steadily diminished by the reaction of rate of erosion upon declivity. Every slope is a member of a series, receiving the water and the waste of the slope above it, and discharging its own water and waste upon the slope below. If one member of the series is eroded with exceptional rapidity, two things immediately result: first, the member above has its level of discharge lowered, and its rate of erosion is thereby increased; and second, the member below, being clogged by an exceptional load of detritus, has its rate of erosion diminished. The acceleration above and the retardation below, diminish the declivity of the member in which the disturbance originated; and as the declivity is reduced the rate of erosion is likewise reduced.

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

III.—SYSTEMS OF DRAINAGE.

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

THE STABILITY OF DRAINAGE LINES.

In corrasion the chief work is performed by the impact and friction of hard and heavy particles moved forward by running water. They are driven against all sides of the channel, but their tendency to sink in water brings them against the bottom with greater frequency and force than against the walls. If the rate of wear be rapid, by far

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

FIG. 56.—The Crest of Mount Holmes.

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

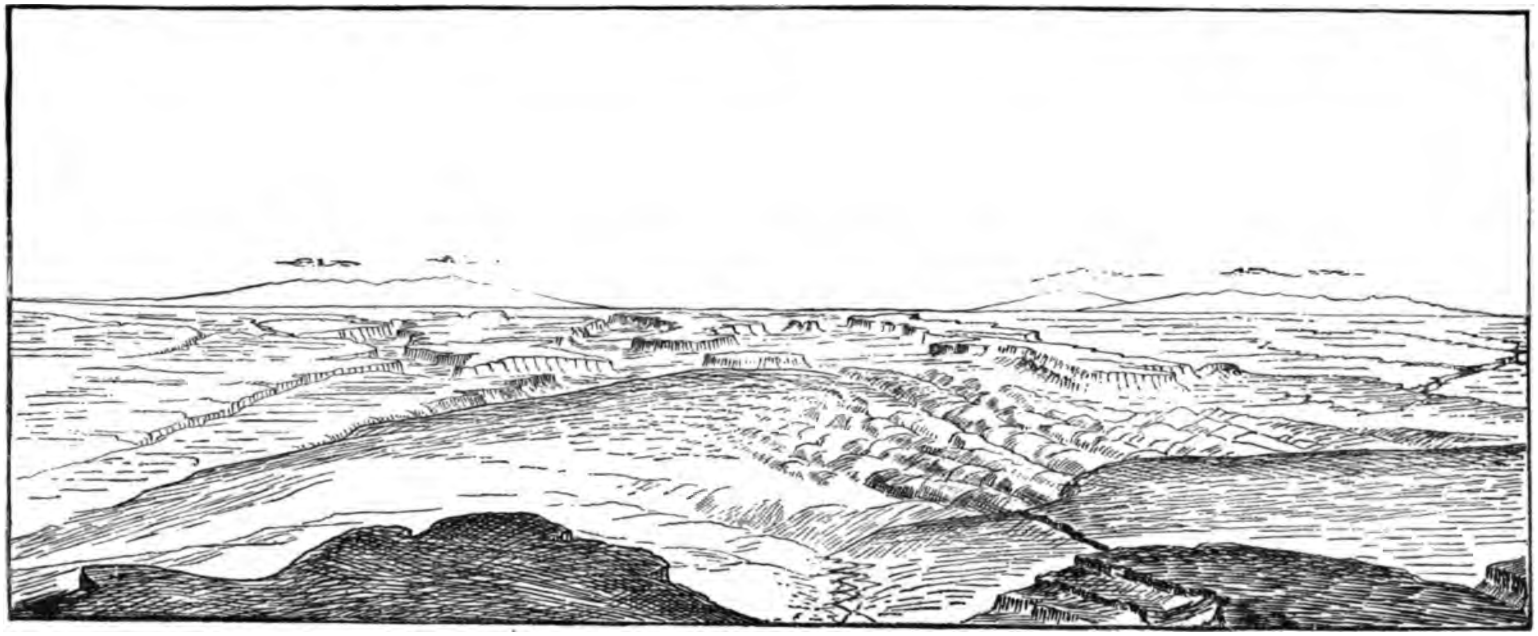

Fig. 57.—General view of the Plateaus lying East of the Henry Mountains.

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 Fremont, 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.

