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.

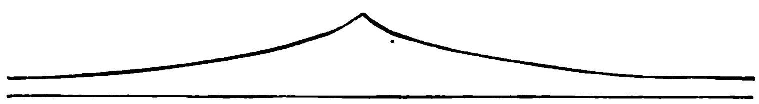


FIG. 54.—Typical profile of the Drainage Slopes of Mountains.

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.)

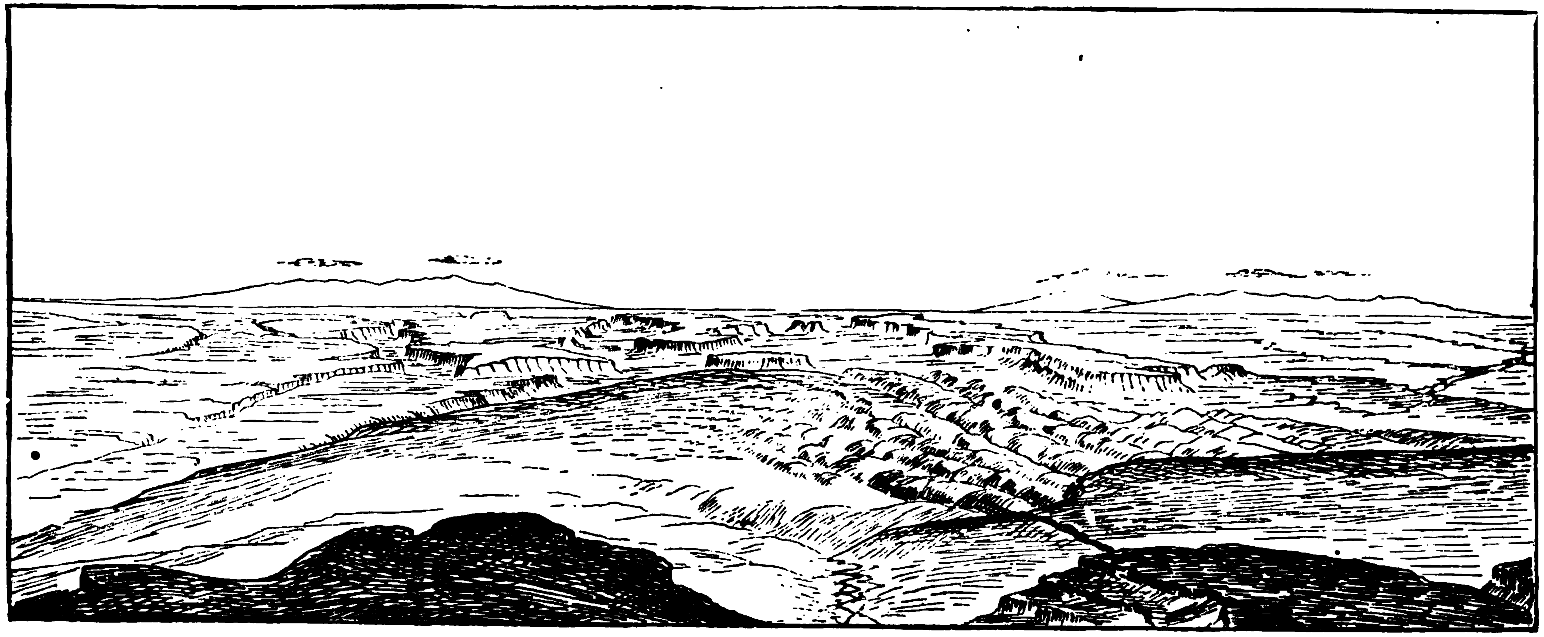


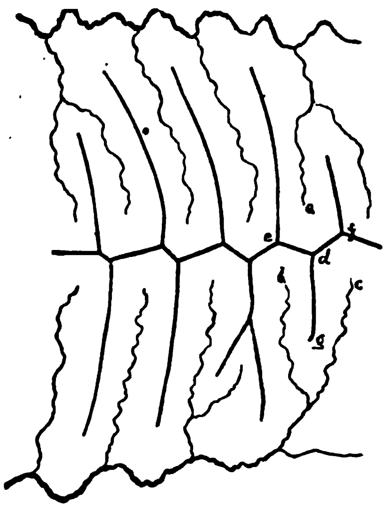
Fig. 57.—General view of the Plateaus lying East of the Henry Mountains.

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 *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 simultataneously determined by the intersection of the three divide lines.



