# GEOMORPHOLOGY OF MOUNTAINOUS DESERTS

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ABSTRACT

The peculiar land forms of the desert are due largely (1) to the paucity of plant growth, in consequence of which (2) disintegrated rock, produced more by physical than by chemical processes, which (3) vary with rock nature (hence granitic rocks assume forms of special interest), does not remain near its source long enough in the earlier stages of erosion to be reduced to very fine texture before (4) it is carried by stream floods or sheet floods toward or to (5) playa basins of rising baselevel; but in an advanced stage of the arid cycle (6) the playa surface may be lowered by the wind, whereupon the rock slopes previously weathered down to sheet-flood grade and buried with sheet-flood waste will be (7) trenched by stream floods with respect to the sinking baselevel, and the buried rock floors will be laid bare until again reduced to sheet-flood grade. But (8) in deserts draining to the ocean these various processes will work with respect to a relatively fixed baselevel; also (9) in deserts where the action of water floods is dominated by wind action, the carving of the surface will be in part independent of any baselevel.

## General considerations

Although this study is largely based on my observations in the mountainous Mojave Desert of southeastern California, the principles announced are believed to be of general application. The land forms there developed during a cycle of arid erosion differ in various respects from those developed in humid regions, chiefly because the absence or scantiness of plant cover and the occasional occurrence of heavy local rains causes the spasmodic removal of much coarse detritus, which, in the presence of plant cover under more frequent but less heavy rains, would (except for soil creep) remain in place until it was weathered to fine-textured soil. Consequently the graded courses of the spasmodic desert floods have, as a rule, a decidedly steeper fall than that of the persistent streams and rivers of humid regions. Moreover, instead of running in well-defined channels after issuing from their rocky mountain valleys upon piedmont detrital slopes, the floods of deserts spread on such slopes in broad and thin sheets, known as "sheet floods." When they dwindle away after a short flow, they leave the slope on which they were developed marked with innumerable minute and intricately enmeshed channels, smaller but otherwise much like those produced by the floods of sprawling and elaborately braided torrents on a mountain-base, aggraded flood plain in a humid region.

The erosional progress of the arid cycle thus conditioned may be accomplished with respect (1) to the slowly rising, local baselevel of an aggrading playa in an enclosed basin; (2) to the slowly sinking baselevel of a degrading playa in an enclosed basin; or (3) to the normal baselevel of the ocean if a desert drains directly to the sea. In the last case the baselevel may be regarded as very slowly rising if the shore is built out by delta growth, or as very slowly sinking if it is cut back by the waves. The variations of ocean level with epochs of glaciation and deglaciation in a glacial period are not here considered.

[1] The author of this paper died February 5, 1934, before the paper was put in type, and the editors have therefore had to assume the responsibility for the slight editorial changes.

Under case 1 a cycle of arid erosion may begin (A) with an initial surface of strong relief due to the breaking of a previously developed peneplain into diversely tilted fault blocks; or (B) with an initial surface of mild relief due to the moderate warping of such a preexistent peneplain; or with a great variety of other forms not here considered.

Desert fault blocks of strong initial relief may be composed of (*a*) nearly homogeneous granitic rocks, the angular joint blocks of which are converted by surface and subsurface weathering into large or small rounded boulders, grains, or dust—that is, into parts of discontinuously graded sizes, because the boulders disintegrate directly into grains and dust, without intermediate scraps. Or the fault blocks may be composed of (*b*) finer-grained and less homogeneous igneous rocks, the angular joint blocks of which weather into subangular large or small boulders, scraps, grains, and dust—that is, into fragments of continuously graded sizes. Stratified rock structures are not here considered.