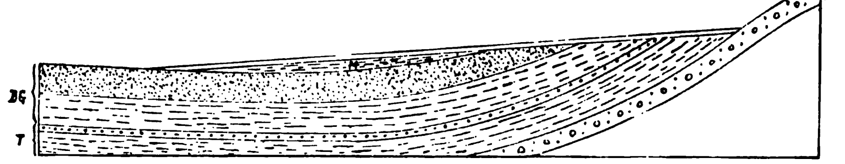

FIG. 61.—Cross-section of the Lewis Creek Plain. M, Masuk Shale. BG, Blue-Gate Group. T, Tununk Group. HF, Henry's Fork conglomerate. Scale, 1 inch = 4,000 feet.

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.

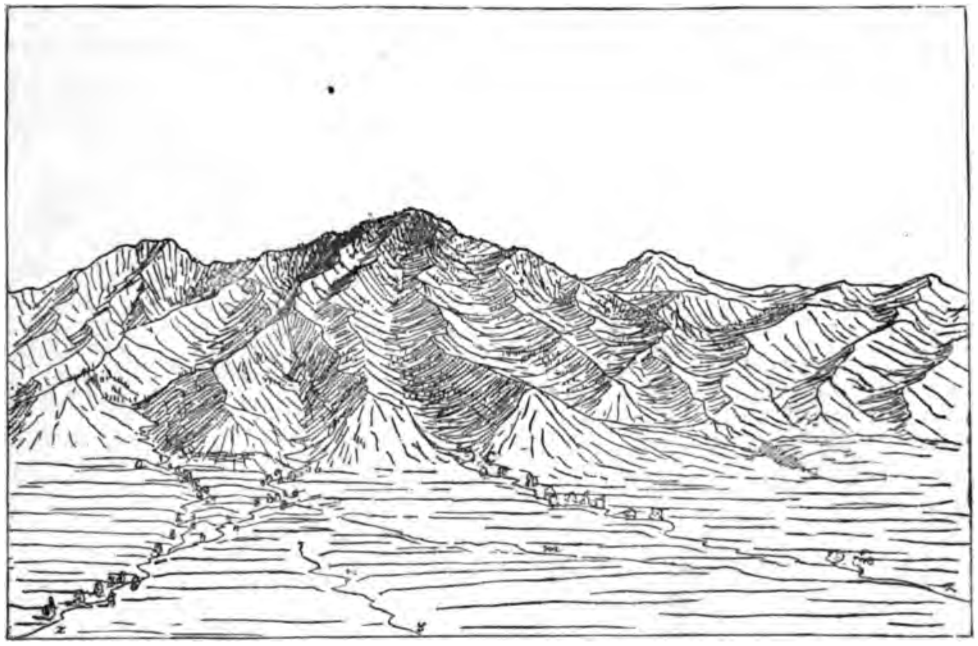

FIG. 62.—Ideal sketch to illustrate the Shifting of waterways on a slope of Planation.

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 Fremont 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.