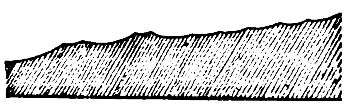


FIG. 58.—Ground-plan of a Bad-land Ridge, showing its relation to Waterways. The smooth lines represent Divides.

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-

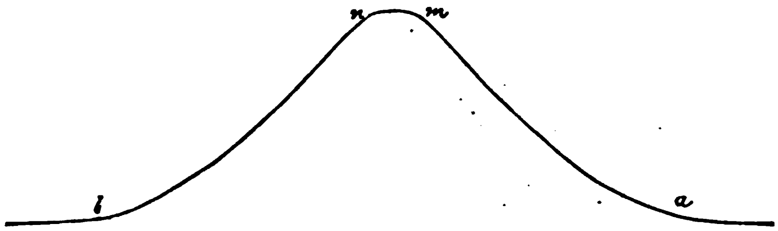


FIG. 60.—Cross-profile of a Bad-land Divide.

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 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.

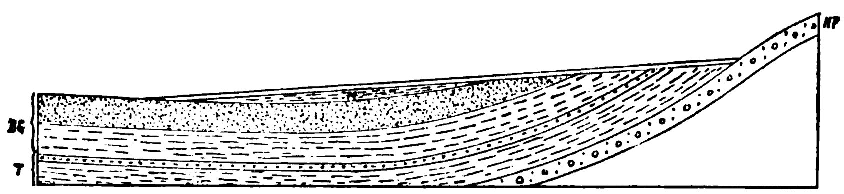


FIG. 61.—Cross-section of the Lewis Creek Plain. M, Masuk Shale. BG, Blue-Gate Group. T, Tununk Group. HF, Henry's Fork conglomerate. Scale, 1 inch = 4,000 feet.

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.

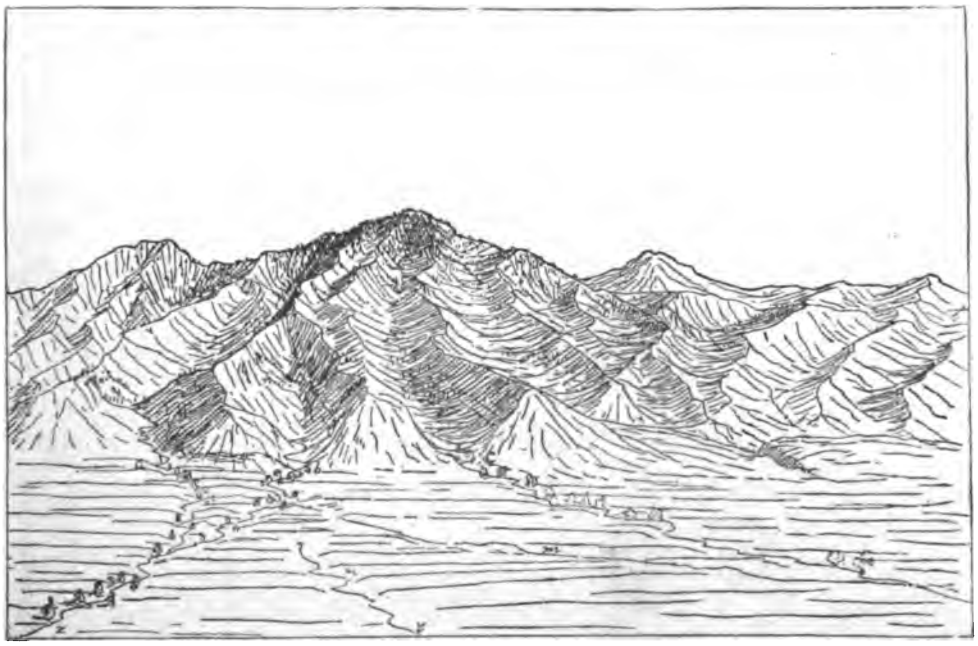


FIG. 62.—Ideal sketch to illustrate the Shifting of waterways on a slope of Planation.

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.