## Desert granitic fault blocks draining to aggrading playas (1A*a*)

Paige (10), Lawson (6, 7), and Bryan (2–4) were the first American geologists to point out—Lawson with the fullest analysis—that the steep scarps of desert granitic fault blocks draining to aggrading playas soon weather back into roughly graded, boulder-clad mountain faces which maintain the same declivity of 30° or 35° as they are retrogressively weathered and washed farther and farther back from their initial front. As they thus retreat they leave a piedmont rock floor, the profile of which is at first decidedly convex, but as its length increases the later developed part of the profile becomes more nearly rectilinear, after the fashion of a hyperbola. The growing rock floor will be buried under a slowly thickening detrital cover, graded to a faintly concave profile by its sheet floods, which there act chiefly as transporting agencies but with a persistent though faint tendency toward aggradation. The thin upper or proximal edge of the cover, where coarse detritus prevails and where a declivity of 4° to 7° is developed, makes a nearly angular junction, like that of its buried rock floor, with the base of the roughly graded mountain face. Its distal termination is the level surface of a playa at a distance of several miles from its beginning; there fine detritus prevails. The cause of the progressive decrease in the declivity of the cover is chiefly a corresponding refinement of its detritus and not a corresponding increase of flood volume; for sheet floods are so local and so short-lived that they rarely grow by down-slope confluence after the fashion of normal rivers. They are of about the same depth everywhere, except in so far as nearness to high mountains may cause their supplying rains to be heavier there than over flat playas.

The mountain face is not steepened at its base where it makes the nearly angular junction with the buried rock floor at the edge of the detrital cover; hence its retrogression and the accompanying growth of the piedmont slope are not accelerated by the lateral erosion of any stream or sheet floods. The retrogression is due solely to the back-weathering of the mountain face. But the downward extent to which such back-weathering proceeds is determined by the gradient given to the piedmont slope by its sheet floods.

Valleys incised in the fault blocks greatly diversify their forms. The valleys soon come to open upon reentrants of the mountain face, and these reentrants are occupied by the baylike extensions of the piedmont rock floor and its detrital cover. On reaching such bays the deep stream floods or torrents of the mountain valleys are quickly broadened and transformed into shallow sheet floods. The down-slope transportation of mountain detritus is accomplished by many successive sheet floods—some originating as torrents in the valleys, some as sheets on the slopes. The dry-period pauses between the floods, perhaps centuries long, commonly suffice for the partial disintegration of detrital fragments, which must have been undisintegrated when swept there.

As the piedmont bays widen by the back-weathering of their enclosing mountain faces, the spurs between them are sharpened to points; and inasmuch as the widening goes on somewhat irregularly, the ends of the points are not infrequently isolated in mounts or knobs. These then dwindle away, maintaining a boulder-clad slope of standard declivity like that of the mountain face, until they are reduced to mere heaps of boulders before they vanish. Here again the reduction of the mounts and knobs is not accelerated by the lateral erosion of stream or sheet floods; it is accomplished only by back-weathering; for, like the retreating mountain face, the isolated mounts and knobs show no basal steepening. Similar forms in humid climates, where streams flow in restricted channels, may undergo basal steepening and in consequence accelerated back-weathering above such steepening, wherever the streams swing against them. Such basal weathering is not characteristic of deserts.

The granitic mountains of the Mojave Desert include a few examples of slightly retreated fault scarps, but many more that appear to have been maturely developed from earlier-formed scarps. The sharpened crests show a confusion of bare crags; the faces are more or less completely covered with a stagnant assemblage of rounded boulders, among which solid ledges appear here and there. The slightly rounded basal angle between mountain face and piedmont slope appears to be of geometric sharpness when seen from a distance of a mile or so. The detritus of the slopes assumes a profile of almost perfect rectilinearity in the first half mile or so on the way toward the flat playas on the heavily aggraded intermont troughs. It may well be believed that the detritus of these smooth-floored troughs has buried many small basins of initial deformation; thus integration of initially small and separate drainage basins is brought about, such as is believed to be characteristic of the advance of the arid cycle in deserts of diverse initial displacements.[2] The detrital slopes rarely show defined watercourses or "washes," even at the heads of the bays; but such "washes" normally occur where two adjacent slopes slant obliquely toward each other, so that their contours make a somewhat angular in-turn, also along the physiographic axis of an aggraded intermont trough; but on broad-floored troughs, across which the contours pass in open curves, the "washes" may be ill defined or braided.