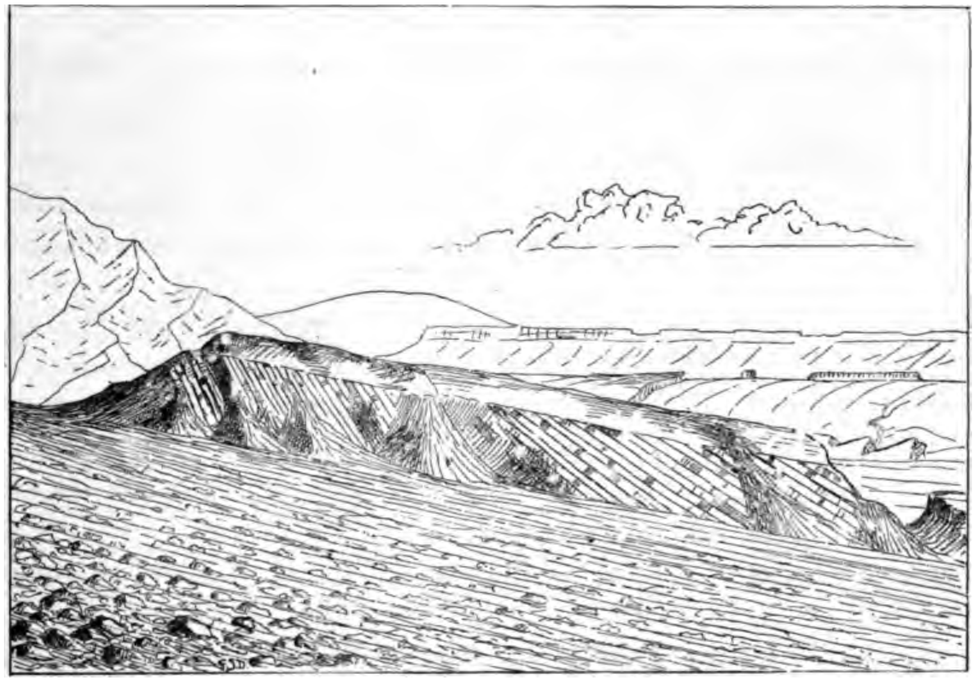

FIG. 63.—A Hill of Planation.

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 Fremont 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 Fremont 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 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

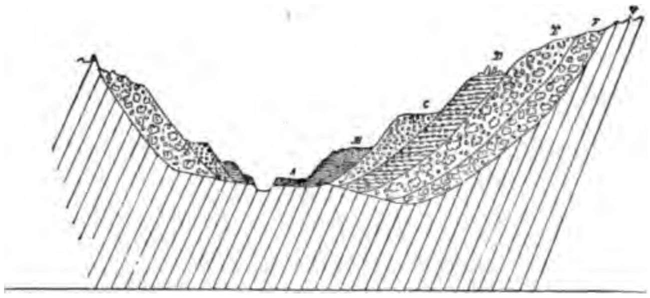

Fig. 64.—Ideal cross-section of a Terraced River Valley, after Hitchcock. A, B, C, D, E, and F, Alluvial deposits. G, Indurated rock, *in situ*.

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

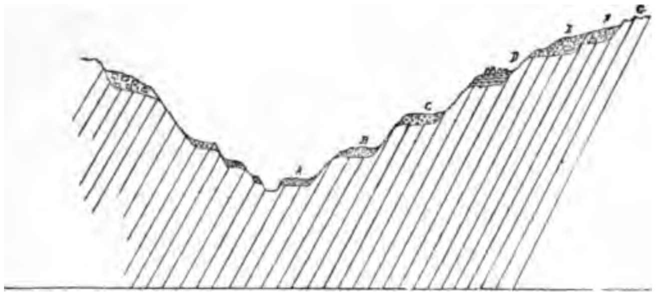

Fig. 65.—Ideal cross-section of a Terraced River Valley, regarded as a result of Planation. A, B, C, &c., Alluvial deposits. G, Preëxistent material from which the valley was excavated.

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

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*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, and May, 1878. See also Johnston'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.

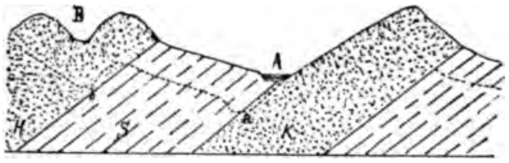

FIG. 66.—Cross-section of inclined strata, to illustrate Monoclinal Shifting of waterways.

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.

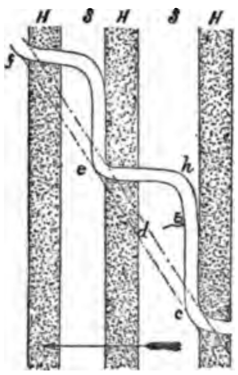

FIG. 67.—Ground plan of outcrops of inclined strata, to illustrate the results of Monoclinal Shifting.

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 Fremont 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 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 out crop of the shale, and riding over a low divide can reach the mouth of the gorge in half the distance.

