted, and are dropped at once. Still larger are only half lifted; that is, they are lifted on the side of the current and rolled over without quitting the bottom. And finally there is a limit to the power of every current, and the largest fragments of its bed are not moved at all.

There is a definite relation between the velocity of a current and the size of the largest bowlder it will roll. It has been shown by Hopkins that the weight of the bowlder is proportioned to the sixth power of the velocity. It is easily shown also that the weight of a suspended particle is proportioned to the sixth power of the velocity of the upward current that will prevent its sinking. But it must not be inferred that the total load of detritus that a stream will transport bears any such relation to the rapidity of its current. The true inference is, that the velocity determines the size-limit of the detritus that a stream can move by rolling, or can hold in suspension.

Every particle which a stream lifts and sustains is a draft upon its energy, and the measure of the draft is the weight (weighed in water) of the particle, multiplied by the distance it would sink in still water in the time during which it is suspended. If for the sake of simplicity we suppose the whole load of a stream to be of uniform particles, then the measure of the energy consumed in their transportation is their total weight multiplied by the distance one of them would sink in the time occupied in their transportation. Since fine particles sink more slowly than coarse, the same consumption of energy will convey a greater load of fine than of coarse.

Again, the energy of a clear stream is entirely consumed in the friction of flow; and the friction bears a direct relation to its velocity. But if detritus be added to the water, then a portion of its energy is diverted to the transportation of the load; and this is done at the expense of the friction of flow, and hence at the expense of velocity. As the energy expended in transportation increases, the velocity diminishes. If the detritus be composed of uniform particles, then we may also say that as the load increases the velocity diminishes. But the diminishing velocity will finally reach a point at which it can barely transport particles of the given size, and when this point is attained, the stream has its maximum load of detritus of the given size. But fine detritus requires less velocity for its transportation than coarse, and will not so soon reduce the current to the limit of its efficiency. A greater percentage of the total energy of the stream can hence be employed by fine detritus than by coarse.

(It should be explained that the friction of flow is in itself a complex affair. The water in contact with the bottom and walls of the channel develops friction by flowing past them, and that which is farther away by flowing past that which is near. The inequality of motion gives rise to cross currents and there is a friction of these upon each other. The ratio or coefficient of friction of water against the substance of the bed, the coefficient of friction of water against water, or the viscosity of water, and the form of the bed, all conspire to determine the resistance of flow and together make up what may be called the coefficient of the friction of flow. The friction depends on its coefficient and on the velocity.)

Thus the capacity of a stream for transportation is enhanced by comminution in two ways. Fine detritus, on the one hand, consumes less energy for the transportation of the same weight, and on the other, it can utilize a greater portion of the stream's energy.

It follows, as a corollary, that the velocity of a fully loaded stream depends *(ceteris paribus)* on the comminution of the material of the load. When a stream has its maximum load of fine detritus, its velocity will be less than when carrying its maximum load of coarse detritus; and the greater load corresponds to the less velocity.

It follows also that a stream which is supplied with heterogeneous *débris* will select the finest. If the finest is sufficient in quantity the current will be so checked by it that the coarser cannot be moved. If the finest is not sufficient the next grade will be taken, and so on.

Transportation and Declivity.

To consider now the relation of declivity to transportation we will assume all other conditions to be constant. Let us suppose that two streams have the same length, the same quantity of water, flow over beds of the same character, and are supplied to their full capacities with detritus of the same kind; but differ in the total amount of fall. Their declivities or rates of fall are proportional to their falls. Since the energy of a stream is measured by the product of its volume and its fall, the relative energies of the two streams are proportional to their falls, and hence proportional to their declivities. The velocities of the two streams, depending, as we have seen above, on the character of the detritus which loads them, are the same; and hence the same amount of energy is consumed by each in the friction of flow. And since the energy which each stream expends in transportation is the residual after deducting what it spends in friction from its total energy, it is evident that the stream with the greater declivity will not merely have the greater energy, but will expend a less percentage of it in friction and a greater percentage in transportation.

Hence declivity favors transportation in a degree that is greater than its simple ratio.

There are two elements of which no account is taken in the preceding discussion, but which need to be mentioned to prevent misapprehension, although they detract in no way from the conclusions.

The first is the addition which the transported detritus makes to the energy of the stream. A stream of water charged with detritus is at once a compound and an unstable fluid. It has been treated merely as an unstable fluid requiring a constant expenditure of energy to maintain its constitution; but looking at it as a compound fluid, it is plain that the energy it develops by its descent is greater than the energy pertaining to the water alone, in the precise ratio of the mass of the mixture to the mass of the simple water.

The second element is the addition which the detritus makes to the friction of flow. The coefficient of friction of the compound stream upon its bottom will always be greater than that of the simple stream of water, and the coefficient of internal friction or the viscosity will be greater than that of pure water, and hence for the same velocity a greater amount of energy will be consumed.

It may be noted in passing, that the energy which is consumed in the friction of the detritus on the stream bed, accomplishes as part of its work the mechanical corrasion of the bed.

Transportation and Quantity of Water.

A stream's friction of flow depends mainly on the character of the bed, on the area of the surface of contact, and on the velocity of the current. When the other elements are constant, the friction varies approximately with the area of contact. The area of contact depends on the length and form of the channel, and on the quantity of water. For streams of the same length and same form of cross-section, but differing in size of cross-section, the area of contact varies directly as the square root of the quantity of water. Hence, *ceteris paribus*, the friction of a stream on its bed is proportioned to the square root of the quantity of water. But as stated above, the total energy of a stream is proportioned directly to the quantity of water; and the total energy is equal to the energy spent in friction, plus the energy spent in transportation. Whence it follows that if a stream change its quantity of water without changing its velocity or other accidents, the total energy will change at the same rate as the quantity of water; the energy spent in friction will change at a less rate, and the energy remaining for transportation will change at a greater rate.

Hence increase in quantity of water favors transportation in a degree that is greater than its simple ratio.

It follows as a corollary that the running water which carries the *débris* of a district loses power by subdivision toward its sources; and that, unless there is a compensating increment of declivity, the tributaries of a river will fail to supply it with the full load it is able to carry.

It is noteworthy also that the obstruction which vegetation opposes to transportation is especially effective in that it is applied at the infinitesimal sources of streams, where the force of the running water is least.

A stream which can transport *débris* of a given size, may be said to be *competent* to such *débris*. Since the maximum particles which streams are able to move are proportioned to the sixth powers of their velocities, competence depends on velocity. Velocity, in turn, depends on declivity and volume, and (inversely) on load.

In brief, the capacity of a stream for transportation is greater for fine *débris* than for coarse.

Its capacity for the transportation of a given kind of *débris* is enlarged in more than simple ratio by increase of declivity; and it is enlarged in more than simple ratio by increase of volume.

The competence of a stream for the transport of *débris* of a given fineness, is limited by a corresponding velocity.

The *rate* of transportation of *débris* of a given fineness may equal the capacity of the transporting stream, or it may be less. When it is less, it is always from the insufficiency of supply. The supply furnished by weathering is never available unless the degree of fineness of the *débris* brings it within the competence of the stream at the point of supply.

The chief point of supply is at the very head of the flowing water. The rain which falls on material that has been disintegrated by weathering, begins after it has saturated the immediate surface to flow off. But it forms a very thin sheet; its friction is great; its velocity is small; and it is competent to pick up only particles of exceeding fineness. If the material is heterogeneous, it discriminates and leaves the coarser particles. As the sheet moves on it becomes deeper and soon begins to gather itself into rills. As the deepening and concentration of water progresses, either its *capacity* increases and the load of fine particles is augmented, or, if fine particles are not in sufficient force, its *competence* increases, and larger ones are lifted. In either case the load is augmented, and as rill joins rill it steadily grows, until the accumulated water finally passes beyond the zone of disintegrated material.

The particles which the feeble initial currents are not competent to move, have to wait either until they are subdivided by the agencies of weathering, or until the deepening of the channels of the rills so far increases the declivities that the currents acquire the requisite velocity, or until some fiercer storm floods the ground with a deeper sheet of water.

Thus rate of transportation, as well as capacity for transportation, is favored by fineness of *débris*, by declivity, and by quantity of water. It is opposed chiefly by vegetation, which holds together that which is loosened by weathering, and shields it from the agent of transportation in the very place where that agent is weakest.

When the current of a stream gradually diminishes in its course—as for example in approaching the ocean—the capacity for transportation also diminishes; and so soon as the capacity becomes less than the load, precipitation begins—the coarser particles being deposited first.

Corrasion and Transportation.

Where a stream has all the load of a given degree of comminution which it is capable of carrying, the entire energy of the descending water and load is consumed in the translation of the water and load and there is none applied to corrasion. If it has an excess of load its velocity is thereby diminished so as to lessen its competence and a portion is dropped. If it has less than a full load it is in condition to receive more and it corrades its bottom.

A fully loaded stream is on the verge between corrasion and deposition. As will be explained in another place, it may wear the walls of its channel, but its wear of one wall will be accompanied by an addition to the opposite wall.

The work of transportation may thus monopolize a stream to the exclusion of corrasion, or the two works may be carried forward at the same time.

Corrasion and Declivity.

The rapidity of mechanical corrasion depends on the hardness, size, and number of the transient fragments, on the hardness of the rock-bed, and on the velocity of the stream. The blows which the moving fragments deal upon the stream-bed are hard in proportion as the fragments are large and the current is swift. They are most effective when the fragments are hard and the bed-rock is soft. They are more numerous and harder upon the bottom of the channel than upon the sides because of the constant tendency of the particles to sink in water. Their number is increased up to a certain limit by the increase of the load of the stream; but when the fragments become greatly crowded at the bottom of a stream their force is partially spent among themselves, and the bed-rock is in the same degree protected. For this reason, and because increase of load causes retardation of current, it is probable that the maximum work of corrasion is performed when the load is far within the transporting capacity.

The element of velocity is of double importance since it determines not only the speed, but to a great extent the size of the pestles which grind the rocks. The coefficients upon which it in turn depends, namely, declivity and quantity of water, have the same importance in corrasion that they have in transportation.

Let us suppose that a stream endowed with a constant volume of water, is at some point continuously supplied with as great a load as it is capable of carrying. For so great a distance as its velocity remains the same, it will neither corrade (downward) nor deposit, but will leave the grade of its bed unchanged. But if in its progress it reaches a place where a less declivity of bed gives a diminished velocity, its capacity for transportation will become less than the load and part of the load will be deposited. Or if in its progress it reaches a place where a greater declivity of bed gives an increased velocity, the capacity for transportation will become greater than the load and there will be corrasion of the bed. In this way a stream which has a supply of *débris* equal to its capacity, tends to build up the gentler slopes of its bed and cut away the steeper. It tends to establish a single, uniform grade.

Let us now suppose that the stream after having obliterated all the inequalities of the grade of its bed loses nearly the whole of its load. Its velocity is at once accelerated and vertical corrasion begins through its whole length. Since the stream has the same declivity and consequently the same velocity at all points, its capacity for corrasion is everywhere the same. Its rate of corrasion however will depend on the character of its bed. Where the rock is hard corrasion will be less rapid than where it is soft, and there will result inequalities of grade. But so soon as there is inequality of grade there is inequality of velocity, and inequality of capacity for corrasion; and where hard rocks have produced declivities, there the capacity for corrasion will be increased. The differentiation will proceed until the capacity for corrasion is everywhere proportioned to the resistance, and no further,—that is, until there is an equilibrium of action.

In general, we may say that a stream tends to equalize its work in all parts of its course. Its power inheres in its fall, and each foot of fall has the same power. When its work is to corrade and the resistance is unequal, it concentrates its energy where the resistance is great by crowding many feet of descent into a small space, and diffuses it where the resistance is small by using but a small fall in a long distance. When its work is to transport, the resistance is constant and the fall is evenly distributed by a uniform grade. When its work includes both transportation and corrasion, as in the usual case, its grades are somewhat unequal; and the inequality is greatest when the load is least.

It is to be remarked that in the case of most streams it is the flood stage which determines the grades of the channel. The load of detritus is usually greatest during the highest floods, and power is conferred so rapidly with increase of quantity of water, that in any event the influence of the stream during its high stage will overpower any influence which may have been exerted at a low stage. That relation of transportation to corrasion which subsists when the water is high will determine the grades of the water-way.

Declivity and Quantity of Water.

The conclusions reached in regard to the relations of corrasion and declivity depend on the assumption that the volume of the stream is the same throughout its whole course, and they consequently apply directly to such portions only of streams as are not increased by tributaries. A simple modification will include the more general case of branching streams.

Let us suppose that two equal streams which join, have the same declivity, and are both fully loaded with detritus of the same kind. If the channel down which they flow after union has also the same declivity, then the joint stream will have a greater velocity than its branches, its capacity for transportation will be more than adequate for the joint load, and it will corrade its bottom. By its corrasion it will diminish the declivity of its bed, and consequently its velocity and capacity for transportation, until its capacity is equal to the total capacity of its tributaries. When an equilibrium of action is reached, the declivity of the main stream will be less than the declivities of its branches. This result does not depend on the assumed equality of the branches, nor upon their number. It is equally true that in any river system which is fully supplied with material for transportation and which has attained a condition of equal action, the declivity of the smaller streams is greater than that of the larger.

Let us further suppose that two equal streams which join, are only partially loaded, and are corrading at a common rate a common rock. If the channel down which they flow after union is in the same rock and has the same declivity, then the joint river will have a greater velocity, and will corrade more rapidly than its branches. By its more rapid corrasion it will diminish the declivity of its bed, until as before there is an equilibrium of action,—the branch having a greater declivity than the main. This result also is independent of the number and equality of the branches; and it is equally true that in any river system which traverses and corrades rock of equal resistance throughout, and which has reached a condition of equal action, the declivity of the smaller streams is greater than that of the larger.

