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ROCK FANS OF ARID REGIONS.

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ABSTRACT.

A theory of origin of piedmont desert rock planes, or pediments, through lateral corrasion by heavily laden streams is briefly outlined. Among the deduced consequences of this theory is the occurrence, near the mountain base, of forms closely resembling alluvial fans but developed by erosion on bedrock. Field investigation reveals the existence of such "rock fans," and several examples are described. It is concluded that the theory of lateral planation is sufficiently supported to deserve consideration among other working hypotheses of pediment origin, and suggestions are offered for further study of the problem.

INTRODUCTION.

In a recent issue of Science[1] the writer elaborated in some detail a theory of origin for desert erosion planes or rock pediments which seems to offer a possible explanation of these forms and their associated phenomena, and which therefore deserves a place among the working hypotheses being tested by students of desert forms. According to this theory there must normally exist in the drainage area of a desert range three concentric zones in each of which the dominant action of streams differs from that in the other two:—(1) An inner zone, *the zone of degradation,* corresponding closely to the mountainous highland, in which vertical down-cutting of streams reaches its maximum relative importance; (2) An intermediate zone, *the zone of lateral corrasion,* surrounding the mountain base, in which lateral cutting by streams attains its maximum relative importance. This is the zone of pediment formation. (3) An outer zone, *the zone of aggradation,* where upbuilding by deposition of alluvium has its maximum relative importance.

[1] Johnson, Douglas, Planes of Lateral Corrasion, Science, 73, 174-177, 1931.

The zone of lateral corrasion gradually encroaches upon the zone of degradation, due to the fact that the mountain front recedes under the sapping action of laterally corrading streams frequently deflected against the mountain base. In turn the zone of aggradation encroaches, for a time, upon the zone of lateral corrasion, the thickening alluvial deposits overlapping the previously formed pediment. In the case of an originally circular mountain mass the end-result would be a far-spreading low rock cone blanketed in considerable part by overlapping alluvial deposits, were it not for the fact that the zone of lateral corrasion, in addition to shifting inward, is vertically lowered as debris from the shrinking and lowering mountain mass becomes progressively less abundant. The effect of this lowering is ultimately to cause an outward as well as an inward migration of the zone of pediment formation, and thus to make a low conical rock pediment, relatively free from alluvium, the ultimate type form of the arid landscape.[2] Since lateral cutting takes place *pari passu* with lateral shifting, unaccompanied by any considerable vertical incision of the streams, no thick "slice" of a pediment need ever be removed as its surface is lowered; although it is recognized that a marked change in physical conditions may in places cause deep trenching of the rock plane, followed by lateral planation at a notably lower horizon.

The foregoing "theory of lateral corrasion" assigns to planation by heavily laden streams not merely the local development attributed to it by Gilbert[3] in his classic work on the Henry Mountains, nor the subordinate importance apparently recognized by Kirk Bryan[4] in his excellent account of the Papago country, but the dominant rôle in producing plane erosion surfaces in arid regions.

In the present paper the term "desert" is employed in the loose sense so common in the literature, it being applied to arid regions generally, and with full recognition of the fact that forms most characteristic of arid regions are also found, under certain conditions, in regions having considerable rainfall. The term "pediment," first applied to a desert rock plane by McGee and later used extensively by Bryan, is considered synonomous with the "suballuvial bench" of Lawson, the

[2] Exception made of possible disturbing effects of wind erosion.

[3] Gilbert, G. K., Report on the Geology of the Henry Mountains. U. S. Geogr. and Geol. Surv. of the Rocky Mountain Region, 170 pp., 1880.

[4] Bryan, K., Erosion and Sedimentation in the Papago Country, Arizona, U. S. G. S. Bull. **730**, 19-90, 1922.

forms described by these three writers being regarded as identical. "Pediment" is preferred, not only from considerations of priority, but also because the rock plane is not always covered with alluvium.

SIGNIFICANCE OF ROCK FANS IN THE THEORY OF LATERAL CORRASION.

Analysis of the theory of lateral corrasion early convinced the writer that the test of its validity must be sought in the comparatively narrow zone where the gently sloping rock plane of the desert floor merges with the steeper scarp of the mountain range. Examination of the rock floor far out from the base of the range need not necessarily yield evidence of discriminative value, since a plane produced chiefly by retreat of the mountain front through weathering in the manner described by Lawson[5] might look little different from one produced by lateral corrasion of streams. It is true that under certain conditions evidence of some value may be found in this zone. "Inselberge" rising sharply from throughgoing slopes which are inclined uniformly away from the parent mass, longitudinal profiles down the rock slope which are concave upward rather than convex, and rock surfaces (often covered by some alluvium) which are fresh rather than weathered, all favor an origin by stream planation rather than by weathering. But for reasons which need not be here discussed, the critical value of features in this zone is not always of the highest. Similarly, the mountain front as a whole is not the most promising field of study, since under any theory of pediment formation weathering must proceed upon the face of the range. In the zone where plane and mountain meet, however, the process of plane formation and mountain retreat should afford conclusive evidence of its *modus operandi.*