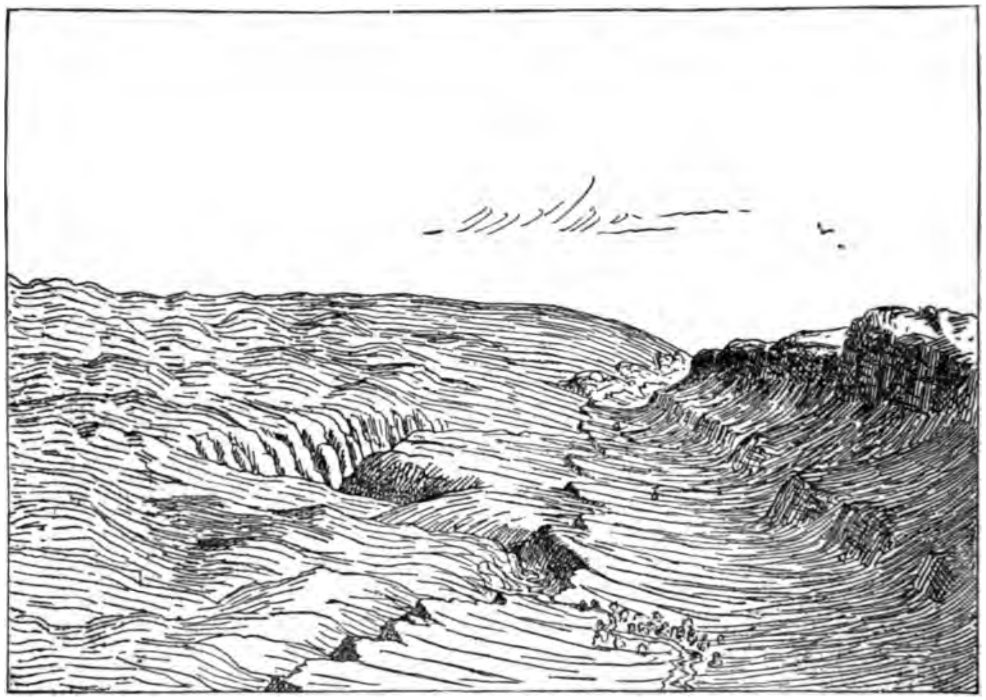

FIG. 68.—Waterpocket Cañon and the Horseshoe Bend of Hoxie Creek.

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.

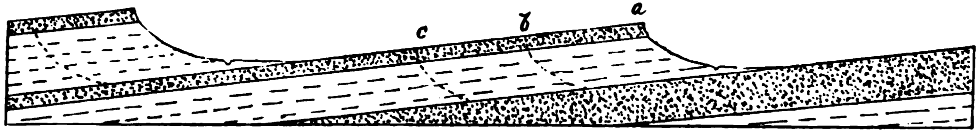

FIG. 69.—Ideal cross-section of inclined strata, to show the Shifting of Divides in Cliff Erosion. Successive positions of a divide are indicated at *a*, *b*, and *c*.

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.

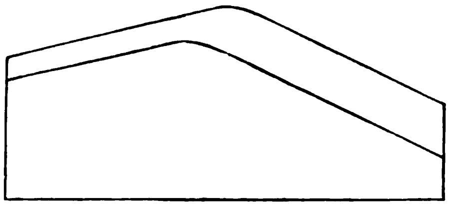

FIG. 70.—Cross-profile of a bad-land divide separating slopes of Unequal Declivity. Two stages of erosion are indicated, to illustrate the horizontal shifting of the divide.

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 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.

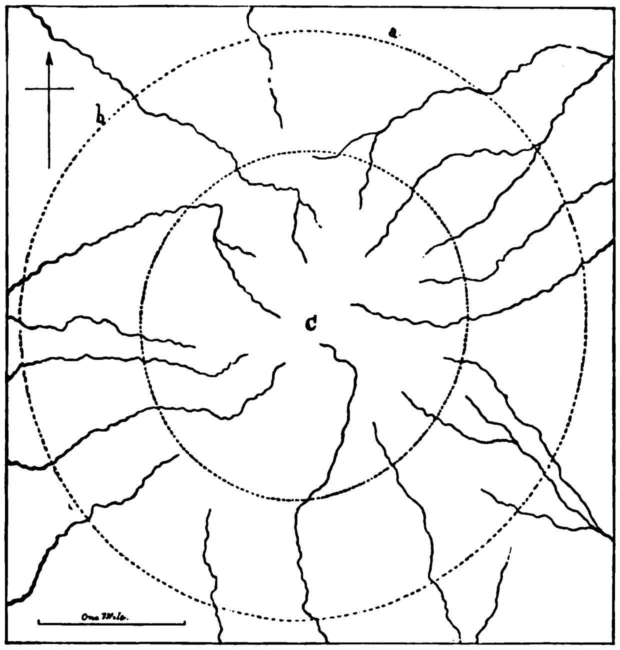

FIG. 71.—Drainage system of the Ellsworth Arch.