In general we may say that, *ceteris paribus, declivity bears an inverse relation to quantity of water.*

(There is an apparent exception to this law, which is specially noteworthy in the sculpture of bad-lands, and will be described in another place).

II. SCULPTURE.

Erosion may be regarded from several points of view. It lays bare rocks which were before covered and concealed, and is thence called *denudation.* It reduces the surfaces of mountains, plateaus, and continents, and is thence called *degradation.* It carves new forms of land from those which before existed, and is thence called *land sculpture.* In the following pages it will be considered as land sculpture, and attention will be called to certain principles of erosion which are concerned in the production of topographic forms.

Sculpture and Declivity.

We have already seen that erosion is favored by declivity. Where the declivity is great the agents of erosion are powerful; where it is small they are weak; where there is no declivity they are powerless. Moreover it has been shown that their power increases with the declivity in more than simple ratio.

It is evident that if steep slopes are worn more rapidly than gentle, the tendency is to abolish all differences of slope and produce uniformity. The law of uniform slope thus opposes diversity of topography, and if not complemented by other laws, would reduce all drainage basins to plains. But in reality it is never free to work out its full results; for it demands a uniformity of conditions which nowhere exists. Only a water sheet of uniform depth, flowing over a surface of homogeneous material, would suffice; and every inequality of water depth or of rock texture produces a corresponding inequality of slope and diversity of form. The reliefs of the landscape exemplify other laws, and the law of uniform slopes is merely the conservative element which limits their results.

Sculpture and Structure; the Law of Structure.

We have already seen that erosion is influenced by rock character. Certain rocks, of which the hard are most conspicuous, oppose a stubborn resistance to erosive agencies; certain others, of which the soft are most conspicuous, oppose a feeble resistance. Erosion is most rapid where the resistance is least, and hence as the soft rocks are worn away the hard are left prominent. The differentiation continues until an equilibrium is reached through the law of declivities. When the ratio of erosive action as dependent on declivities becomes equal to the ratio of resistances as dependent on rock character, there is equality of action. In the structure of the earth's crust hard and soft rocks are grouped with infinite diversity of arrangement. They are in masses of all forms, and dimensions, and positions; and from these forms are carved an infinite variety of topographic reliefs.

In so far as the law of structure controls sculpture, hard masses stand as eminences and soft are carved in valleys.

The Law of Divides.

We have seen that the declivity over which water flows bears an inverse relation to the quantity of water. If we follow a stream from its mouth upward and pass successively the mouths of its tributaries, we find its volume gradually less and less and its grade steeper and steeper, until finally at its head we reach the steepest grade of all. If we draw the profile of the river on paper, we produce a curve concave upward and with the greatest curvature at the upper end. The same law applies to every tributary and even to the slopes over which the freshly fallen rain flows in a sheet before it is gathered into rills. The nearer the water-shed or divide the steeper the slope; the farther away the less the slope.

It is in accordance with this law that mountains are steepest at their crests. The profile of a mountain if taken along drainage lines is concave outward as represented in the diagram; and this is purely a matter of sculpture, the uplifts from which mountains are carved rarely if ever assuming this form.

FIG. 54.—Typical profile of the Drainage Slopes of Mountains.

Under the *law of Structure* and the *law of Divides* combined, the features of the earth are carved. Declivities are steep in proportion as their material is hard; and they are steep in proportion as they are near divides.

The distribution of hard and soft rocks, or the geological structure, and the distribution of drainage lines and water-sheds, are coefficient conditions on which depends the sculpture of the land. In the sequel it will be shown that the distribution of drainage lines and water-sheds depends in part on that of hard and soft rocks.

In some places the first of the two conditions is the more important, in others the second. In the bed of a stream without tributaries the grade depends on the structure of the underlying rocks. In rock which is homogeneous and structureless all slopes depend on the distribution of divides and drainage lines.

The relative importance of the two conditions is especially affected by climate, and the influence of this factor is so great that it may claim rank as a third condition of sculpture.

Sculpture and Climate.

The Henry Mountains consist topographically of five individuals, separated by low passes, and practically independent in climate. At the same time they are all of one type of structure, being constituted by similar aggregation of hard and soft rocks. Their altitudes appear in the following table.

	Altitude above the sea.
Mount Ellen	11, 250 feet.
Mount Pennell	11, 150 feet.
Mount Hillers	10, 500 feet.
Mount Ellsworth	8, 000 feet.
Mount Holmes	7, 775 feet.

The plain on which they stand has a mean altitude of 5,500 feet, and is a desert. A large proportion of the rain which falls in the region is caught by the mountains, and especially by the higher mountains. Of this there is abundant proof in the distribution of vegetation and of springs.

The vegetation of the plain is exceedingly meager, comprising only sparsely set grasses and shrubs, and in favored spots the dwarf cedar of the West (*Juniperus occidentalis*).

Mount Ellen, which has a continuous ridge two miles long and more than 11,000 feet high, bears cedar about its base, mingled higher up with piñon (*Pinus edulis*), and succeeded above by the yellow pine (*P. ponderosa*), spruce (*Abies Douglasii*), fir (*A. Engelmanni*), and aspen (*Populus tremuloides*). The pines are scattering, but the cedars are close set, and the firs are in dense groves. The upper slopes where not timbered are matted with luxuriant grasses and herbs. The summits are naked.

Mount Pennell sends a single peak only to the height of the Ellen ridge. Its vegetation is nearly the same, but the timber extends almost to the summit.

Mount Hillers is 650 feet lower. Its timber reaches to the principal summit, but is less dense than on the higher mountains. The range of trees is the same.

Mount Ellsworth, 2,500 feet lower than Mount Hillers, bears neither fir, spruce, pine nor aspen. Cedar and piñon climb to the summit, but are not so thickly set as on the lower slopes of the larger mountains. The grasses are less rank and grow in scattered bunches.

Mount Holmes, a few feet lower, has the same flora, with the addition of a score of spruce trees, high up on the northern flank. Its summits are bare.

In a word, the luxuriance of vegetation, and the annual rainfall, of which it is the index, are proportioned to the altitude.

Consider now the forms of the mountain tops.

In Figure 55 are pictured the summit forms of Mount Ellen. The crests are rounded; the slopes are uniform and smooth. Examination has shown that the constituent rocks are of varying degrees of hardness, trachyte dikes alternating with sandstones and shales; but these variations rarely find expression in the sculptured forms.

In Figure 56 are the summit crags of Mount Holmes. They are dikes of trachyte denuded by a discriminating erosion of their encasements of sandstone, and carved in bold relief. In virtue of their superior hardness they survive the general degradation.

The other mountains are intermediate in the character of their sculpture. Mount Pennell is nearly as smooth as Mount Ellen. Mount Ellsworth is

FIG. 55.—The Crest of Mount Ellen, as seen from Ellen Peak.

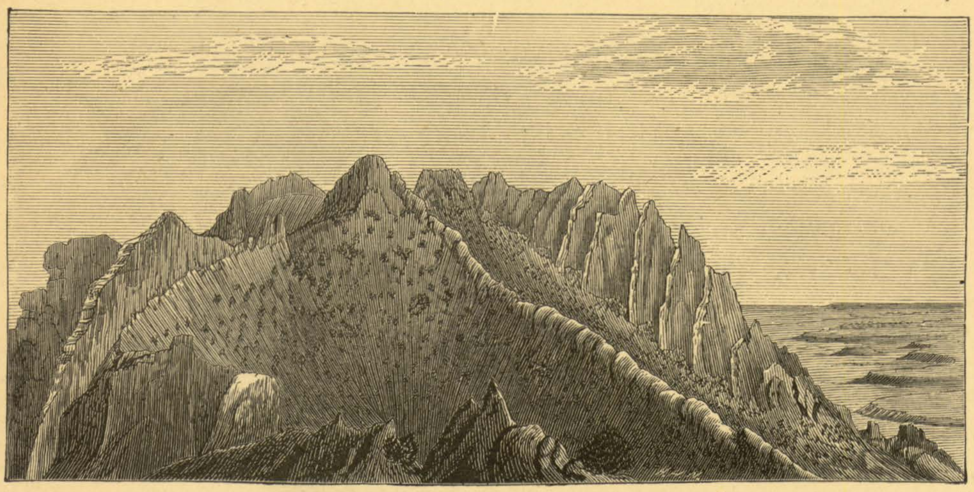


FIG. 56.—The Crest of Mount Holmes.

nearly as rugged as Mount Holmes. One may ride to the crest of Mount Ellen and to the summit of Mount Pennell; he may lead his sure-footed cayuse to the top of Mount Hillers; but Mounts Ellsworth and Holmes are not to be scaled by horses. The mountaineer must climb to reach their summits, and for part of the way use hands as well as feet.

In a word, the ruggedness of the summits or the differentiation of hard and soft by sculpture, is proportioned inversely to the altitude. And rainfall, which in these mountains depends directly on altitude, is proportioned inversely to ruggedness.

The explanation of this coincidence depends on the general relations of vegetation to erosion.

We have seen that vegetation favors the disintegration of rocks and retards the transportation of the disintegrated material. Where vegetation is profuse there is always an excess of material awaiting transportation, and the limit to the rate of erosion comes to be merely the limit to the rate of transportation. And since the diversities of rock texture, such as hardness and softness, affect only the rate of disintegration (weathering and corrasion) and not the rate of transportation, these diversities do not affect the rate of erosion in regions of profuse vegetation, and do not produce corresponding diversities of form.

On the other hand, where vegetation is scant or absent, transportation and corrasion are favored, while weathering is retarded. There is no accumulation of disintegrated material. The rate of erosion is limited by the rate of weathering, and that varies with the diversity of rock texture. The soft are eaten away faster than the hard; and the structure is embodied in the topographic forms.

Thus a moist climate by stimulating vegetation produces a sculpture independent of diversities of rock texture, and a dry climate by repressing vegetation produces a sculpture dependent on those diversities. With great moisture the law of divides is supreme; with aridity, the law of structure.

Hence it is that the upper slopes of the loftier of the Henry Mountains are so carved as to conceal the structure, while the lower slopes of the same mountains and the entire forms of the less lofty mountains are so carved as to reveal the structure; and hence too it is that the arid plateaus of the Colorado Basin abound in cliffs and cañons, and offer facilities to the student of geological structure which no humid region can afford.

Here too is the answer to the question so often asked, "whether the rains and rivers which excavated the cañons and carved the cliffs were not mightier than the rains and rivers of to-day." Aridity being an essential condition of this peculiar type of sculpture, we may be sure that through long ages it has characterized the climate of the Colorado Basin. A climate of great rainfall, as Professor Powell has already pointed out in his "Exploration of the Colorado," would have produced curves and gentle slopes in place of the actual angles and cliffs.

Bad-lands.

Mountain forms in general depend more on the law of divides than on the law of structure, but their independence of structure is rarely perfect, and it is difficult to discriminate the results of the two principles. For the investigation of the workings of the law of divides it is better to select examples from regions which afford no variety of rock texture and are hence unaffected in their erosion by the law of structure. Such examples are found in *bad-lands.*

Where a homogeneous, soft rock is subjected to rapid degradation in an arid climate, its surface becomes absolutely bare of vegetation and is carved into forms of great regularity and beauty. In the neighborhood of the Henry Mountains, the Blue Gate and Tununk shales are of this character, and their exposures afford many opportunities for the study of the principles of sculpture. I was able to devote no time to them, but in riding across them my attention was attracted by some of the more striking features, and these I will venture to present, although I am conscious that they form but a small part of the whole material which the bad-lands may be made to yield.

If we examine a bad-land ridge, separating two drainage lines and forming a divide between them, we find an arrangement of secondary ridges and secondary drainage lines, similar to that represented in the diagram, (Figure 58.)

