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.

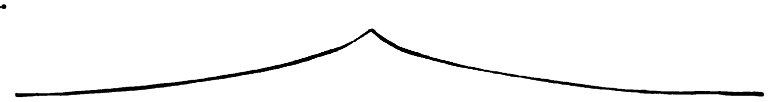


FIG. 54.—Typical profile of the Drainage Slopes of Mountains.

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 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.

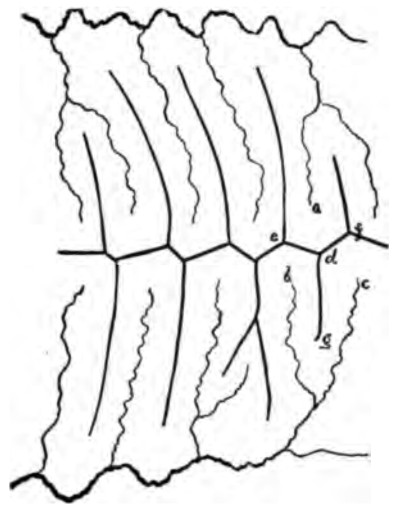
If we examine a bad-land ridge, separating two drainage lines and forming a divide between them, we find an arrangement of secondary ridges and secondary drainage lines, similar to that represented in the diagram, (Figure 58.)

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 *ed* 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.



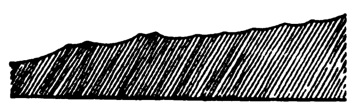


FIG. 58.—Ground-plan of a Bad-land Ridge, showing its relation to Waterways. The smooth lines represent Divides.
FIG. 59.—Profile of the same ridge.

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-

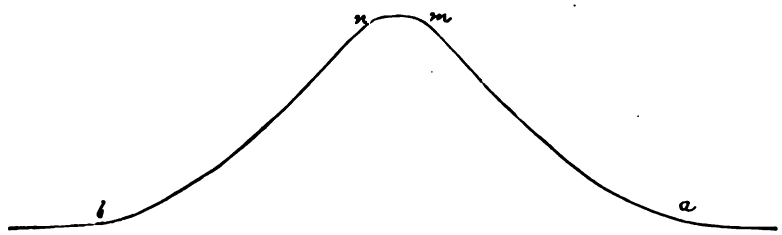


FIG. 60.—Cross-profile of a Bad-land Divide.

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

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

FIG. 56.—The Crest of Mount Holmes.

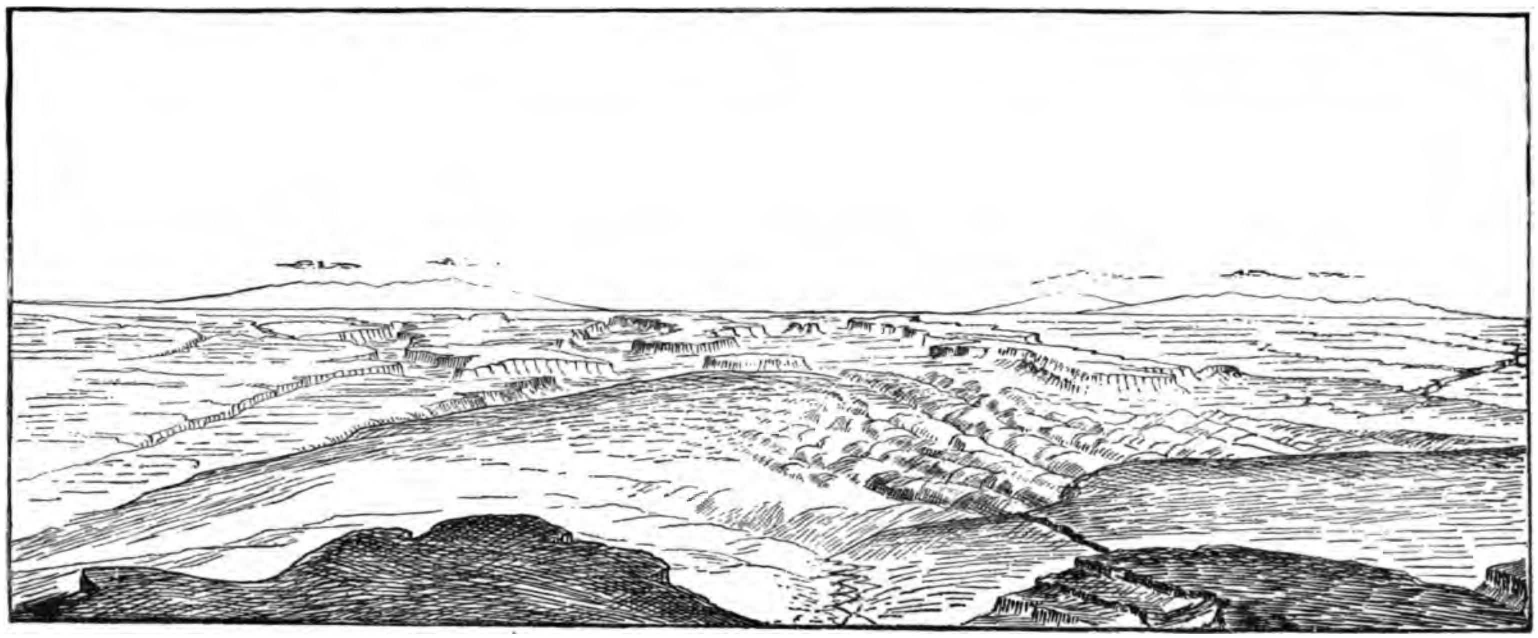


FIG. 57.—General view of the Plateaus lying East of the Henry Mountains.