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 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.

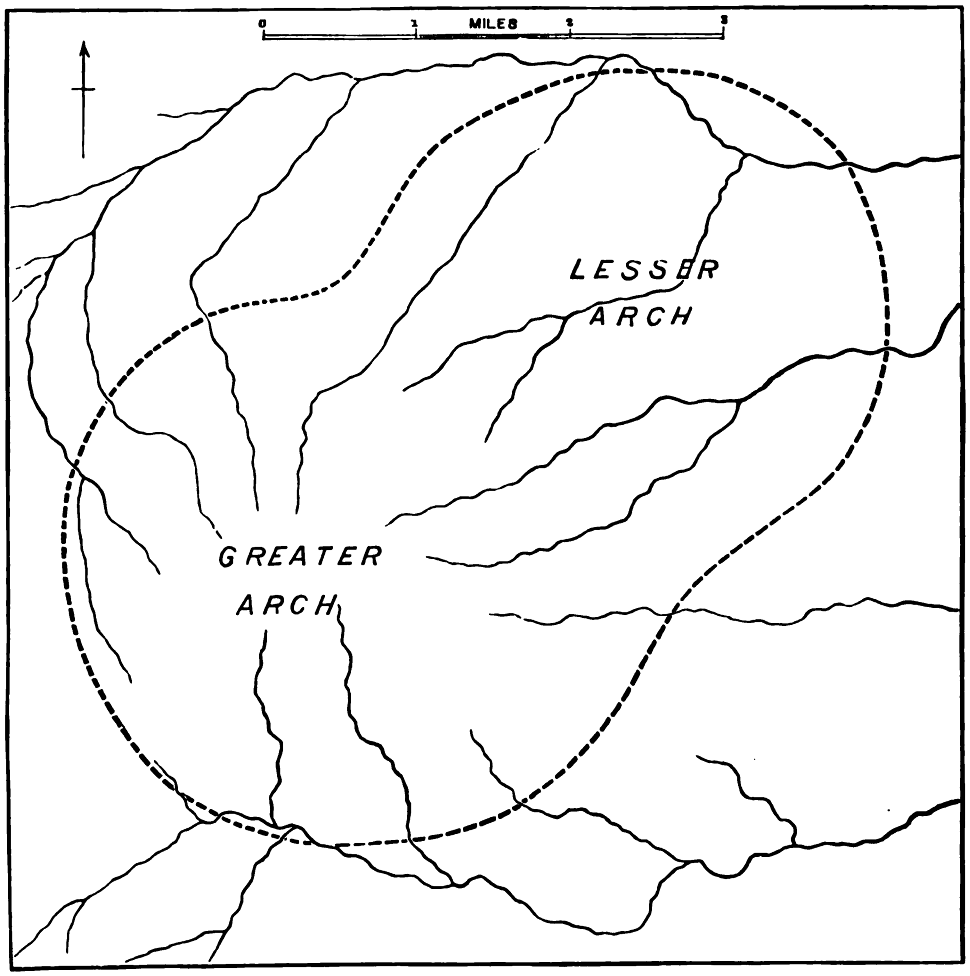

FIG. 72.—Drainage system of the Holmes Arches.

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.

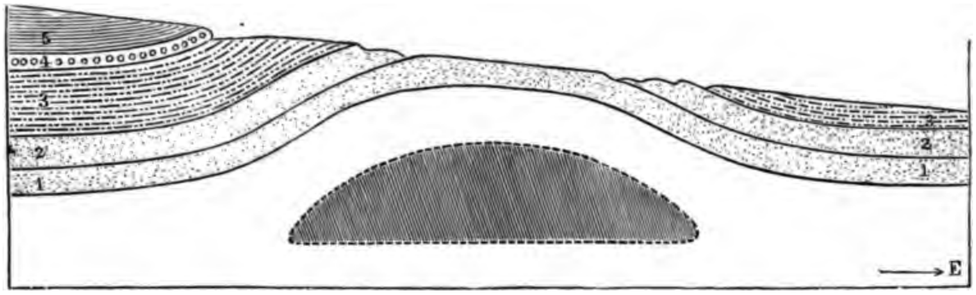

FIG. 73.—Cross-section of the Pulpit Arch, showing its truncation.

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.