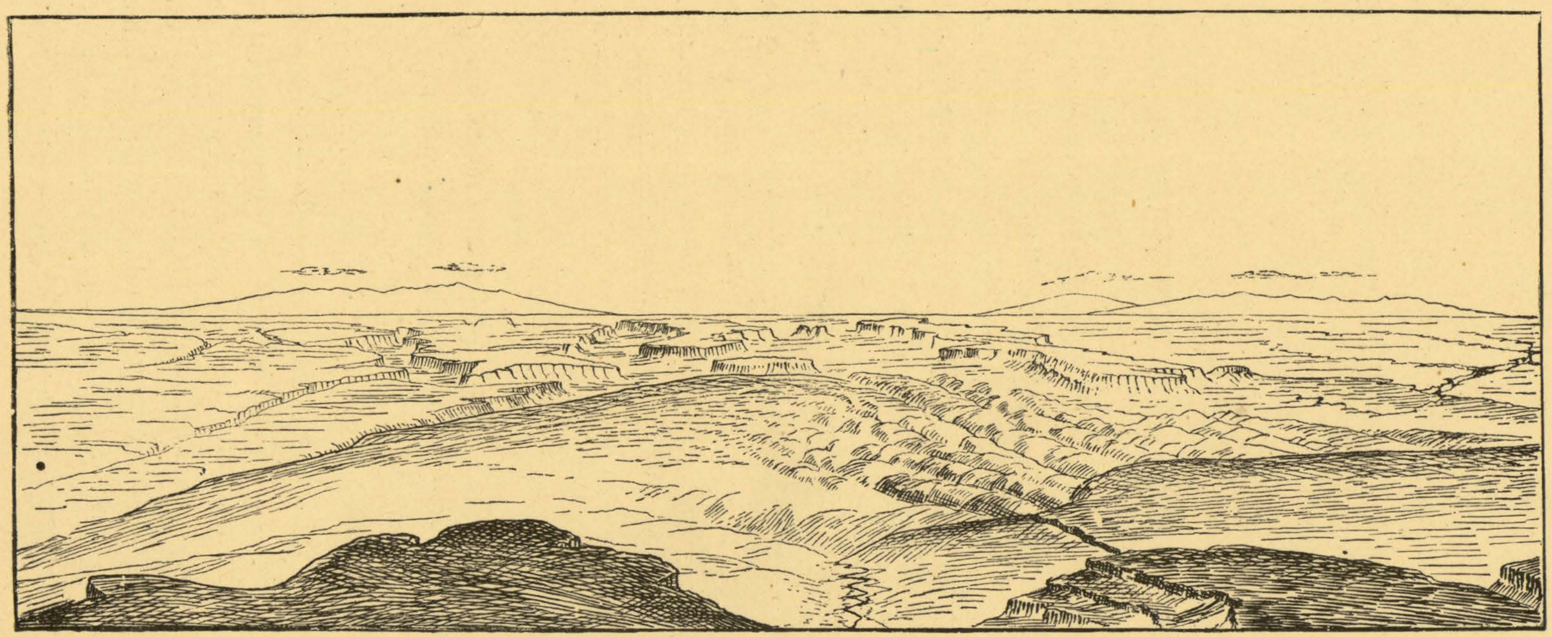


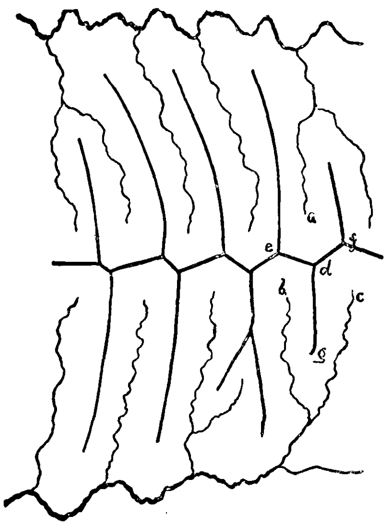
FIG. 57.—General view of the Plateaus lying East of the Henry Mountains.

The general course of the main ridge being straight, its course in detail is found to bear a simple relation to the secondary ridges. Wherever a secondary joins, the main ridge turns, its angle being directly toward the secondary. The divide thus follows a zigzag course, being deflected to the right or left by each lateral spur.

The altitude of the main ridge is correspondingly related to the secondary ridges. At every point of union there is a maximum, and in the intervals are saddles. The maxima are not all equal, but bear some relation to the magnitudes of the corresponding secondary ridges, and are especially accented where two or more secondaries join at the same point. (See profile in Figure 59.)

I conceive that the explanation of these phenomena is as follows: The heads of the secondary drainage lines laid down in the diagram are in nature tolerably definite points. The water which during rain converges at one of these points is there abruptly concentrated in volume. Above the point it is a sheet, or at least is divided into many rills. Below it, it is a single stream with greatly increased power of transportation and corrasion. The principle of equal action gives to the concentrated stream a less declivity than to the diffused sheet, and—what is especially important—it tends to produce an equal grade in all directions upward from the point of convergence. The converging surface becomes hopper-shaped or funnel-shaped; and as the point of convergence is lowered by corrasion, the walls of the funnel are eaten back equally in all directions—except of course the direction of the stream. The influence of the stream in stimulating erosion above its head is thus extended radially and equally through an arc of 180°, of which the center is at the point of convergence.

Where two streams head near each other, the influence of each tends to pare away the divide between them, and by paring to carry it farther back. The position of the divide is determined by the two influences combined and represents the line of equilibrium between them. The influences being radial from the points of convergence, the line of equilibrium is tangential, and is consequently at right angles to a line connecting the two points. Thus, for example, if *a*, *b*, and *c* (Figure 58) are the points of convergence at the heads of three drainage lines, the divide line *cd* is at right angles to a line connecting *a* and *b*, and the divides *fd* and *gd* are similarly determined. The point *d* is simultaneously determined by the intersection of the three divide lines.



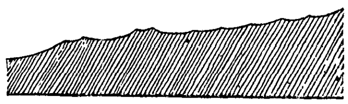


FIG. 58.—Ground-plan of a Bad-land Ridge, showing its relation to Water-ways. The smooth lines represent Divides.

FIG. 59.—Profile of the same ridge.

Furthermore, since that point of the line *ed* which lies directly between *a* and *b* is nearest to those points, it is the point of the divide most subject to the erosive influences which radiate from *a* and *b*, and it is consequently degraded lower than the contiguous portions of the divide. The points *d* and *e* are less reduced; and *d*, which can be shown by similar reasoning to stand higher than the adjacent portion of either of the three ridges which there unite, is a local maximum.

There is one other peculiarity of bad-land forms which is of great significance, but which I shall nevertheless not undertake to explain. According to the law of divides, as stated in a previous paragraph, the profile of any slope in bad-lands should be concave upward, and the slope should be steepest at the divide. The union or intersection of two slopes on a divide should produce an angle. But in point of fact the slopes do not unite in an angle. They unite in a curve, and the profile of a drainage slope instead of being concave all the way to its summit, changes its curvature and becomes convex. Figure 60 represents a profile from *a* to *b* of Figure 58. From *a* to *m* and from *b* to *n* the slopes are concave, but from *m* to *n* there is a convex curvature. Where the flanking slopes are as steep as represented in the diagram, the convexity on the crest of a ridge has a breadth of only two or three yards, but where the flanking slopes are gentle, its breadth is several times as great. It is never absent.

Thus in the sculpture of the bad-lands there is revealed an exception to the law of divides,—an exception which cannot be referred to accidents of structure, and which is as persistent in its recurrence as are the features which conform to the law,—an exception which in some unexplained way is part of the law. Our analysis of the agencies and conditions of erosion, on the one hand, has led to the conclusion that (where structure does not pre-

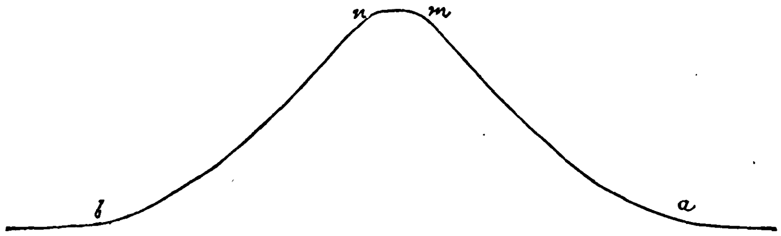


FIG. 60.—Cross-profile of a Bad-land Divide.

vent) the declivities of a continuous drainage slope increase as the quantities of water flowing over them decrease; and that they are great in proportion as they are near divides. Our observation, on the other hand, shows that the declivities increase as the quantities of water diminish, up to a certain point where the quantity is very small, and then decrease; and that declivities are great in proportion as they are near divides, unless they are *very* near divides. Evidently some factor has been overlooked in the analysis,—a factor which in the main is less important than the flow of water, but which asserts its existence at those points where the flow of water is exceedingly small, and is there supreme.

Equal Action and Interdependence.

The tendency to equality of action, or to the establishment of a dynamic equilibrium, has already been pointed out in the discussion of the principles of erosion and of sculpture, but one of its most important results has not been noticed.

Of the main conditions which determine the rate of erosion, namely, quantity of running water, vegetation, texture of rock, and declivity, only the last is reciprocally determined by rate of erosion. Declivity originates in upheaval, or in the displacements of the earth's crust by which mountains and continents are formed; but it receives its distribution in detail in accordance with the laws of erosion. Wherever by reason of change in any of the conditions the erosive agents come to have locally exceptional power, that power is steadily diminished by the reaction of rate of erosion upon declivity. Every slope is a member of a series, receiving the water and the waste of the slope above it, and discharging its own water and waste upon the slope below. If one member of the series is eroded with exceptional rapidity, two things immediately result: first, the member above has its level of discharge lowered, and its rate of erosion is thereby increased; and second, the member below, being clogged by an exceptional load of detritus, has its rate of erosion diminished. The acceleration above and the retardation below, diminish the declivity of the member in which the disturbance originated; and as the declivity is reduced the rate of erosion is likewise reduced.

But the effect does not stop here. The disturbance which has been transferred from one member of the series to the two which adjoin it, is by them transmitted to others, and does not cease until it has reached the confines of the drainage basin. For in each basin all lines of drainage unite in a main line, and a disturbance upon any line is communicated through it to the main line and thence to every tributary. And as any member of the system may influence all the others, so each member is influenced by every other. There is an interdependence throughout the system.

III.—SYSTEMS OF DRAINAGE.

To know well the drainage of a region two systems of lines must be ascertained—the drainage lines and the divides. The maxima of surface on which waters part, and the minima of surface in which waters join, are alike intimately associated with the sculpture of the earth and with the history of the earth's structure; and the student of either sculpture or history can well afford to study them. In the following pages certain conditions which affect their permanence and transformations are discussed.

THE STABILITY OF DRAINAGE LINES.

In corrasion the chief work is performed by the impact and friction of hard and heavy particles moved forward by running water. They are driven against all sides of the channel, but their tendency to sink in water brings them against the bottom with greater frequency and force than against the walls. If the rate of wear be rapid, by far the greater part of it is applied to the bottom, and the downward corrasion is so much more powerful than the lateral that the effect of the latter is practically lost, and the channel of the stream, without varying the position of its banks, carves its way vertically into the rock beneath. It is only when corrasion is exceedingly slow that the lateral wear becomes of importance; and hence as a rule the position of a stream bed is permanent.

The stability of drainage lines is especially illustrated in regions of displacement. If a mountain is slowly lifted athwart the course of a stream, the corrasion of the latter is accelerated by the increase of declivity, and instead of being turned aside by the uplift, it persistently holds its place and carves a channel into the mountain as the mountain rises. For example the deep clefts which intersect the Wasatch range owe their existence to the fact that at the time of the beginning of the uplift which has made the range, there were streams flowing across the line of its trend which were too powerful to be turned back by the growing ridge. The same relation has been shown by Professor Powell where the Green River crosses the uplift of the Uinta Mountains, and in many instances throughout the Rocky Mountain region it may be said that rivers have cut their way through mountains merely because they had established their courses before the inception of the displacement, and could not be diverted by an obstruction which was thrown up with the slowness of mountain uplift.

THE INSTABILITY OF DRAINAGE LINES.

The stability of waterways being the rule, every case of instability requires an explanation; and in the study of such exceptional cases there have been found a number of different methods by which the courses of streams are shifted. The more important will be noted.

Ponding.

When a mountain uplift crosses the course of a stream, it often happens that the rate of uplift is too rapid to be equaled by the corrasion of the stream, and the uprising rock becomes a dam over which the water still runs, but above which there is accumulated a pond or lake. Whenever this takes place, the pond catches all the *débris* of the upper course of the stream, and the water which overflows at the outlet having been relieved of its load is almost powerless for corrasion, and cannot continue its contest with the uplift unless the pond is silted up with detritus. As the uplift progresses the level of the pond is raised higher and higher, until finally it finds a new outlet at some other point. The original outlet is at once abandoned, and the new one becomes a permanent part of the course of the stream. As a rule it is only large streams which hold their courses while mountains rise; the smaller are turned back by ponding, and are usually diverted so as to join the larger.

The disturbances which divert drainage lines are not always of the sort which produce mountains. The same results may follow the most gentle undulations of plains. It required a movement of a few feet only to change the outlet of Lakes Michigan, Huron, and Superior from the Illinois River to the St. Clair; and in the tilting which turned Lake Winipeg from the Mississippi to the Nelson no abrupt slopes were produced. If the entire history of the latter case were worked out, it would probably appear that the Saskatchewan River which rises in the Rocky Mountains beyond our northern boundary, was formerly the upper course of the Mississippi, and that when, by the rising of land in Minnesota or its sinking at the north, a barrier was formed, the water was ponded and Lake Winipeg came into existence. By the continuance of the movement of the land the lake was increased until it overflowed into Hudson's Bay; and by its further continuance, combined with the corrasion of the outlet, the lake has been again diminished. When eventually the lake disappears the revolution will be complete, and the Saskatchewan will flow directly to Hudson's Bay, as it once flowed directly to the Gulf of Mexico. (See the "Physical Features of the Valley of the Minnesota River," by General G. K. Warren.)

Planation.

It has been shown in the discussion of the relations of transportation and corrasion that downward wear ceases when the load equals the capacity for transportation. Whenever the load reduces the downward corrasion to little or nothing, lateral corrasion becomes relatively and actually of importance. The first result of the wearing of the walls of a stream's channel is the formation of a flood-plain. As an effect of momentum the current is always swiftest along the outside of a curve of the channel, and it is there that the wearing is performed; while at the inner side of the curve the current is so slow that part of the load is deposited. In this way the width of the channel remains the same while its position is shifted, and every part of the valley which it has crossed in its shiftings comes to be covered by a deposit which does not rise above the highest level of the water. The surface of this deposit is hence appropriately called the *flood-plain* of the stream. The deposit is of nearly uniform depth, descending no lower than the bottom of the water-channel, and it rests upon a tolerably even surface of the rock or other material which is corraded by the stream. The process of carving away the rock so as to produce an even surface, and at the same time covering it with an alluvial deposit, is the process of *planation.*

It sometimes happens that two adjacent streams by extending their areas of planation eat through the dividing ridge and join their channels. The stream which has the higher surface at the point of contact, quickly abandons the lower part of its channel and becomes a branch of the other, having shifted its course by planation.