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[2] A much larger example of drainage integration occurred when the northeastward-flowing Mojave River in the west-central part of its desert formed a lake in its terminal playa basin in the glacial period, for it then flowed over and cut down a low divide which had previously separated it from a long, lower-lying intermont trough, the northern, lowest part of which is Death Valley.

After a maximum variety of mountain form has been developed with a considerable breadth of graded piedmont slopes, which may be taken to characterize the maturity of the arid cycle, the proximal edge of the detrital cover becomes thinner and thinner as it is extended farther and farther up-slope in pursuit of the retreating mountain face; and its then practically rectilinear proximal extension thus comes to lie more and more nearly in contact with the slowly flattening rock floor beneath it, thus simulating the relation of an asymptote to its hyperbola. Eventually the rock floor is laid bare, except for mere veneers of detritus in intermittent transit down its slope during spasmodic sheet floods. The floor then has, for a short length of its total profile, a gradient adapted to transportation only, without aggradation or degradation.

Sooner or later in this past-mature stage a mountain face must meet the opposite face of its block, and its height must thereafter be decreased, for any further retreat will lower the craggy mountain crest. Thus in time the load of detritus washed down from the face comes to be less than that which the sheet floods can sweep away. They, always efficient workers, thereupon begin to rob the rock floor by taking up some of its deep-weathered detritus, which they have previously been unable to move. That is, though still acting chiefly as transporting agencies, they now manifest a slight degrading tendency on the upper slope, yet preserve their aggrading tendency on the lower slope. After this change of sheet-flood behavior is introduced, all of the rock floor later developed will exhibit a convex profile. Hence the penultimate form of the mountain mass, after practically all its residual crags have been consumed, will be that of a circular or oval dome or an elongated arch. The profile of these penultimate forms will have a double curvature, with the point of inflexion lying where floor-robbing begins. It may happen, however, that the two sides of such a dome or arch will "break joint" where they meet at their heads, so that they are separated by a bluff. In such case the bluff will continue to retreat, undercutting the higher slope until the two slopes make a more accordant junction.

As long as a desert region remains undisturbed, its domes and arches will be worn down by sheet-flood robbing to fainter and fainter convexity, while its playas will be filled up to higher and higher levels and broader and broader extent, except in so far as this eventuality is prevented by an increasing exportation of playa dust by the winds. The reduction of convexity of the domes or arches involves the apparent paradox that they are most rapidly (though very, very slowly) degraded at their summits, where they are flattest, and are not at all degraded at the contour of profile inflexion, where they are steepest. Below that contour degradation is replaced by aggradation, which is ordinarily slower than summit degradation because the area there is larger. This process is analogous to the degradation of round-topped mounts and hills in humid regions, lately analyzed by Lawson (7); but degradation there continues in diminishing measure to the stream lines.

A remarkably perfect example of a desert granitic dome, standing near the south end of the Ivanpah Range in the north-central part of the Mojave Desert, may take the name "Cima" from a nearby station of the Union Pacific Railroad. It is 5,700 feet in altitude. Its convex summit area, bearing scattered boulders singly or in heaps and well clothed with a forest of Joshua trees (*Yucca arborescens*) and scattered cedars, occupies the upper 700 feet of the smoothly degraded mass, with a diameter of 2½ miles. Less degraded masses, flanked with graded piedmont slopes, adjoin the dome on the west and east. Its aggraded lower slopes descend to a broad-floored intermont trough below 4,000 feet on the north, and to a narrower trough that slants down below 3,000 feet on the south. Domes of fainter convexity are to be seen in the western part of the desert, which is a true peneplain of arid degradation; its higher parts are still being worn down with respect to the aggrading playas of its lower parts.