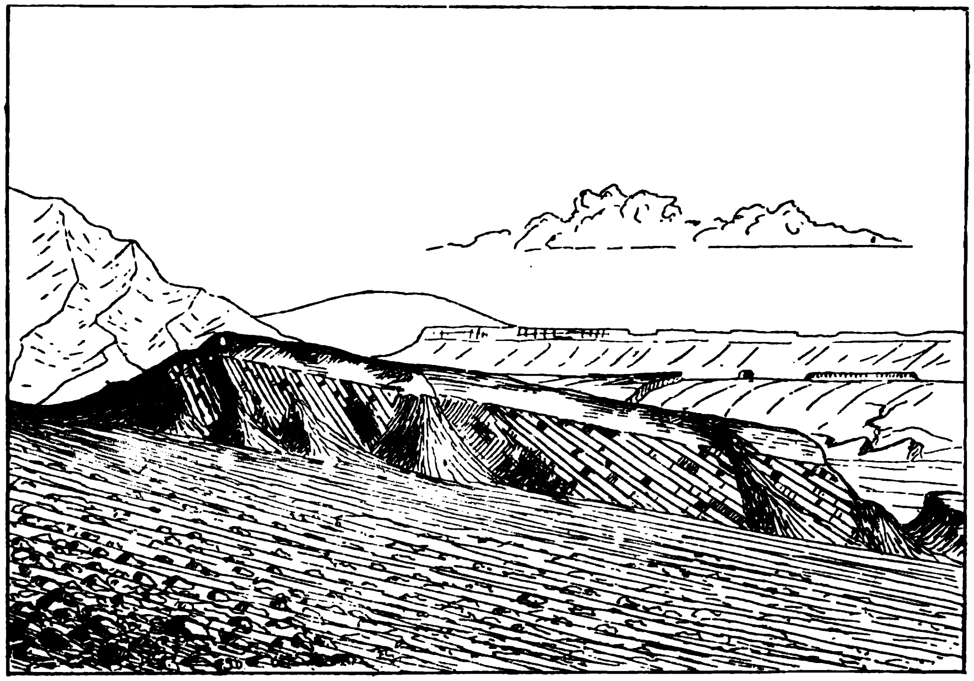


FIG. 63.—A Hill of Planation.

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

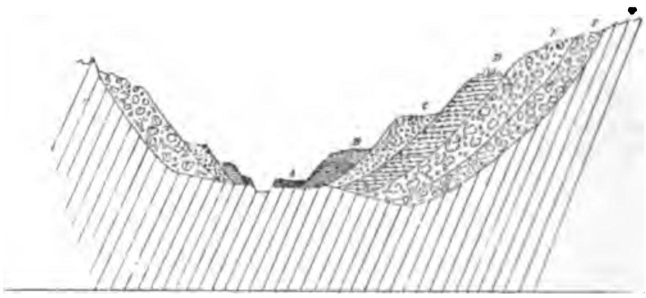


FIG. 64.—Ideal cross-section of a Terraced River Valley, after Hitchcock. A, B, C, D, E, and F, Alluvial deposits. G, Indurated rock, *in situ*.

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

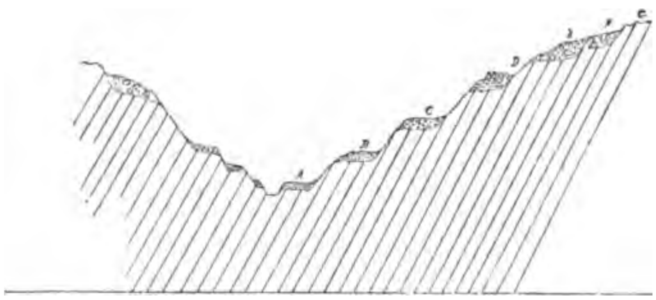


Fig. 65.—Ideal cross-section of a Terraced River Valley, regarded as a result of Planation. A, B, C, &c., Alluvial deposits. G, Preëxistent material from which the valley was excavated.

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.

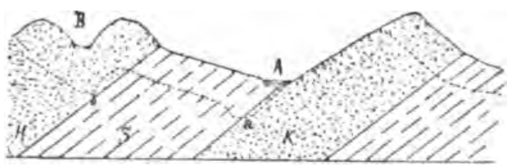


FIG. 66.—Cross-section of inclined strata, to illustrate Monoclinal Shifting of waterways.

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.

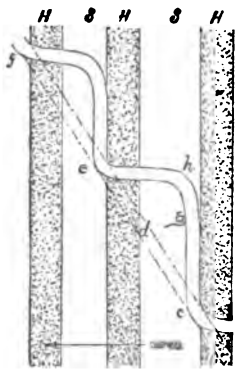


FIG. 67.—Ground plan of outcrops of inclined strata, to illustrate the results of Monoclinal Shifting.