The slopes of the Henry Mountains illustrate the process in a peculiarly striking manner. The streams which flow down them are limited in their rate of degradation at both ends. At their sources, erosion is opposed by the hardness of the rocks; the trachytes and metamorphics of the mountain tops are carved very slowly. At their mouths, they discharge into the Colorado and the Dirty Devil, and cannot sink their channels more rapidly than do those rivers. Between the mountains and the rivers, they cross rocks which are soft in comparison with the trachyte, but they can deepen their channels with no greater rapidity than at their ends. The grades have adjusted themselves accordingly. Among the hard rocks of the mountains the declivities are great, so as to give efficiency to the eroding water. Among the sedimentary rocks of the base they are small in comparison, the chief work of the streams being the transportation of the trachyte *débris.* So greatly are the streams concerned in transportation, and so little in downward corrasion (outside the trachyte region), that their grades are almost unaffected by the differences of rock texture, and they pass through sandstone and shale with nearly the same declivity.

The rate of downward corrasion being thus limited by extraneous conditions, and the instrument of corrasion—the *débris* of the hard trachyte—being efficient, lateral corrasion is limited only by the resistance which the banks of the streams oppose. Where the material of the banks is a firm sandstone, narrow flood-plains are formed; and where it is a shale, broad ones. In the Gray Cliff and Vermilion Cliff sandstones flat-bottomed cañons are excavated; but in the great shale beds broad valleys are opened, and the flood-plains of adjacent streams coalesce to form continuous plains. The broadest plains are as a rule carved from the thickest beds of shale, and these are found at the top of the Jura-Trias and near the base of the Cretaceous. Where the streams from the mountains cross the Blue Gate, the Tununk, or the Flaming Gorge shale at a favorable angle, a plain is the result.

The plain which lies at the southern and western bases of Mount Hillers is carved chiefly from the Tununk shale (see Figure 27). The plain sloping eastward from Mount Pennell (Figure 36) is carved from the Blue Gate and Tununk shales. The Lewis Creek plain, which lies at the western base of Mount Ellen, is formed from the Blue Gate, Tununk, and Masuk shales, and the planation which produced it has so perfectly truncated the Tununk and Blue Gate sandstones that their outcrops cannot be traced (Figures 61, 39, and 42). The plain which truncates the Crescent arch (Figure 49) is carved in chief part from the Flaming Gorge shale. Toward the east it is limited by the outcrops of the Henry's Fork conglomerate, but toward the mountain it cuts across the edge of the same conglomerate and extends over Tununk shale to the margin of the trachyte.

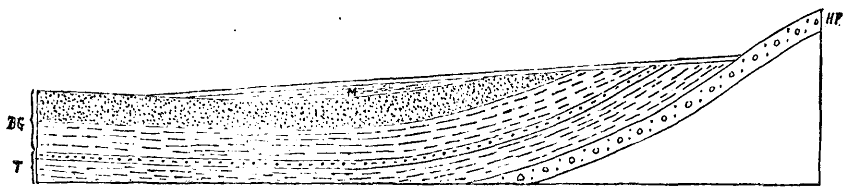


FIG. 61.—Cross-section of the Lewis Creek Plain. M, Masuk Shale. BG, Blue-Gate Group. T, Tununk Group. HF, Henry's Fork conglomerate. Scale, 1 inch = 4,000 feet.

The streams which made these plains and which maintain them, accomplish their work by a continual shifting of their channels; and where the plains are best developed they employ another method of shifting—a method which in its proper logical order must be treated in the discussion of alluvial cones, but which is practically combined in the Henry Mountains with the method of planation. The supply of detritus derived from the erosion of the trachyte is not entirely constant. Not only is more carried out in one season than another and in one year than another, but the work is accomplished in part by sudden storms which create great floods and as suddenly cease. It results from this irregularity that the channels are sometimes choked by *débris*, and that by the choking of the channels the streams are turned aside to seek new courses upon the general plain. The abandoned courses remain plainly marked, and one who looks down on them from some commanding eminence can often trace out many stages in the history of the drainage. Where a series of streams emerge from adjacent mountain gorges upon a common plain, their shiftings bring about frequent unions and separations, and produce a variety of combinations.

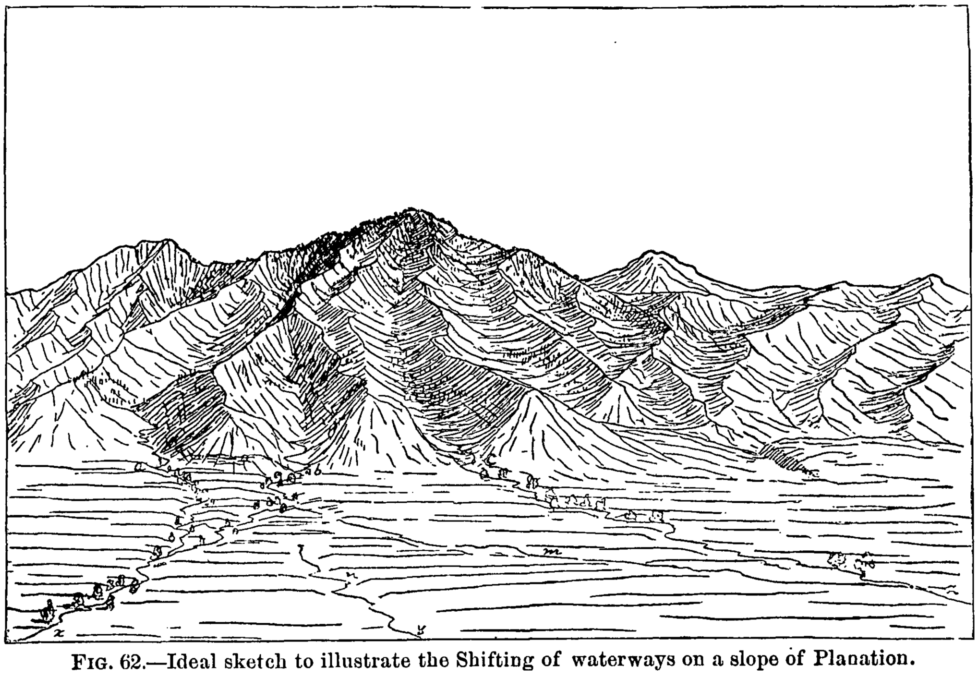


FIG. 62.—Ideal sketch to illustrate the Shifting of waterways on a slope of Planation.

The accompanying sketch, Figure 62, is not from nature, but it serves to illustrate the character of the changes. The streams which issue from the mountain gorges *a* and *b* join and flow to *z;* while that which issues at *c* flows alone to *x*. An abandoned channel, *n*, shows that the stream from *b* was formerly united with that from *c*, and flowed to *x;* and another channel, *m*, shows that it has at some time maintained an independent course to *y*. By such shiftings streams are sometimes changed from one drainage system to another; the hypothetical courses, *x*, *y*, and *z*, may lead to different rivers, and to different oceans.

An instance occurs on the western flank of the mountains. One of the principal heads of Pine Alcove Creek rises on the south slope of Mount Ellen and another on the northwest slope of Mount Pennell. The two unite and flow southward to the Colorado River. They do not now cross an area of planation, but at an earlier stage of the degradation they did; and the portions of that plain which survive, indicate by the direction of their slopes that one or both of the streams may have then discharged its water into Lewis Creek, which runs northward to the Dirty Devil River.

As the general degradation of the region progresses the streams and their plains sink lower, and eventually each plain is sunk completely through the shale whose softness made it possible. So soon as the streams reach harder rock their lateral corrasion is checked, and they are no longer free to change their ways. Wherever they chance to run at that time, there they stay and carve for themselves cañons. Portions of the deserted plains remain between the cañons, and having a durable capping of trachyte gravel are long preserved. Such stranded fragments abound on the slopes of the mountains, and in them one may read many pages of the history of the degradation. They form tabular hills with sloping tops and even profiles. The top of each hill is covered with a uniform layer of gravel, beneath which the solid rock is smoothly truncated. The slope of the hill depends on the grade of the ancient stream, and is independent of the hardness and dip of the strata.

The illustration represents a *hill of planation* on the north slope of Mount Ellsworth. It is built of the Gray Cliff sandstone and Flaming Gorge shale, inclined at angles varying from 25° to 45°; but notwithstanding their variety of texture and dip the edges of the strata are evenly cut away, so that their upper surface constitutes a plane. The stream which performed this truncation afterward cut deeper into the strata and carved the lower table which forms the foreground of the sketch. It has now abandoned this plain also and flows through a still deeper channel on the opposite side of the hill.

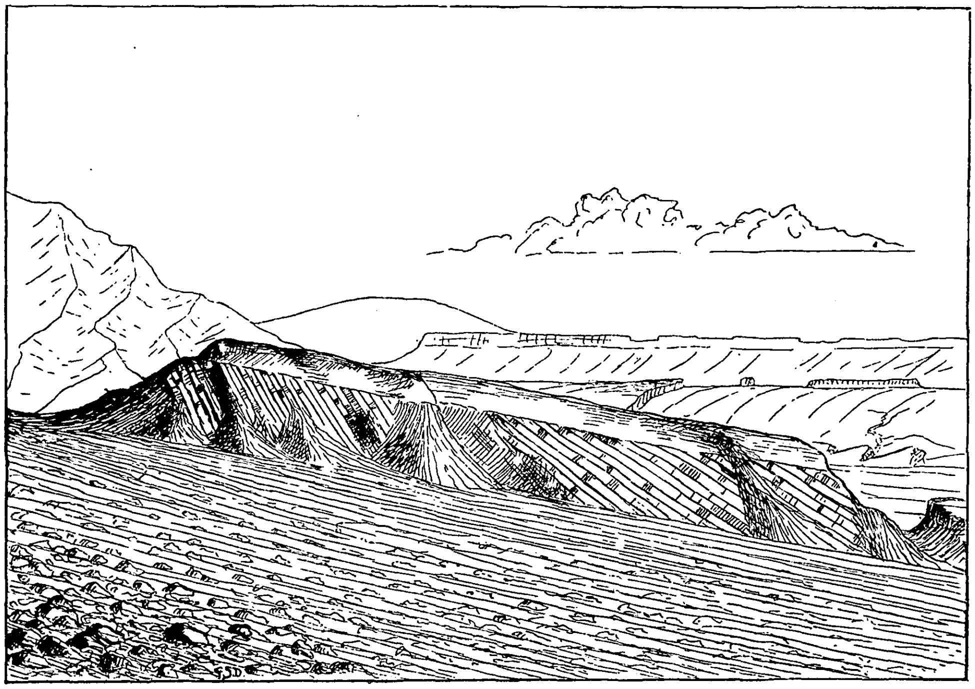


FIG. 63.—A Hill of Planation.

The phenomena of planation are further illustrated in the region which lies to the northwest of the Henry Mountains. Tantalus and Temple Creeks, rising under the edge of the Aquarius Plateau, transport the trachyte of the plateau across the region of the Waterpocket flexure to the Dirty Devil River. Their flood-plains are not now of great extent, but when their drainage lines ran a few hundred feet higher they appear to have carved into a single plain a broad exposure of the Flaming Gorge shale, which then lay between the Waterpocket and Blue Gate flexures.

At the Red Gate where the Dirty Devil River passes from a district of trachyte plateaus to the district of the Great Flexures, it follows for a few miles the outcrop of the Shinarump shale, and the remnants of its abandoned flood-plains form a series of terraces upon each bank. Small streams from the sides have cut across the benches and displayed their structure. Each one is carved from the rock *in situ*, but each is covered by a layer of the rounded river gravel. The whole are results of planation; and they serve to connect the somewhat peculiar features of the mountain slopes with the ordinary terraces of rivers.

River terraces as a rule are carved out, and not built up. They are always the vestiges of flood-plains, and flood-plains are usually produced by lateral corrasion. There are instances, especially near the sea-coast, of river-plains which have originated by the silting up of valleys, and have been afterward partially destroyed by the same rivers when some change of

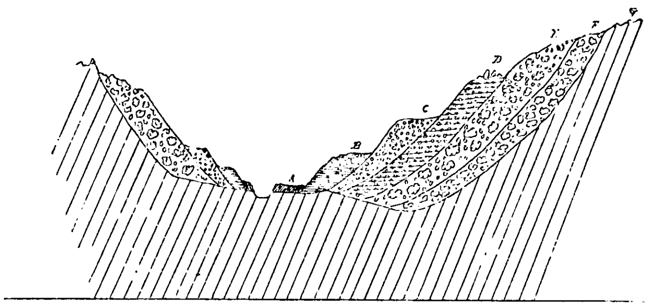


FIG. 64.—Ideal cross-section of a Terraced River Valley, after Hitchcock. A, B, C, D, E, and F, Alluvial deposits. G, Indurated rock, *in situ*.

level permitted them to cut their channels deeper; and these instances, conspiring with the fact that the surfaces of flood-plains are alluvial, and with the fact that many terraces in glacial regions are carved from unconsolidated drift, have led some American geologists into the error of supposing that river terraces in general are the records of sedimentation, when in fact they record the stages of a progressive corrasion. The ideal section of a terraced river valley which I reproduce from Hitchcock (Surface Geology, Plate XII, figure 1) regards each terrace as the remnant of a separate deposit, built up from the bottom of the valley. To illustrate my own idea I have copied his profile (Figure 65) and interpreted its features as the results of lateral corrasion or planation, giving each bench a capping of alluvium, but constituting it otherwise of the preëxistent material of the valley. The preëxistent material in the region of the Henry Mountains is always rock *in situ*, but in the Northern States it often includes glacial drift, modified or unmodified.