The best example of an elongated dome or arch lies east of the Johannesburg mining district, in the northern part of the desert, some 90 miles west of the Cima dome. It may take the name "Cuddeback" from the playa at its southwestern base, about 2,500 feet in altitude. The arch is about 20 miles long from northwest to southeast; it is 2½ miles wide at the 3,700-foot contour line, and its broadly convex and remarkably even crest runs at about 4,000 feet; but it is interrupted here and there by several good-sized residual mounts, which rise 600 feet higher. The long, double-curved profile of the western slope is very impressive: it is so beautifully graded. A few examples of domes and arches have been noted in which bluffs, as much as 300 feet in height, separate the opposite slopes.

Inasmuch as the domes and arches described above are best explained as the penultimate forms of granitic fault blocks, they would appear to represent old, worn-down fault-block mountains, younger and bolder examples of which abound in the Basin and Range province of Nevada, Utah, and Arizona. If so, a dome or arch of relatively narrow convexity would be the product of a strongly uplifted fault block, the retreating faces of which continued to shed abundant detritus until it was nearly consumed. On the other hand, a dome of broad convexity, like Cima, or a broad arch, like Cuddeback, would be the residual of a less elevated block, the retreating faces of which were so low that their detritus ceased to load the piedmont sheet floods to capacity while the mountain mass still had a considerable breadth. The Cuddeback arch gives confirmation of this inference, because its northernmost surmount is the residual of a lava-capped highland at a moderate height above the arch crest; and this indicates that the large fault block of the peneplain, out of which the arch has been developed, was, after gaining its lava cover, not greatly uplifted.

### Nongranitic desert mountains (1A*b*)

Nongranitic igneous mountain masses, the rocks of which weather into subangular fragments of all sizes, are reduced from whatever forms of strong relief they initially possessed to rounded forms, the irregularly graded slopes of which are largely covered with moderately coarse detritus, instead of being boulder-clad like granitic mountains. Owing to their lack of homogeneity, ragged ledges, rarely craggy like the crests of granitic mountains, crop out here and there; they doubtless represent extraresistant rock cores.

Because the detritus is of all sizes, the graded faces of these mountains are, after they have retreated somewhat by back-weathering, convex above and concave below. Their base in particular is very unlike that of granitic mountains in having a well-developed, detritus-covered, concave rock slope connecting the mountain face above it with the more heavily buried rock floor below it. Profiles of this kind are evidently the product of down-wash and down-creep from the back-weathering face; they could not possibly be the result of lateral erosion by piedmont stream or sheet floods. Embayed faces and isolated spur ends are here developed like those of granitic mountains, except for the persistent presence of the concave basal profile. The piedmont detrital cover slopes forward with a faintly concave profile to its terminal playa.

In an advanced stage of degradation nongranitic mountains are resolved into groups of mounts or hills, each convex summit presumably representing a resistant rock core. The hill slopes, thinly clad with rather fine detritus and having almost rectilinear profiles, blend insensibly into the presumably heavier cover of the buried rock floor. Many examples of these forms in various stages of development from mature to old are found in the south-central part of the Mojave Desert. There the massive Ord Mountains (not to be confused with the Ord Mountain some 30 miles farther west) may be regarded as maturely carved; their concave basal profiles are beautifully developed; their summit convexities are less regular. Various unnamed groups of subdued or old mounts and hills in the same district represent the advanced stages of the arid cycle.

## Conversion of sheet floods into stream floods

If at any stage of desert-mountain development a change of conditions causes the graded piedmont slopes to be eroded, their sheet floods are soon transformed into hardly less spasmodic stream floods, which strip off the detrital cover and erode trenches of less or greater depth in the rock floor. After the stream floods grade their deepened courses, the trench floors are broadened, partly by lateral erosion but largely by back-weathering during the long intervals between floods. Thus the intertrench ridges, slowly wearing away, assume isolated and stickleback residual forms before they disappear. In time the surface becomes so smooth that sheet floods are reestablished, but at a lower plane than before.