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

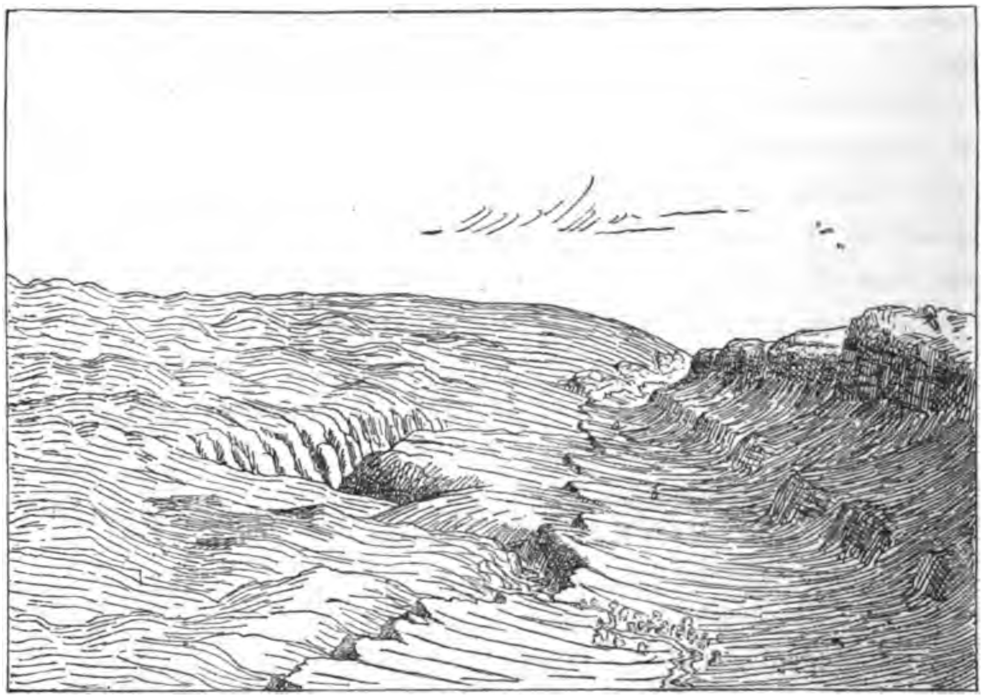


FIG. 68.—Waterpocket Cañon and the Horseshoe Bend of Hoxie Creek.

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 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.

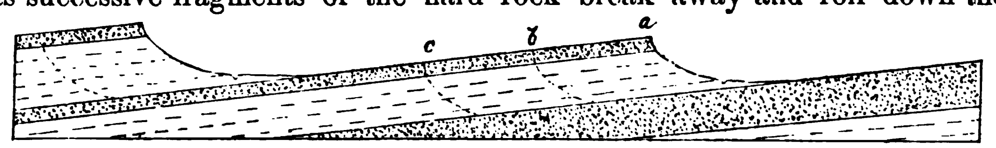


FIG. 69.—Ideal cross-section of inclined strata, to show the Shifting of Divides in Cliff Erosion. Successive positions of a divide are indicated at *a*, *b*, and *c*.

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.

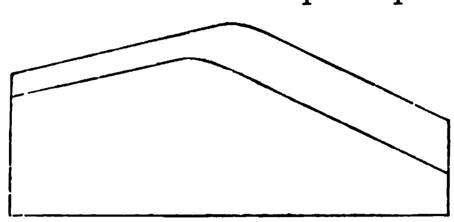


FIG. 70.—Cross-profile of a bad-land divide separating slopes of Unequal Declivity. Two stages of erosion are indicated, to illustrate the horizontal shifting of the divide.

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

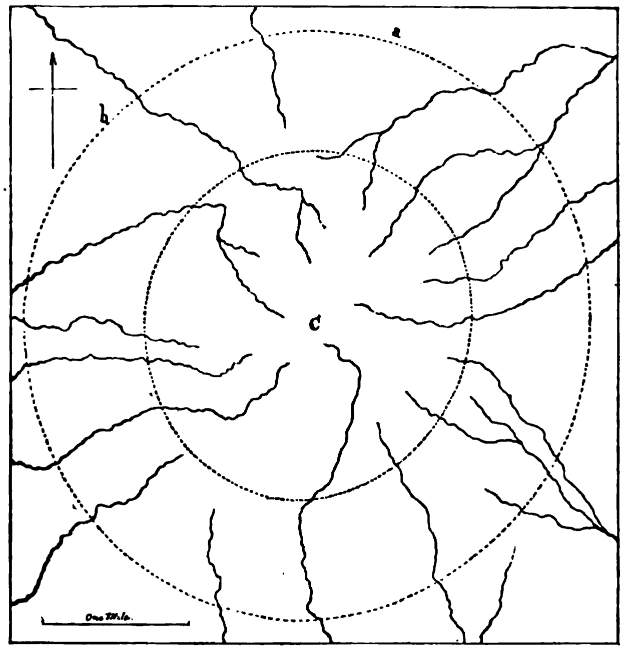


FIG. 71.—Drainage system of the Ellsworth Arch.