There is a kindred error, as I conceive, involved in the assumption that the streams which occupied the upper and broader flood-plains of a valley were greater than those which have succeeded them. They may have been, or they may not. In the process of lateral corrasion all the material that is worn from the bank has to be transported by the water, and where the bank is high the work proceeds less rapidly than where it is low. A stream which degrades its immediate valley more rapidly than the surrounding country is degraded (and the streams which abound in terraces are of this character) steadily increases the height of the banks which must be excavated in planation and diminishes the extent of its flood-plain; and

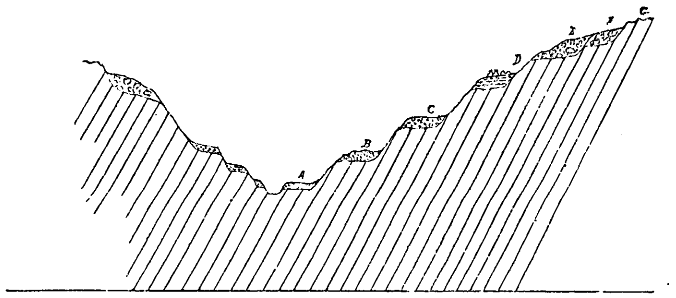


FIG. 65.—Ideal cross-section of a Terraced River Valley, regarded as a result of Planation. A, B, C, &c., Alluvial deposits. G, Preëxistent material from which the valley was excavated.

this might occur even if the volume of the stream was progressively increasing instead of diminishing.

Of the same order also is the mistake, occasionally made of ignoring the excavation which a stream has performed, and assuming that when the upper terraces were made the valley was as open as at present, and the volume of flowing water was great enough to fill it.

Alluvial Cones.

Wherever a stream is engaged in deposition instead of corrasion—wherever it deposits its load—there is a shifting of channel by a third process. The deposition of sediment takes place upon the bottom of the channel and upon its immediate banks, and this continues until the channel bottom is higher than the adjacent country. The wall of the channel is then broken through at some point, and the water abandons its old bed for one which is lower. Such occurrences belong to the histories of all river deltas, and the devastation they have wrought at the mouths of large rivers has enforced attention to their phenomena and stimulated a study of their causes.

The same thing happens among the mountains. Wherever, as in Nevada and Western Utah, the valleys are the receptacles of the detritus washed out from the mountains, the foot-slopes of the mountains consist of a series of alluvial cones. From each mountain gorge the products of its erosion are discharged into the valley. The stream which bears the *débris* builds up the bed of its channel until it is higher than the adjacent land and then abandons it, and by the repetition of this process accumulates a conical hill of detritus which slopes equally in all directions from the mouth of the mountain gorge. At one time or another the water runs over every part of the cone and leaves it by every part of its base; and it sometimes happens that the opposite slopes of the cone lead to different drainage systems.

An illustration may be seen in Red Rock Pass at the north end of Cache Valley, Idaho. Lake Bonneville, the ancient expansion of Great Salt Lake,* here found outlet to the basin of the Columbia, and the channel carved by its water is plainly marked. For a distance of twelve miles the bed of the channel is nearly level, with a width of a thousand feet. Midway, Marsh Creek enters it from the east, and has built an alluvial cone which extends to the opposite bank and divides it into two parts. In the construction of the cone Marsh Creek has flowed alternately to the north and to the south, being in one case a tributary to the Snake and Columbia Rivers and to the Pacific Ocean, and in the other to the Bear River and Great Salt Lake. So far as the creek is known to white men it is a tributary of the Snake, but an irrigating ditch that has been dug upon its cone carries part of its water to the Bear.

Another illustration exists at the mouth of the Colorado River. As

*Lake Bonneville is described in volume III (Geology) of the "U. S. Geog. Surveys West of the 100th Meridian," pp. 88–104; and less fully in the American Naturalist for November, 1876, and the American Journal of Science for March, 1876, p. 228. See also Johnson's Cyclopedia, article "Sevier Lake."

has been shown by Blake in the fifth volume of the Pacific Railroad Reports (p. 236), the delta of the Colorado—or in other words the alluvial cone which is built at its mouth—has extended itself completely across the Gulf of California, severing the upper end from the lower and from the ocean, and converting it into a lake. In continuing the upbuilding of the delta the river has flowed alternately into the lower gulf and into its severed segment. At the present day its mouth opens to the lower gulf; but at rare intervals a portion of its water runs by the channel known as "New River" to the opposite side of the delta. While it is abandoned by the river the lake basin is dry, and it is known to human history only as the Colorado Desert. Its bottom, which is lower than the surface of the ocean, is strewn with the remains of the life its waters sustained, and its beaches are patiently awaiting the cycle of change which is slowly but surely preparing to restore to them their parent waves.

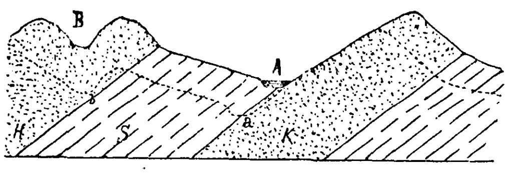


FIG. 66.—Cross-section of inclined strata, to illustrate Monoclinal Shifting of waterways.

Monoclinal Shifting.

In a fourth manner drainage lines are unstable.

In a region of inclined strata there is a tendency on the part of streams which traverse soft beds to continue therein, and there is a tendency to eliminate drainage lines from hard beds. In Figure 66, *S* represents a homogeneous soft bed, and *H* and *K*, homogeneous hard beds. *A* and *B* are streams flowing through channels opened in the soft rock, and in the hard. As the general degradation progresses the stream at *a* abrades both sides of its channel with equal force; but it fails to corrade them at equal rates because of the inequality of the resistance. It results that the channel does not cut its way vertically into the hard rock, but works obliquely downward without changing its relation to the two beds; so that when the degradation has reached the stage indicated by the dotted line, the stream flows at *a*, having been shifted horizontally by circumstances dependent on the dip and order of the strata.

At the same time the stream at *B*, encountering homogeneous material, cuts its way vertically downward to *b;* and a continuance of the process carries it completely through the hard rock and into the soft. Once in the soft it tends like the other streams to remain there; and in the course of time it finds its way to the lower edge and establishes a channel like that at *A*.

The effect of this process on the course of a stream which runs obliquely across inclined beds is shown in Figure 67. The outcrops of a series of hard and soft strata, *H*, *H*, *H* and *S*, *S*, are represented in ground plan, and the direction of their dip is indicated by the arrow. Supposing that a stream is thrown across them in the direction of the dotted lines and that the land is then degraded, the following changes will take place. The portion of the stream from *c* to *d* will sink through the soft rock down to the surface of the hard, and then follow down the slope of the hard, until at last its whole course will be transferred to the line of separation between the two, and its position (with reference to the outcrops which will then have succeeded the original) will be represented by the line *g c*. The portion from *e* to *d* sinking first through the hard bed and then through the soft, will be deflected in the same manner to the position *e h g*. The points *e* and *c* will retain their original relations to the strata. The same changes will affect the portion from *e* to *f;* and the original oblique course will be converted into two sets of courses, of which one will follow the strike of the strata and the other will cross the strike at right angles.

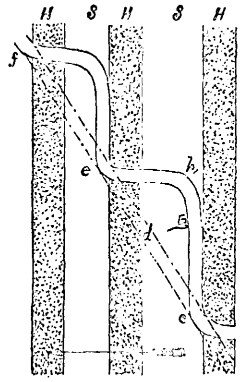


FIG. 67.—Ground plan of outcrops of inclined strata, to illustrate the results of Monoclinal Shifting.

The character of these changes is independent of the direction of the current. They are not individually of great amount, and they do not often divert streams from one drainage system to another nor change their general directions. Their chief effects are seen in the details of drainage systems and in the production of topographic forms. The tendency of hard strata to rid themselves of waterways and of soft strata to accumulate them, is a prime element of the process which carves hills from the hard and valleys from the soft. Where hard rocks are crossed by waterways they cannot stand higher than the adjacent parts of the waterways; but where they are not so crossed they become divides, and the "law of divides" conspires with the "law of structure" to carve eminences from them.

The tendency of waterways to escape from hard strata and to abide in soft, and their tendency to follow the strike of soft strata and to cross hard at right angles, are tendencies only and do not always prevail. They are opposed by the tendency of drainage lines to stability. If the dip of the strata is small, or if the differences of hardness are slight, or if the changes of texture are gradual instead of abrupt, monoclinal shifting is greatly reduced.

Waterpocket Cañon is one of the most remarkable of monoclinal valleys; and it serves to illustrate both the rule of monoclinal shifting and its exception. The principal bed of soft rock which outcrops along the line of the Waterpocket flexure is the Flaming Gorge shale, having a thickness of more than one thousand feet. Through nearly the whole extent of the outcrop a valley is carved from it, but the valley is not a unit in drainage. At the north it is crossed by the Dirty Devil River and by Temple and Tantalus Creeks, and the adjacent portions slope toward those streams. At the south it is occupied for thirty miles by a single waterway—the longest monoclinal drainage line with which I am acquainted. The valley here bears the name of Waterpocket Cañon, and descends all the way from the Masuk Plateau to the Colorado River. The upper part of the cañon is dry except in time of rain, but the lower carries a perpetual stream known as Hoxie Creek. Whatever may have been the original meanderings of the latter they are now restrained, and it is limited to the narrow belt in which the shale outcrops. As the cañon is worn deeper the channel steadily shifts its position down the slope of the underlying Gray Cliff sandstone, and carves away the shale. But there is one exceptional point where it has not done this. When the bottom of the cañon was a thousand feet higher the creek failed, at a place where the dip of the strata was comparatively small, to shift its channel as it deepened it, and began to cut its way into the massive sandstone. Having once entered the hard rock it could not retreat but sank deeper and deeper, carving a narrow gorge through which it still runs making a detour from the main valley. The traveler who follows down Waterpocket Cañon now comes to a place where the creek turns from

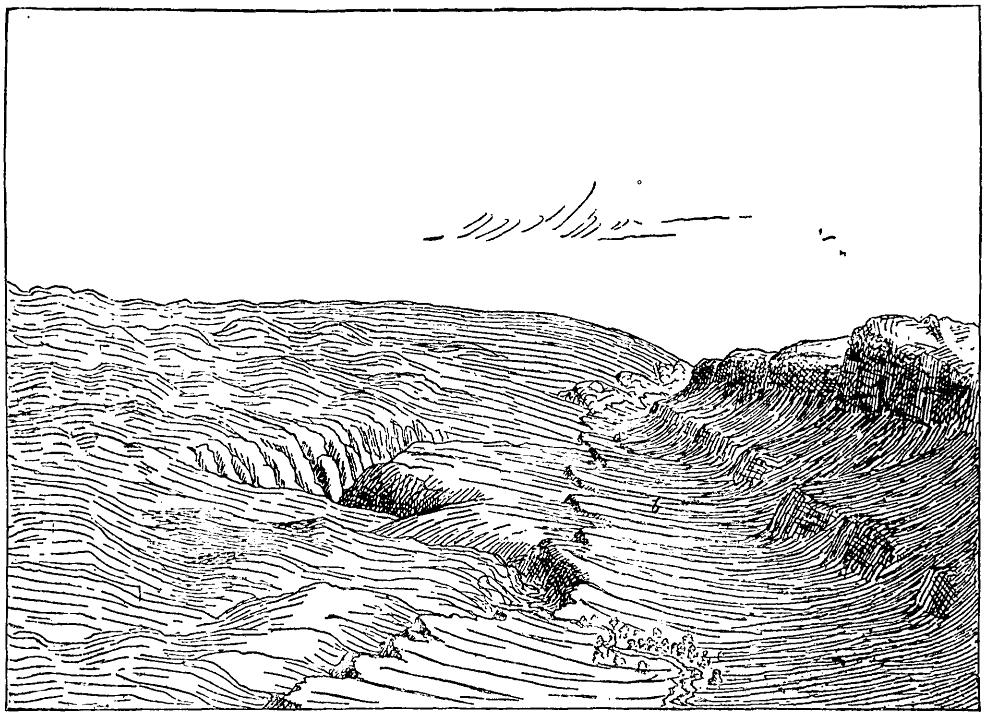


FIG. 68.—Waterpocket Cañon and the Horseshoe Bend of Hoxie Creek.

the open cañon of the shale and enters a dark cleft in the sandstone. He can follow the course of the water (on foot), and will be repaid for the wetting of his feet by the strange beauty of the defile. For nearly three miles he will thread his way through a gorge walled in by the smooth, curved faces of the massive sandstone, and so narrow and devious that it is gloomy for lack of sunlight; and then he will emerge once more into the open cañon. Or if he prefer he can keep to his saddle, to the open daylight, and to the outcrop of the shale, and riding over a low divide can reach the mouth of the gorge in half the distance.

THE STABILITY OF DIVIDES.

The rain drops which fall upon the two sides of a divide flow in opposite directions. However near to the dividing line they reach the earth the work of each is apportioned to its own slope. It disintegrates and transports the material of its own drainage slope only. The divide is the line across which no water flows—across which there is no transportation. It receives the minimum of water, for it has only that which falls directly upon it, and every other point receives in addition that which flows from higher points. It is higher than the surfaces which adjoin it, and since less water is applied to its degradation it tends to remain higher. It tends to maintain its position.

Opposed to this tendency there are others which lead to

THE INSTABILITY OF DIVIDES,

and which will now be considered.

Ponding, Planation, and Alluviation.