Several examples of more or less trenched piedmont slopes, from which the detrital cover has thus been incompletely stripped, are found in the Mojave Desert. The most striking example results from the deepening of its course by the Mojave River next to the southwest border of the desert; near the river cover stripping and rock-floor trenching are well advanced, but 3 or 4 miles back from the river both stripping and trenching weaken and disappear. At the east end of the desert a westward swing of the powerful Colorado River, some 20 miles north of the railroad-division town of Needles, has undercut the graded basal slope of a broad granitic arch and caused the sharp dissection of its east side by many subparallel stream-flood trenches; but sheet floods still control the west side of the same arch.

Several excellent examples of more or less stripped and trenched rock floors, piedmont to much-consumed mountain masses, are known near Tucson, in southeastern Arizona. Some of the best trenched of these are associated with the deepened intermont course of the intermittently northward-flowing San Pedro

River, a branch of the westward-flowing Gila River. The adjoining piedmont slopes, which had been graded with respect to this stream before the deepening of its course, are now well trenched.

### Desert forms of moderate initial relief (1B)

On a desert surface of moderate initial deformation the preexistent stream systems, revived by up-warping, or new stream systems consequent upon the warping proceed to erode a multitude of branching valleys in the uplifted areas and thus dissect them into correspondingly branching hills and spurs, the detritus being swept away to aggrading playas, as in the cases considered above. But by reason of the absence of strong initial scarps that would leave well-developed and detritus-covered rock floors as they weathered back, no rock floor is here developed until the intervalley spurs and hills are worn down in a late stage of the cycle: until then the hilly uplands merge with gradually lessening relief into the lower aggraded areas. Furthermore, inasmuch as the dissection of the up-warped surfaces is performed by small headwater streamlets, their little valleys will be deepened more slowly than the back-weathering of their low sides; and they will therefore have widely opened, apparently mature forms even in their first youth—all the more so if the initial deformation is slow. Thus, in the absence of initial scarps, back-weathering is here replaced by down-wearing. Eventually the down-wearing of the hills and spurs, although extremely slow, comes to be faster than the retarded deepening of the innumerable little valleys. At this stage groups of diversely fading hills should be expected in uplands of nonhomogeneous structure, but fairly regular and mildly hilly domes or arches should be expected in granitic areas.

A good number of incompletely degraded hilly areas, apparently the product of the conditions and processes just described, are to be seen in certain parts of the western Mojave Desert; they are as a rule so inconspicuous topographically that their little hills are not shown on topographic maps. The best example of a granitic dome produced in this way is traversed by the Cave Spring road to Death Valley. I have named it the "Noble Dome," after Dr. L. F. Noble, of the United States Geological Survey, in whose company I first had opportunity of crossing it several years ago. Part of its broad convexity shows faint, topographically microscopic swells, apparently the residuals of former hills, between very faint little valleys. There no sheet floods can sweep the surface; the drainage must be effected by minutely subdivided stream floods. But an adjacent part has lost whatever swells it ever had and is so smooth that it must be subject to sheet flooding. A hilly arch crest is found several miles northeast of the Johannesburg mining district, at the northern border of the Mojave Desert.

### Degradation with respect to degrading playas (2A)

In desert regions of strong initial relief playas must usually be aggraded during the earlier stages of the arid cycle, because the down-wash of detritus from higher to lower ground is then so active that it cannot be counterbalanced by the deflation of playa dust. But after such down-wash is diminished by the double diminution of relief due to down-wearing of the highlands and up-filling of the lowlands, it is conceivable that dust exportation from playas may exceed dust in-wash. It is therefore under conditions which are not likely to be reached in a mountainous desert until the cycle of erosion is well advanced—although they may be reached sooner in a desert of low initial relief—that the remaining degradation of the higher areas may be accomplished with respect to the slowly sinking baselevel of a degrading playa.