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

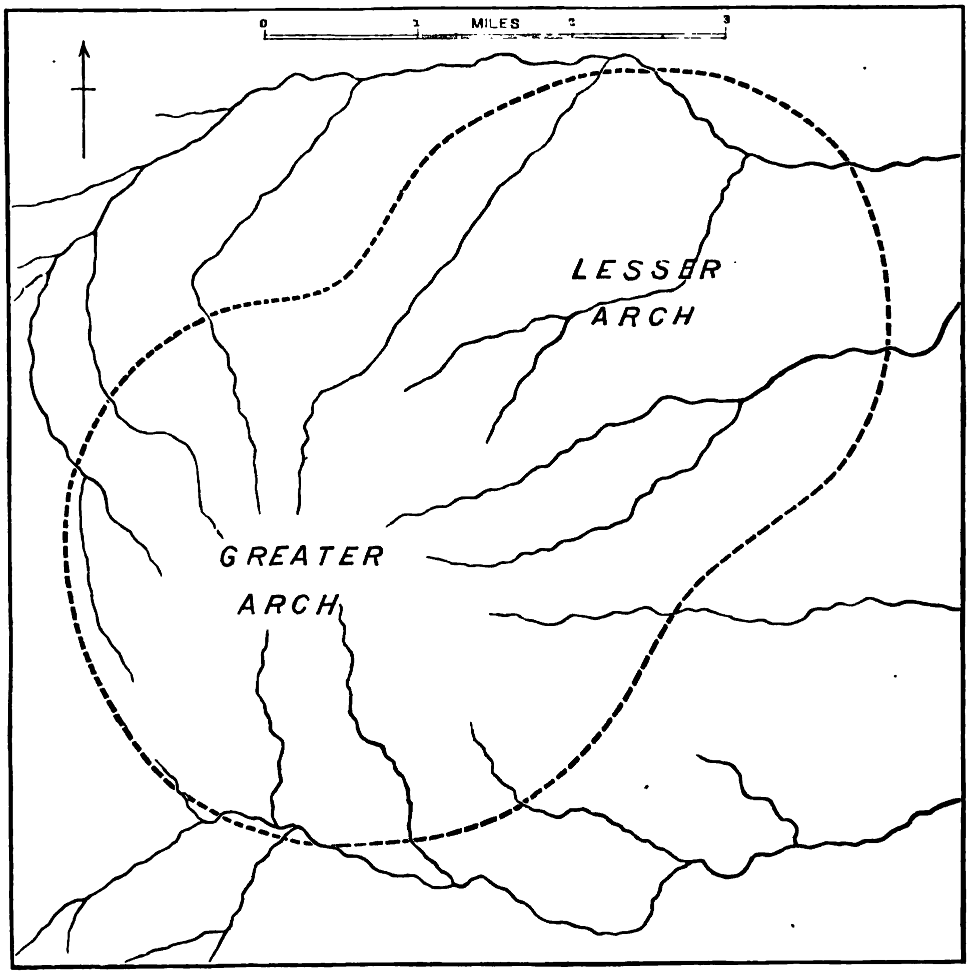


FIG. 72.—Drainage system of the Holmes Arches.

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.

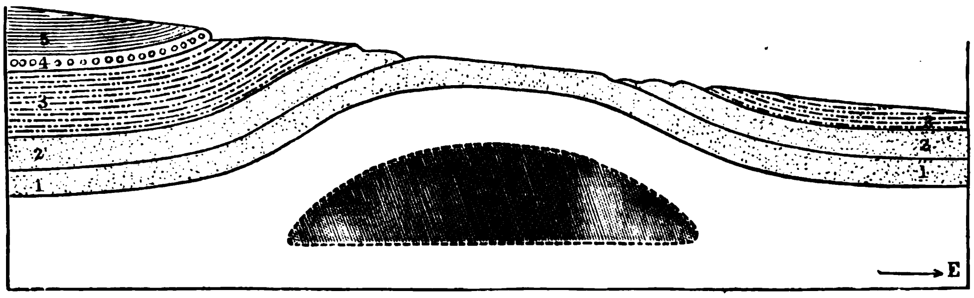


FIG. 73.—Cross-section of the Pulpit Arch, showing its truncation.

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.