Whenever by ponding, a stream or a system of streams which have belonged to one drainage system are diverted so as to join another there is coincidently a change of divides. The general divide between the two systems is shifted from one side to the other of the area which changes its allegiance. The line which was formerly the main divide becomes instead a subordinate divide separating portions of the drainage system which has increased its area; and on the other hand a line which had been a subordinate divide is promoted to the rank of a main divide. In like manner the shifting of streams from one system of drainage to another by the extension of flood-plains, or by the building of alluvial cones or deltas, involves a simultaneous shifting of the divides which bound the drainage systems.

The changes which are produced by these methods are *per saltum.* When a pond or lake opens a new outlet and abandons its old one there is a short interregnum during which the drainage is divided between the two outlets, and the watershed separating the drainage systems is double. But in no other sense is the change gradual. The divide occupies no intermediate positions between its original and its final. And the same may be said of the changes by planation and alluviation. In each case a tract of country is transferred bodily from one river system to another, and in each case the watershed makes a leap.

But there are other methods of change, by which dividing lines move *slowly* across the land; and to these we will proceed.

Monoclinal Shifting.

In regions of inclined strata, the same process which gathers the waterways into the outcrops of the softer beds converts the outcrops of the harder into divides. As the degradation progresses the waterways and divides descend obliquely and retain the same relations to the beds. The waterways continuously select the soft because they resist erosion feebly, and the watersheds as continuously select the hard because they resist erosion strongly. If the inclination of the strata is gentle, each hard bed becomes the cap of a sloping table bounded by a cliff, and the erosion of the cliff is by sapping. The divide is at the brow of the cliff, and as successive fragments of the hard rock break away and roll down the

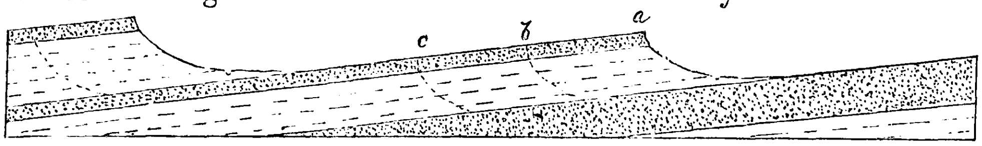


FIG. 69.—Ideal cross-section of inclined strata, to show the Shifting of Divides in Cliff Erosion. Successive positions of a divide are indicated at *a*, *b*, and *c*.

slope the divide is shifted. The process is illustrated in the Pink Cliffs of Southern Utah. They face to the south, and their escarpment is drained by streams flowing to the Colorado. The table which they limit inclines to the north and bears the head-waters of the Sevier. As the erosion of the cliffs steadily carries them back and restricts the table, the drainage area of the Colorado is increased and that of the "Great Basin", to which the Sevier River is tributary, is diminished.

Unequal and Equal Declivities.

In homogeneous material, and with equal quantities of water, the rate of erosion of two slopes depends upon their declivities. The steeper is degraded the faster. It is evident that when the two slopes are upon opposite sides of a divide the more rapid wearing of the steeper carries the divide toward the side of the gentler. The action ceases and the divide becomes stationary only when the profile of the divide has been rendered symmetric.

FIG. 70.—Cross-profile of a bad-land divide separating slopes of Unequal Declivity. Two stages of erosion are indicated, to illustrate the horizontal shifting of the divide.

It is to this law that bad-lands owe much of their beauty. They acquire their smooth curves under what I have called the "law of divides", but the symmetry of each ridge and each spur is due to the law of equal declivities. By the law of divides all the slopes upon one side of a ridge are made interdependent. By the law of equal declivities a relation is established between the slopes which adjoin the crest on opposite sides, and by this means the slopes of the whole ridge, from base to base, are rendered interdependent.

One result of the interdependence of slopes is that a bad-land ridge separating two waterways which have the same level, stands midway between them; while a ridge separating two waterways which have different levels, stands nearer to the one which is higher.

It results also that if one of the waterways is corraded more rapidly than the other the divide moves steadily toward the latter, and eventually, if the process continues, reaches it. When this occurs, the stream with the higher valley abandons the lower part of its course and joins its water to that of the lower stream. Thus from the shifting of divides there arises yet another method of the shifting of waterways, a method which it will be convenient to characterize as that of *abstraction*. A stream which for any reason is able to corrade its bottom more rapidly than do its neighbors, expands its valley at their expense, and eventually "abstracts" them. And conversely, a stream which for any reason is able to corrade its bottom less rapidly than its neighbors, has its valley contracted by their encroachments and is eventually "abstracted" by one or the other.

The diverse circumstances which may lead to these results need not be enumerated, but there is one case which is specially noteworthy on account of its relation to the principles of sculpture. Suppose that two streams which run parallel and near to each other corrade the same material and degrade their channels at the same rate. Their divide will run midway. But if in the course of time one of the streams encounters a peculiarly hard mass of rock while the other does not, its rate of corrasion above the obstruction will be checked. The unobstructed stream will outstrip it, will encroach upon its valley, and will at last abstract it; and the incipient corrasion of the hard mass will be stopped. Thus by abstraction as well as by monoclinal shifting, streams are eliminated from hard rocks.

Résumé.—There is a tendency to permanence on the part of drainage lines and divides, and they are not displaced without adequate cause. Hence every change which is known to occur demands and admits of an explanation.

(*a*) There are four ways in which abrupt changes are made. Streams are diverted from one drainage system to another, and the watersheds which separate the systems are rearranged,

(1) by *ponding*, due to the elevation or depression of portions of the land;
(2) by *planation*, or the extension of flood-plains by lateral corrasion;
(3) by *alluviation*, or in the process of building alluvial cones and deltas; and
(4) by *abstraction*.

(*b*) There are two ways in which gradual changes are effected:

(1) When the rock texture is variable, it modifies and controls by *monoclinal shifting* the distribution in detail of divides and waterways.
(2) When the rock texture is uniform, the positions of divides are adjusted in accordance with the principle of *equal declivities*.

The abrupt changes are of geographic import; the gradual, of topographic.

The methods which have been enumerated are not the only ones by which drainage systems are modified, but they are the chief. Very rarely streams are "ponded" and diverted to new courses through the damming of their valleys by glaciers or by volcanic *ejecta* or by land-slips. More frequently they are obstructed by the growing alluvial cones of stronger streams, but only the smallest streams will yield their "right of way" for such cause, and the results are insignificant.

The rotation of the earth, just as it gives direction to the trade-winds and to ocean currents, tends to deflect rivers. In the southern hemisphere streams are crowded against their left banks and in northern against the right. But this influence is exceedingly small. Mr. Ferrel's investigations show that in latitude 45° and for a current velocity of ten miles an hour, it is measured by less than one twenty-thousandth part of the weight of the water (American Journal of Science, January, 1861). If its effects are ever appreciable it must be where lateral corrasion is rapid; and even there it is probable that the chief result is an inclination of the flood-plain toward one bank or the other, amounting at most to two or three minutes.

CONSEQUENT AND INCONSEQUENT DRAINAGE.

If a series of sediments accumulated in an ocean or lake be subjected to a system of displacements while still under water, and then be converted to dry land by elevation *en masse* or by the retirement of the water, the rains which fall on them will inaugurate a drainage system perfectly conformable with the system of displacements. Streams will rise along the crest of each anticlinal, will flow from it in the direction of the steepest dip, will unite in the synclinals, and will follow them lengthwise. The axis of each synclinal will be marked by a watercourse; the axis of each anticlinal by a watershed. Such a system is said to be *consequent* on the structure.

If however a rock series is affected by a system of displacements after the series has become continental, it will have already acquired a system of waterways, and *provided the displacements are produced slowly* the waters will not be diverted from their accustomed ways. The effect of local elevation will be to stimulate local corrasion, and each river that crosses a line of uplift will inch by inch as the land rises deepen its channel and valorously maintain its original course. It will result that the directions of the drainage lines will be independent of the displacements. Such a drainage system is said to be *antecedent* to the structure.

But if in the latter case the displacements are produced rapidly the drainage system will be rearranged and will become consequent to the structure. It has frequently happened that displacements formed with moderate rapidity have given rise to a drainage system of mixed character in which the courses of the larger streams are antecedent and those of the smaller are consequent.

There is a fourth case. Suppose a rock series that has been folded and eroded to be again submerged, and to receive a new accumulation of unconforming sediments. Suppose further that it once more emerges and that the new sediments are eroded from its surface. Then the drainage system will have been given by the form of the upper surface of the superior strata, but will be independent of the structure of the inferior series, into which it will descend vertically as the degradation progresses. Such a drainage system is said to be *superimposed by sedimentation* upon the structure of the older series of strata.

Fifth. The drainage of an alluvial cone or of a delta is independent of the structure of the bed-rock beneath; and if in the course of time erosion takes the place of deposition and the alluvial formation is cut through, the drainage system which is acquired by the rocks beneath is not consequent upon their structure but is *superimposed by alluviation.*

Sixth. The drainage of a district of planation is independent of the structure of the rock from which it is carved; and when in the progress of degradation the beds favorable to lateral corrasion are destroyed and the waterways become permanent, their system may be said to be *superimposed by planation.*

In brief, systems of drainage, in their relation to structure, are

- (A) *consequent*
  - (a) by emergence, when the displacements are subaqueous, and
  - (b) by sudden displacement;
- (B) *antecedent*; and
- (C) *superimposed*
  - (a) by sedimentation, or subaqueous deposition,
  - (b) by alluviation, or subaërial deposition, and
  - (c) by planation.

THE DRAINAGE OF THE HENRY MOUNTAINS

is consequent on the laccolitic displacements. The uplifting of a laccolite, like the upbuilding of a volcanic cone, is an event of so rapid progress that the corrasion of a stream bed cannot keep pace with it. We do not know that the site of the mountains was dry land at the time of their elevation; but if it was, then whatever streams crossed it were obstructed and turned from their courses. If it was not, there were no preëxistent waterways, and the new ones, formed by the first rain which fell upon the domes of strata, radiated from the crests in all directions. The result in either case would be the same, and we cannot determine from the present drainage system whether the domes were lifted from the bed of the Tertiary lake or arose after its subsidence.

But while the drainage of the Henry Mountains is consequent as a whole, it is not consequent in all its details, and the character of its partial inconsequence is worthy of examination.

Let us begin with the simplest case. The drainage system of Mount Ellsworth is more purely consequent than any other with which I am acquainted. In the accompanying chart the point *c* marks the crest of the Ellsworth dome; the inner circle represents the line of maximum dip of the

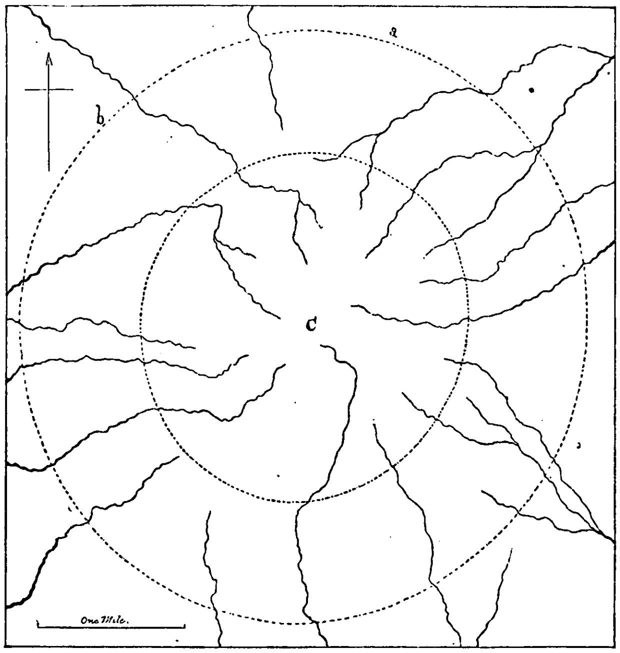


FIG. 71.—Drainage system of the Ellsworth Arch.

arching strata and the outer circle the limit of the disturbance. It will be seen that all the waterways radiate from the crest and follow closely the directions in which the strata incline. At *a* the Ellsworth arch touches that of Mount Holmes and at *b* that of Mount Hillers; and the effect of the compound inclination is to modify the directions of a few of the waterways.