The sheet floods, which had been previously working as actively transporting and faintly aggrading agencies on the piedmont slopes, then become faintly degrading agencies, while maintaining their activity as transporters on essentially the same slightly concave profiles as before. It is not likely that they will be transformed into stream floods under these conditions, because the progress of playa degradation causes so slow an erosional degradation of the piedmont slopes. Such degradation as is accomplished will, however, involve the gradual stripping and shaving down of more and more of the previously buried rock floor, beginning at its head and continuing toward its deep buried base. At the same time the headward extension of the rock floor will go on as fast as the mountain face retreats; but that addition to its area will be produced and kept without any detrital cover. In the late stages of the cycle a convex granitic dome or a group of nongranitic hills may be produced, as explained above; but in the meantime the degradation of the earlier-produced and originally covered part of the floor will proceed with faintly concave centripetal profiles at a lower and lower level, even to the point of its degradational debasement under the whole of the previously playa-covered basin of initial deformation.

There seems to be good reason for interpreting in this way some of the broad "gobis" or flat, rock-floored desert plains, 50 to 100 miles across, in the still larger mountain-rimmed basins of Mongolia, so admirably described by Berkey and Morris (1). Such gobis are not, as has generally been believed from their earlier descriptions, composed of level-bedded sediments washed from the surrounding mountains into a basin after the basin had been produced by deformation; they are level erosion surfaces, which bevel the younger and weaker central strata of a compound structural mass after a basining deformation had been given to it. The evidence for this is set forth in the following quotation from Berkey and Morris (1, p. 336), who describe a gobi as

> a wonderfully smooth country, sloping very gently [10 feet to a mile] except where it has been recently deformed. It bevels horizontal and tilted strata with almost equal smoothness and in places overlaps [extends into] the complex rocks of the ancient floor [on which the later strata of the basined structure lie unconformably]. It is of comparatively recent origin, as it overlies [truncates] all the sedimentary formations, including the latest Pliocene and earliest Pleistocene. . . . In some places the expanse is so broad that the horizon appears as unbroken and as level as the sea circle around a ship. . . . Sediments many hundreds of feet thick have certainly been eroded and exported from the region.

The detritus that must have been washed in from the surrounding mountains, as well as that furnished by the basin floor, would therefore seem to have been exported from the basin by the winds, although the authors quoted are not assured of this explanation; and the gobi floor would seem thus to have been debased below the bottom of the original basin of deformation. As far as detritus was washed in and locally weathered, it must have been blown away; and it presumably went to form the extensive loess deposits of China, as well as to shower the adjoining floor of the western Pacific with minute dust grains. In any case these vast erosion plains, apparently dead level across their central areas, rise centrifugally in faintly concave profiles toward the still unconsumed mountains of the basin rims, for there the slanting surface of the rock floor "attains a gradient of 5° to 7° and even 10°." Down slope it "merges into the smooth erosion surface" of the central plain. Hence the rock floor is here concave, steepest at the margin and flattest in the center, as above explained, and not convex like the buried rock floors, steepest near the center and least steep at the margin, that are formed with respect to aggrading playas.

The marginal slope of these Mongolian basins is, moreover, "marked by an infinite network of shallow rill courses and is thinly and unevenly strewn with small chips of native rock"; but the rock "is so deeply weathered and disintegrated that we found it impossible to secure fresh samples, except in the walls of the deeper gullies," these gullies or trenches apparently being the work of stream floods to be described below. "The wind does not contribute to the carving of the erosion surface except in a very minor degree; the chief rôle must be ascribed to the myriad short-lived streamlets [of thin sheet floods?] acting on the weathered rock." Thus these extraordinary desert basins seem to exemplify the far-advanced, deflational rock floors, deductively described at the end of the fourth preceding paragraph.

Not only so: some of the gobis have, strangely enough, entered into a second cycle of arid degradation, in consequence of the very recent deflational excavation of smaller hollows, as much as 5 miles in diameter and 400 or 500 feet in depth, where the earlier-degraded rock floors are composed of weak strata. In consequence of this the centripetal floods, which still flow largely as sheets on the little-trenched marginal slopes, have been transformed into trench-cutting streams where they approach the newly excavated hollows; yet the hollows contain "surprisingly little waste." Hence they "could not possibly be excavated without the work of the wind; no other agency could lift material out of an enclosed lowland."