Turning now to Mount Holmes, we find that its two domes are not equally respected by the drainage lines. The crest of the Greater arch (see Figure 72) is the center of a radiating system, but the crest of the Lesser

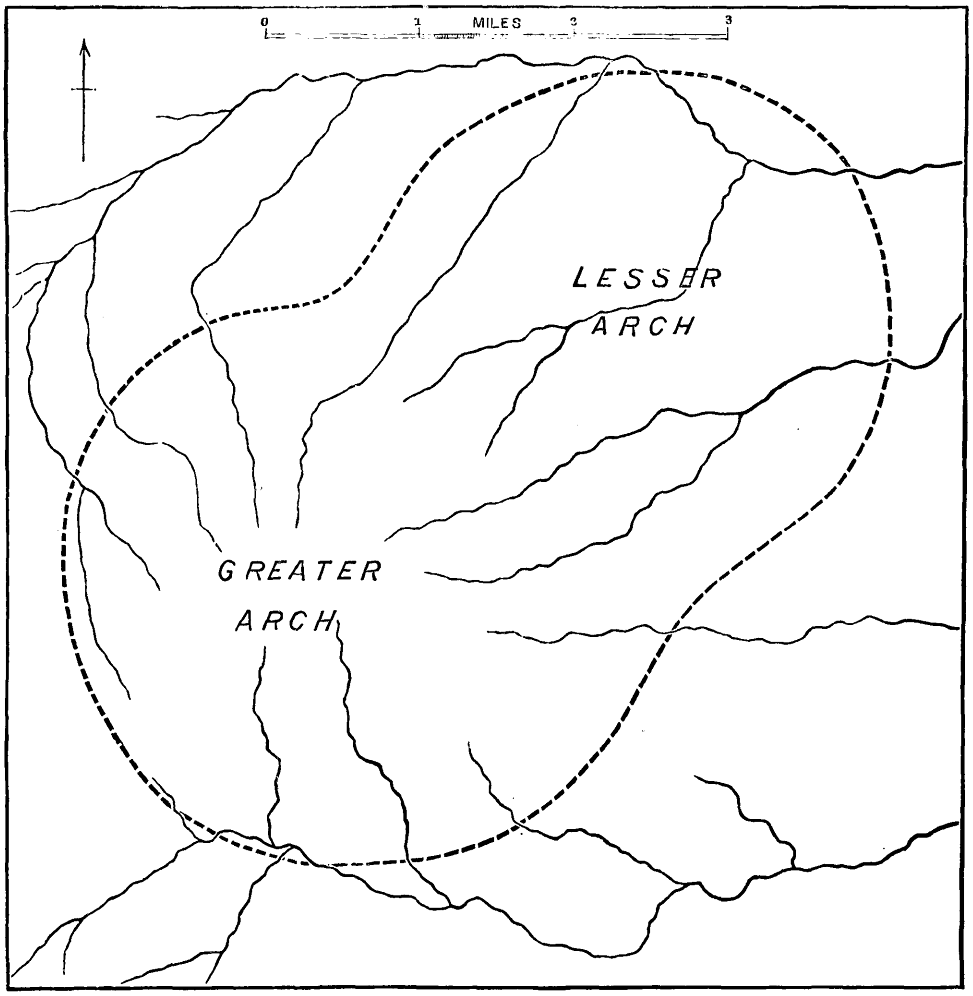


FIG. 72.—Drainage system of the Holmes Arches.

arch is not; and waterways arising on the Greater traverse the Lesser from side to side. More than this, a waterway after following the margin of the Lesser arch turns toward it and penetrates the flank of the arch for some distance. In a word, the drainage of the Greater arch is consequent on the structure, while the drainage of the Lesser arch is inconsequent.

There are at least two ways in which this state of affairs may have arisen.

First, the Greater arch may have been lifted so long before the Lesser that its waterways were carved too deeply to be diverted by the gentle flexure of the latter. The drainage of the Lesser would in that case be classed as antecedent. If the Lesser arch were first formed and carved, the lifting of the Greater might throw a stream across its summit; but it could not initiate the waterways which skirt the slopes of the Lesser, especially if those slopes were already furrowed by streams which descended them. If the establishment of the drainage system depended on the order of uplift, the Greater arch is surely the older.

Second, the drainage of the Lesser arch may have been imposed upon it by planation at a very late stage of the degradation. Whatever was the origin of the arches, and whatever was the depth of cover which they sustained, the Greater is certain to have been a center of drainage from the time of its formation. When it was first lifted it became a drainage center because it was an eminence; and afterward it remained an eminence because it was a drainage center. When in the progress of the denudation its dikes were exposed, their hardness checked the wear of the summit and its eminence became more pronounced. It was perhaps at about this time that the last of the Cretaceous rocks were removed from the summits and slopes of the two arches and the Flaming Gorge shale was laid bare, and so soon as this occurred the conditions for lateral corrasion were complete. With trachyte in the peaks and shale upon the slopes planation would naturally result, and a drainage system would be arranged about the dikes as a center without regard to the curves of the strata. The subsequent removal of the shale would impart its drainage to the underlying sandstones.

Either hypothesis is competent to explain the facts, but the data do not warrant the adoption of one to the exclusion of the other. The waterways of the Lesser arch may be either antecedent, or superimposed by planation. The Greater arch may have been the first to rise or the last.

The drainage of Mount Hillers is consequent to the main uplift and to the majority of the minor, but to the Pulpit arch it is inconsequent. In this case there is no question that the arch has been truncated by planation. (Figure 73.) The Hillers dome, rising five times as high as the Pulpit, became the center of drainage for the cluster, and the trachyte-laden streams which it sent forth were able to pare away completely the lower arch while it was still unprotected by the hardness of its nucleus. The foot-plain of Mount Hillers, which extends unbroken to the outcrop of the Henry's Fork conglomerate, is continued on several lines across the Pulpit arch, although in the intervals the central area is deeply excavated. The planation stage is just completed, and an epoch of fixed waterways is inaugurated.

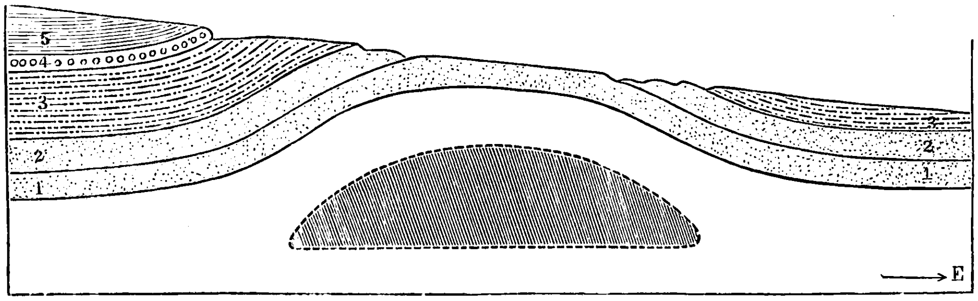


FIG. 73.—Cross-section of the Pulpit Arch, showing its truncation.

The drainage of Mount Pennell is consequent in regard to the main uplift, but inconsequent to some of the minor. A stream which rises on the north flank not merely runs across one of the upper series of laccolites,—a companion to the Sentinel,—but has cut into it and divided it nearly to the base. It is probable that the position of the waterway was fixed by planation, but no remnant of the plain was seen.

Too little is known of the structure of the central area of Mount Ellen to assert its relation to the drainage. About its base there are five laccolites which have lost all or nearly all their cover, and each of these is a local center of drainage, avoided by the streams which head in the mountain crest. Four others have been laid bare at a few points only, and these are each crossed by one or two streams from higher levels. The remainder are not exposed at all, and their arches are crossed by numerous parallel streams. The Crescent arch is freshly truncated by planation, and the Dana and Maze bear proof that they have at some time been truncated. The laccolites which stand highest with reference to the general surface are exempt from cross-drainage, and the arches which lie low are completely overrun.

If we go back in imagination to a time when the erosion of the mountain was so little advanced that the stream-beds were three thousand feet higher than they now are, we may suppose that very little trachyte was laid bare. As the surface was degraded and a few laccolites were exposed, it would probably happen that some of the then-existing streams would be so placed as to run across the trachyte. But being unarmed as yet by the *débris* of similar material they would corrade it very slowly; and the adjoining streams having only shale to encounter, would so far outstrip them as eventually to divert them by the process of "abstraction". In this way the first-bared laccolites might be freed from cross-drainage and permitted to acquire such radiating systems of waterways as we find them to possess. At a later stage when trachyte was exposed at many points and all streams were loaded with its waste, the power to corrade was increased, and the lower-lying laccolites could not turn aside the streams which overran them.

The work of planation is so frequently seen about the flanks of the Henry Mountains that there seems no violence in referring all the cross-drainage of lateral arches to its action; and if that is done the history of the erosion of the mountains takes the following form:

When the laccolites were intruded, the mounds which they uplifted either rose from the bed of a lake or else turned back all streams which crossed their sites; and in either case they established upon their flanks a new and "consequent" set of waterways. The highest mounds became centers of drainage, and sent their streams either across or between the lower. All the streams of the disturbed region rose within it and flowed outward. The degradation of the mounds probably began before the uplift was complete, but of this there is no evidence. As it proceeded the convex forms of the mounds were quickly obliterated and concave profiles were substituted. The rocks which were first excavated were not uniform in texture, but they were all sedimentary and were soft as compared to the trachyte. The Tertiary and probably the Upper Cretaceous were removed from the summits before any of the igneous rocks were brought to light, and during their removal the tendency of divides to permanence kept the drainage centers or maxima of surface at substantially the same points. When at length the trachyte was reached its hardness introduced a new factor. The eminences which contained it were established more firmly as maxima, and their rate of degradation was checked. With the checking of summit degradation and the addition of trachyte to the transported material, planation began upon the flanks, and by its action the whole drainage has been reformed. One by one the lower laccolites are unearthed, and each one adds to the complexity and to the permanence of the drainage.

If the displacements were completed before the erosion began, the mountains were then of greater magnitude than at any later date. Before the igneous nuclei were laid bare and while sedimentary rocks only were subject to erosion, the rate of degradation was more rapid than it has been since the hardness and toughness of the trachyte have opposed it. If the surrounding plain has been worn away at a uniform rate, the height of the mountains (above the plain) must have first diminished to a minimum and afterward increased. The minimum occurred at the beginning of the erosion of the trachyte, and at that time the mountains may even have been reduced to the rank of hills. They owe their present magnitude, not to the uplifting of the land in Middle Tertiary time, but to the contrast between the incoherence of the sandstones and shales of the Mesozoic series and the extreme durability of the laccolites which their destruction has laid bare. And if the waste of the plain shall continue at a like uniform rate in the future, it is safe to prophesy that the mountains will for a while continue to increase in relative altitude. The phase which will give the maximum resistance to degradation has been reached in none of the mountains, except perhaps Mount Hillers. In Mount Ellen the laccolites of the upper zone only have been denuded; the greater masses which underlie them will hold their place more stubbornly. The main bodies of Mounts Ellsworth, Holmes, and Pennell are unassailed, and the present prominence of their forms has been accomplished simply by the valor of their skirmish lines of dikes and spurs. In attaching to the least of the peaks the name of my friend Mr. Holmes, I am confident that I commemorate his attainments by a monument which will be more conspicuous to future generations and races than it is to the present.

CHAPTER VI.

ECONOMIC.

There is little to add to what has already been said of the economic value of the mountains, and this chapter is hardly more than a regrouping of facts scattered through those that precede.

Coal.—Possibly some valuable though restricted deposit was overlooked; but it is safe to say that no thick and continuous bed will be found. The Cretaceous sandstones all contain thin and local beds—enough to mark them as coal-bearing rocks—but there are no seams of value. The best outcrop was seen in the bank of the south branch of Lewis Creek where it crosses the upturned edge of the Blue Gate sandstone. The seam has a thickness of four feet only, and is not well disposed for mining.

But if the Cretaceous coals were well developed it is to be doubted if they would ever be used. They could have no local market. They could not be carried to the east or south on account of the cañons. If taken northward they would have to compete with the coal of Castle Valley, which is more convenient and very abundant. If taken westward to the metal mines of Nevada and Western Utah they would be undersold by the more accessible coals found on the headwaters of the Virgin River and Kanab Creek, and even by those of the Kaiparowits Plateau.

The *Gypsum* and *Building Stones* of the region need not be described. They are plentiful in many parts of Utah, and however abundant in this remote place can never be in demand.

Gold, Silver, etc.—Three parties of "prospectors" have at different times made unsuccessful search for metalliferous veins. In the course of my survey I spent more than a month's time among the crystalline and metamorphic formations of the mountain tops, and although directing my attention constantly to the rocks, did not discover a fissure vein. Combining these negative data with certain theoretic considerations which are set forth in the fourth chapter, I am led to the very confident opinion that the essential conditions for the production of fissure veins have not existed in the Henry Mountains, and hence that there are no valuable deposits of the precious metals. The same theoretic considerations apply to other mountains of the same character, and I venture to predict that gold and silver will not be found in paying quantity in Navajo Mountain, the Sierra la Sal, the Sierra Abajo, the Sierra Carisso, or the Sierra La Lata.

Agricultural Land.—Bowl Creek, both branches of Lewis Creek, and the south branch of Trachyte Creek can readily be led to tracts of land sufficiently level for farming, and each furnishes enough water to irrigate several hundred acres. It is possible that these tracts will prove useful for farming, but they lie a little too high to be assured of a favorable climate. The lowest has an altitude of 6,000, and the highest of 6,800 feet.

Grazing Land.—Above the altitude of 7,500 feet there are many tracts of good grass, available for grazing through the greater part of the year but covered by snow in the winter. Below that level there is a greater area of inferior grass, available through the whole year. By using one portion in summer and the other in winter the mountains could be made to give permanent support to a herd of 3,000 or 4,000 cattle. With such overstocking as is often practiced in Utah they may subsist 10,000 animals for one or two years.

Timber.—The trees worthy to be classed as timber are of three species—fir (*Abies Engelmanni*), Douglass spruce (*A. Douglasii*), and yellow pine (*Pinus ponderosa*). The pine is the most valuable and the fir the most abundant. The fir grows upon the mountain slopes, above the level of 7,500 feet and forms thick-set forests. The total area which it covers is not far from twenty-five square miles. The spruce mingles with the fir at the lower edges of the forests; and the pine forms a few open groves a little lower down the slopes.

It is to be doubted if the trees will ever be cut. Other timber of the same quality and superior in quantity lies between it and the settlements, and neither railroad nor mine nor town is likely to create a local demand.

Coal, building stone, gypsum, and timber have no value for lack of a market, either present or prospective; gold and silver are not found; and there is little or no land that can be successfully farmed. Only for grazing have the mountains a money value.

INDEX.