It would thus seem that, through the long-enduring later stages of the first cycle of gobi development, sheet floods must have acted as effective even though slow degrading agencies with respect to a slowly lowering central playa; for it must be understood that the centripetal slopes that gradually slant down from the mountain rims toward the flat floors, as well as the flat floors themselves, consist largely of bare rock; while in the early stage of the second cycle, now current, a small beginning has been made (during which the sheet floods are transformed in their lower courses into stream floods) in the great task of reducing the entire basin to a lower level.

### Arid degradation with respect to the ocean as baselevel (3A)

It is conceivable that a desert draining to the ocean might here and there discharge so great a quantity of detritus as to prograde the shore with deltas that would grow outward faster than the waves could cut them back; but this does not seem a likely contingency, because the ceaseless action of the waves will as a rule be able to dispose of the intermittently supplied detritus. Hence the case of a prograding ocean shore of a desert need not be considered here. If such a shore should be found on a protected coast, as in some bay of the Red Sea, it should be accompanied by forms similar to those of desert areas draining to aggrading playas in enclosed basins, except that the rate of aggradation on the graded piedmont slopes should probably be slower.

The case of a retrograding desert shore is more probable. Let the initial forms be those of diversely tilted fault blocks. A graded slope, on which sheet floods will flow to the shore, will soon be developed piedmont to the fault block nearest the sea, perhaps partly by degradation of the desert surface but more largely by its aggradation. On such a slope the sheet floods must work as actively transporting and slowly degrading agencies.[3] As fast as a rock floor is retrogressively developed, it must here remain bare instead of being buried under detritus; and as the mountain mass is more and more consumed the rock floor must be worn down to a lower and lower declivity; but it will always be bare, except for mere veneers of detritus in transit to the sea.

McGee's account (9) of Seriland, a coastal part of Sonora, the northwesternmost province of Mexico, where it fronts upon the Gulf of California, seems to place it in this class of desert forms. He noted that where a low coastal cliff, significant of a retrograding shore line, undercuts the floor of planed rock piedmont to the coastal mountains, "there is more of alluvium-free granite than of graniteless alluvium." Unfortunately his account of this coastal district is very brief. Fuller account was, however, given by this skillful observer of the inland part of the same desert (8), which is drained to the same coast; and as the drainage passes at certain points through narrow, steep-walled gorges in mountain ranges, the following interpretation is proposed for its development.

The ranges appear to have originated as diversely displaced fault blocks, like those of Arizona next to the north; and as such it is highly probable that their initial intermont troughs were for a time without discharge to the sea, the climate being far too dry for the trough basins to fill with overflowing lakes. Under such conditions the basins would be aggraded with waste down-washed from the mountains, and at the same time piedmont rock floors, buried under aggrading detritus, would be developed, because the drainage would then be to aggrading playas. Each trough floor would thus be built up to higher and higher levels, and in time an outflow might be established at the lowest sag of the enclosing mountains: for just there the least in-wash of detritus would be received, and the trough-floor playa would therefore be pushed toward the sag until overflow resulted. The headward erosion of a stream course on the exterior slope of such

[3] Exception may have to be made to this brief statement in case aggradation continues for a time after the graded slope is first attained; but of the four causes for such aggradation which are believed to operate during the approach to maturity of a river in a humid region—namely, increase of load due to increased highland dissection by headwaters, shoaling and widening of the river as it first reaches grade, loss of stream volume to creeping flow in aggrading deposits on the valley floor, and lengthening of stream course as meanders are developed on a broadening flood plain—only the first seems of importance in an arid region.

a sag would hasten this eventuality. McGee, indeed, mentions that process as the chief one in producing outward drainage. He first states that "the greater waterways by which they [the intermont plains or 'valleys'] are connected ultimately trend westward through the bounding ranges and down the general slope to the sea" (8, p. 94). He further says that there has been "a northeastward migration of the divides. It is to this migration that the westward deflection of the principal rivers is due" (8, p. 94).