Plate I.
Curtis Creek
Rabbit Valley
Red Gate
Blue Gate
DIRTY DEVIL RIVER
Lewis Creek
Bowl Creek
Temple Creek
Tantalus Creek
AQUARIUS PLATEAU
HENRY MOUNTAINS
Crescent Creek
38°
MASUK PLATEAU
Pine Creek
Trachyte Creek
Boulder Creek
Winslow Creek
CIRCLE CLIFFS
Alcove Creek
Potato Valley
ESCALANTE RIVER
KAIPAROWITS PLATEAU
Hoxie Creek
COLORADO RIVER
MAP
of the
HENRY MOUNTAINS
AND
VICINITY.
Photographed from a model in relief.
Triangulation by A. H. Thompson.
Topography by W.H.Graves.
Scale of Miles.
0 5 10 15

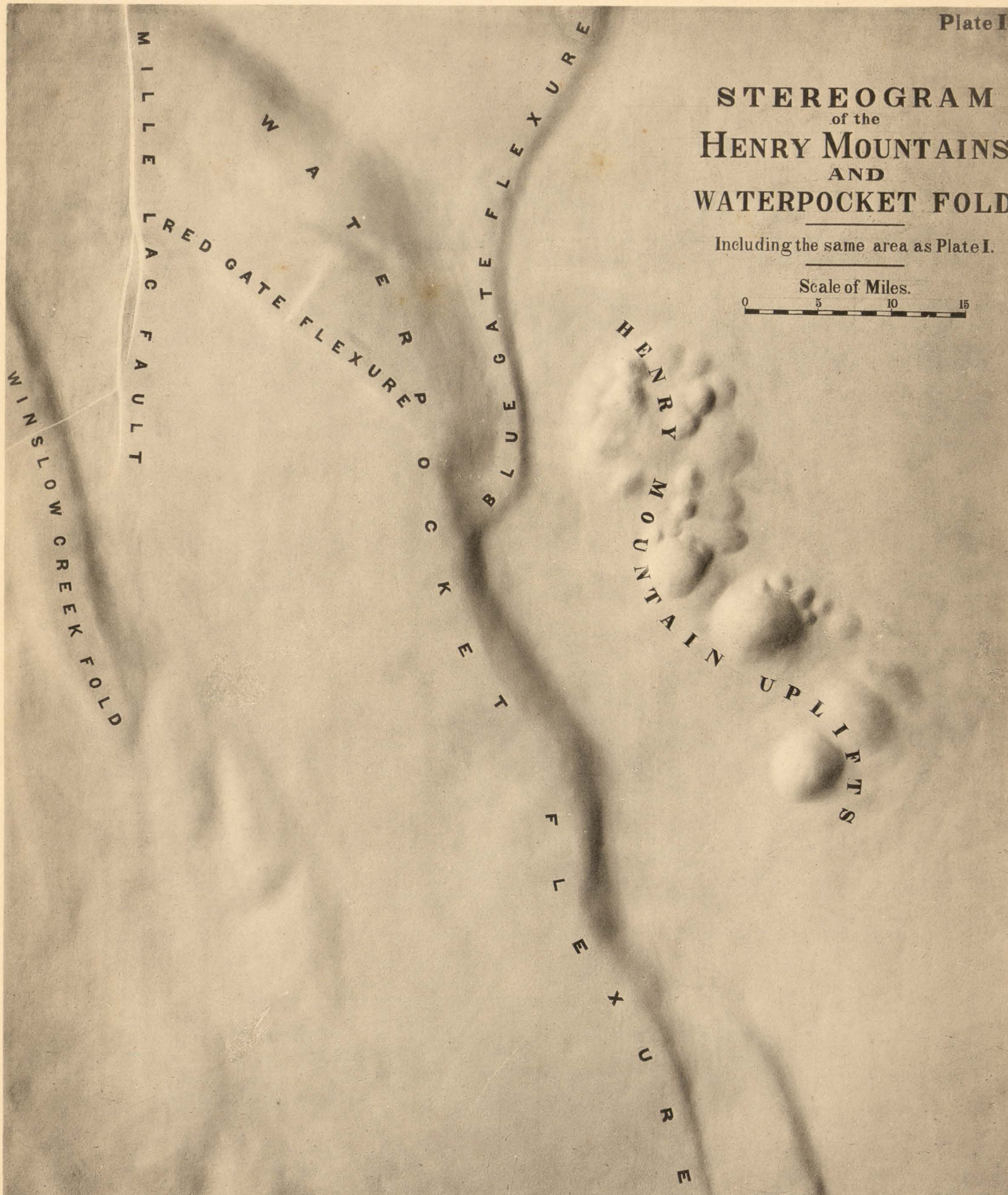
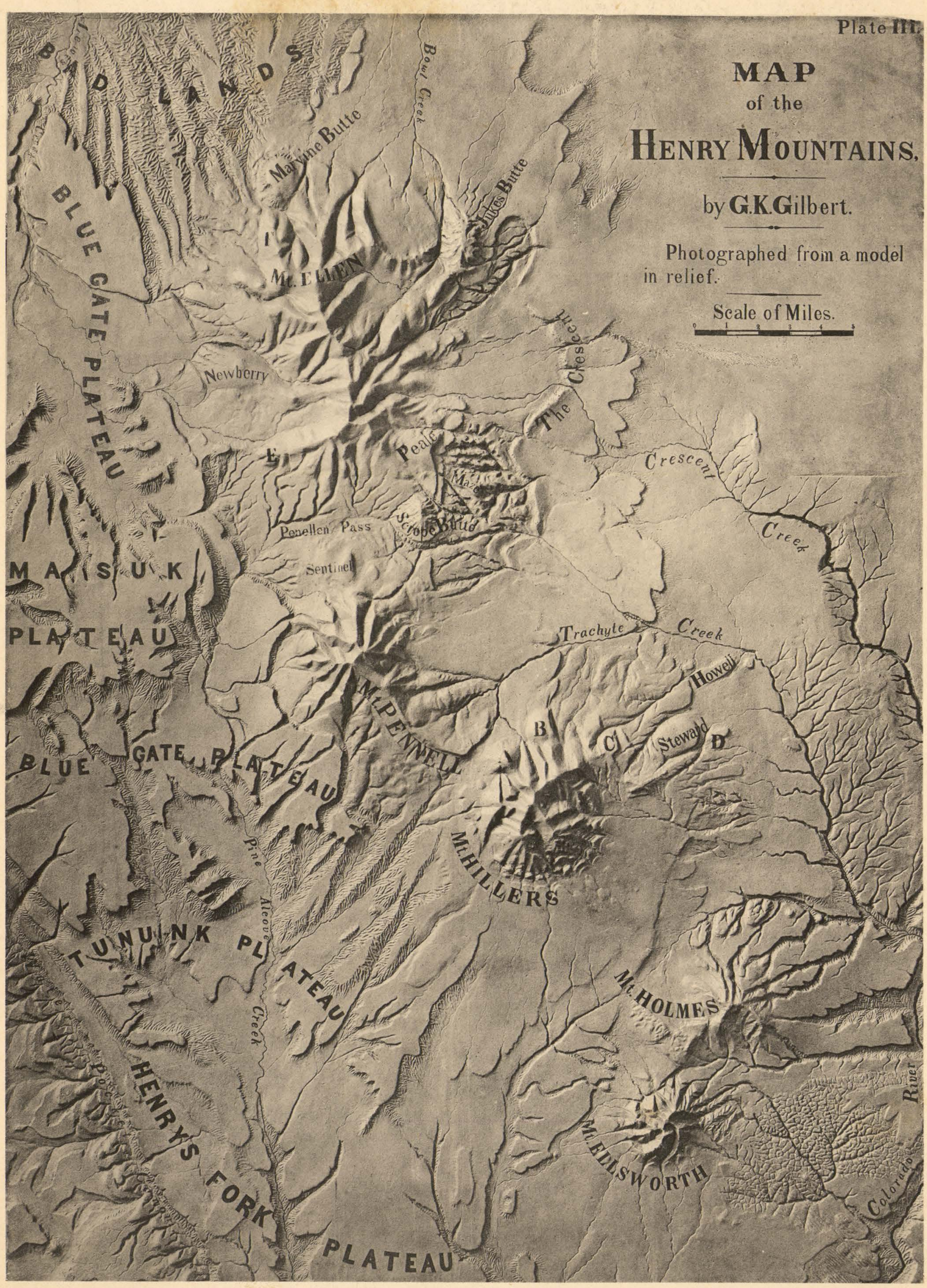


Plate II

STEREOGRAM
of the
HENRY MOUNTAINS
AND
WATERPOCKET FOLD.

Including the same area as Plate I.


MAP
of the
HENRY MOUNTAINS,
by G.K.Gilbert.
Photographed from a model in relief.
Scale of Miles.
BAD LANDS
Bowl Creek
Marvine Butte
Jukes Butte
BLUE GATE PLATEAU
Mt. ELLEN
Newberry
The Crescent
Peale
Crescent Creek
Penellen Pass
Scrope Butte
Sentinel
MA SUK PLATEAU
Trachyte Creek
Howell
Mt. PENNELL
B
C
Steward
D
BLUE GATE PLATEAU
Pine Alcove Creek
Mt. HILLERS
TUNUNK PLATEAU
Mt. HOLMES
HENRYS FORK PLATEAU
Mt. ELLSWORTH
Colorado River

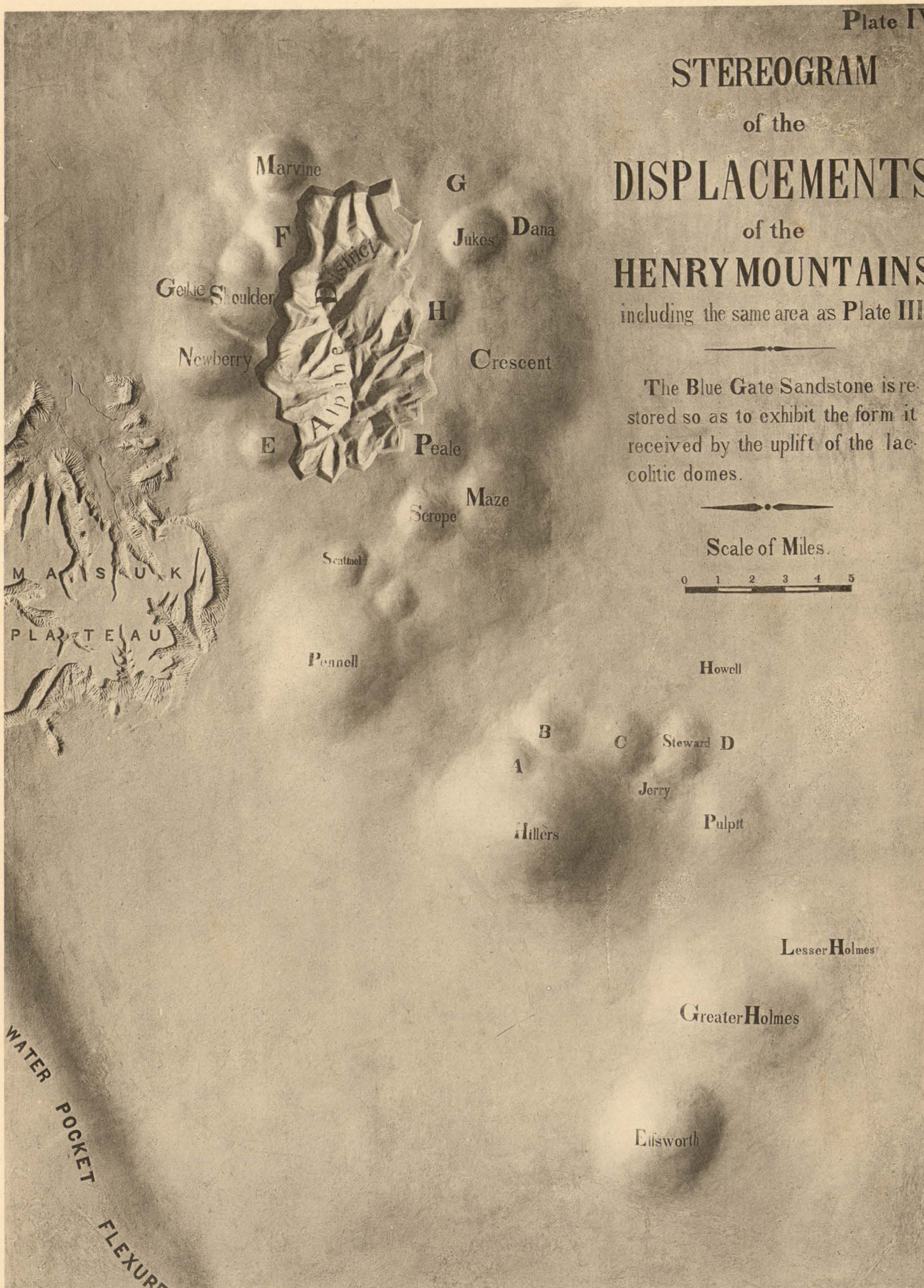


Plate IV

STEREOGRAM of the DISPLACEMENTS of the HENRY MOUNTAINS

including the same area as Plate III.

The Blue Gate Sandstone is restored so as to exhibit the form it received by the uplift of the laccolitic domes.

CRETACEOUS
- Ma-suk' Sandstone.
- Blue Gate Sandstone.
- Tu-nunk' and Henry's Fork Sandstones.

JURA-TRIAS
- Flaming Gorge Group.
- Gray Cliff and Vermilion Cliff Groups.
- Shin-ar'-ump Group.

CARBONIFEROUS; Aubrey Group.

Trachyte.

THE HELIOTYPE PRINTING CO. 220 DEVONSHIRE ST. BOSTON.