After a basin outlet was developed, it would be rapidly cut down in a steep-walled gorge; the detritus of the aggraded basin should be as actively eroded by an axial stream, which might well maintain a graded course to the deepening outlet gorge; the sheet floods on the piedmont slopes would thereupon be converted into stream floods; the slopes would be trenched, the trenches would widen, the intertrench ridges would be consumed, and a new piedmont slope of faintly concave profile, partly showing bare rock, partly beveled beds of detritus, would be developed at a lower level than that of its predecessor. Thereafter the reestablished sheet floods would act as active transporting and as slow degrading agencies. Thus in time the mountains themselves would be reduced to convex domes or arches if composed of granitic rocks, or to groups of mounts and hills if composed of massive, nongranitic rocks; but that stage is by no means yet reached in Sonora.

It is to extensive rock floors some distance inland from the coast, which seem to be of such origin, that McGee's fuller descriptions apply. Some of his most explicit statements are as follows:

> Much of the [intermont] valley-plain area is not alluvium, but planed rock. . . . Of the plain, something like a half, or two-fifths of the entire area, is planed rock, leaving only a like fraction of thin alluvium [the mountains occupying the remaining fifth]. This relation seems hardly credible. . . . For 5 miles from the mountain base [Sierra de Tonuco] . . . the wheels grind over granite half the time. . . . The alluvial veneer appears barely to conceal the granite over an area larger than that occupied by the sierra [8, pp. 90–92].

A typical valley plain south of the Baboquivari Range bears alluvial deposits which

> have the customary air of great depth, yet . . . they are usually but a yard or two in thickness for several miles from the mountains and rest on an eroded surface of nondecomposed mountain rocks [8, pp. 102–103]. . . . Over dozens or scores of square miles in carefully examined localities hard rocks like those of the mountains, and with no sign of decomposition, are planed down as smooth as the subsoil by the plowshare. . . . These planed surfaces are not rare or exceptional; . . . their area may be estimated as two-fifths of the entire area, or over 100,000 square miles [8, pp. 108–109].

Two other fifths may be in part occupied by the basal part of the original filling of the deformed intermont basins, the rock bottom of which has not yet been revealed, as it appears to have been in the Mongolian gobis.

McGee makes no very clear statement as to the profile of the rock floors, but it may be gathered that they are steeper near the mountains and therefore have faintly concave profiles. In one place he asserts that "the plain is slightly concave." Elsewhere he describes the plain as "tilting up laterally into the bounding ranges," but this is not clear. Rock fans at canyon mouths are mentioned, and they are evidently steeper than the rock floor farther forward. Hence the bare rock floor, here developed with respect to a practically fixed baselevel, has a concave profile like the Mongolian examples, which have been developed with respect to a sinking baselevel, and not a convex profile like the buried rock floors developed with respect to a rising baselevel. The nondecomposed condition of the bare rock is the only unexpected feature.[4]

McGee has been criticized as exaggerating the area of the bare-rock surface in his valley plains, by those familiar with rock floors buried under a detrital cover in basins draining to aggrading playas; but his account is too explicit, too circumspect, to be seriously inexact. Indeed, if the interpretation of his Sonoran region above given is correct, the large area of bare-rock floor that he described is altogether expectable as a normal feature, in view of its drainage to the ocean. His conclusion that "the general effect of sheet flooding in the Sonoran district is to carve baselevel plains, lightly veneered by the carving material," has also been unfavorably criticized, but again apparently by those who have not studied deserts in nonenclosed basins. In view of his excellent description of a sheet flood in action it is, indeed, difficult to see why his estimate of the "efficiency of the sheet flood in corrasion" should not be accepted. A reexamination of his ground, with the various conditions of arid degradation here outlined in mind, is much to be desired.

Fuller discussion of the above-outlined principles, for the illustration of some of which many desert forms in California and Arizona are adduced, may be found in my paper noted below (5).

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[4] Editors' note: See reference 11, added by the editors, and description of sediments of Baboquivari Mountains and profiles of the rock floor in reference 2, pp. 61–63, figs. 14, 20, and 21, or reference 3, pp. 100–101, figs. 12, 30, and 15.