A purely theoretical study of what we might expect to find in this zone under different theories of pediment formation led to a result quite unanticipated. It became evident that if the pediment is a product of lateral planation, and the mountain front retreats mainly through trimming of its frontal spurs as the shifting streams from time to time impinge against them, the zone in question should exhibit a series of relatively flat semi-cones, or less than semi-cones. Each partial cone

[5] Lawson, A. C., The Epigene Profiles of the Desert, Univ. of Calif., Dept. of Geol. Bull. **9**, 23-48, 1915.

would appear to be an ordinary alluvial fan where deposition of debris was plentiful; but in the absence of such debris it should be a bedrock surface having the form of a typical fan, and apexing like the alluvial fan at the mouth of the canyon from which issued the sculpturing stream. That this must be the case will be evident to anyone who will visualize the geometric form described by an inclined stream relatively (but not rigidly) fixed in position at the point of issuance from the canyon mouth, and shifting more and more widely below that point. The alluvial fan is the expression of that form where deposition alone has occurred, or where considerable deposition has accompanied erosion of bedrock. The "rock fan," as I propose to call it for lack of a better name, is the same form where retreat of a mountain front has let streams operate on the solid mass of the range, and where erosion has exceeded deposition.

This result of the deductive processes came as a complete surprise, and was, I must confess, treated at first with cautious skepticism. Alluvial fans were widely known features. But in many excursions through arid regions I had observed nothing resembling the "rock fans" required by this analysis, nor could I recall mention of such forms in the literature. It was not until several years of intermittent field search had been rewarded by discovery of the type example I was seeking, and after the substance of this paper had been presented before Section E of the American Association at its Pasadena summer meeting in 1931, that I found rock fans had been briefly mentioned by McGee, although not explained by him (see below, section entitled "Rock Fans of the Coyote Mountains").

It was evident, on further thought, that rock fans, if they existed, should normally be covered by alluvium, and so appear to the observer as ordinary alluvial fans. This might explain the fact that they had escaped detection by so many students of desert forms. It thus became obvious that careful scrutiny of the critical zone where plane and mountain meet must be made in many localities, in the hope of finding some few where the alluvium would be sufficiently trenched, or sufficiently washed away, to reveal rock fans if they existed. Should such search fail to find them, grave doubt must attach to the theory of pediment formation by lateral planation. On the other hand, should they be found to constitute a common feature of desert landscapes, retreat of the mountain front chiefly by weathering would seem to be excluded wherever they occur, and the validity of the weathering theory of pediment formation would be open to question.

The conclusions suggested in the last sentence preceding will be valid only in case rock fans must be carved by streams, and cannot be produced by simple weathering back of the mountain front. So far as I have been able to analyze the problem, such is the case. Lawson[6] believes that where the inner edge of the alluvial embankment consists of a series of fans, retreat of the mountain base by weathering will take place at a higher level opposite the apices of the fans than in the inter-fan depressions; and he believes also that retreat opposite the apices will proceed on a steeper slope. If we accept Lawson's reasoning, analysis will show that after the mountain front has retreated in the manner specified for a considerable distance, the residual pediment must show a sort of fluting perpendicular to the range base. Low parallel ridges having faintly concave sides will alternate with broad depressions, the vertical distance between ridge crests and depression floors progressively increasing toward the mountains. Profiles across the fluted pediment parallel to the mountain front (and hence transverse to the fluting) will be identical in character, whether made close to the mountain or far out, with a profile across a series of alluvial fans made immediately at the mountain base. But no profile across the fluted pediment can duplicate the profile secured across coalescing alluvial fans some distance out from the mountain base, where oblique transection of fan radii gives broad rounded curves convex upward. This is because the process of retreat described cannot produce rock fans with radii descending equally in all directions from apices located at the mountain base.

Bryan[7] notes that at certain localities he found the pediment surface unusually steep opposite canyon mouths, and explains the phenomenon thus: "This exception seems to be due to especially resistant boulders which have been brought down by the stream and dropped at the canyon mouth, causing the stream to spread and lose its carrying power. The boulders, until they weather into fragments small enough to be moved, protect and preserve a steeper slope than is normal to the pediment." Bryan's description suggests the presence of rock fans, although he does not recognize them as such. Hence it might be argued that more or less fan-like forms, with high

[6] Op. cit., p. 43.
[7] Op. cit., p. 54.

apices opposite canyon mouths, could be produced by selective protection in the manner described. But a brief analysis will be sufficient to convince the reader that nothing resembling the symmetrical rock fans described in the following pages could originate in this way. One may perhaps entertain the hypothesis that hard-rock fan surfaces may in some measure be protected by an alluvial cover of coarse debris. But before the rock fan can be protected it must be formed; and the only agent competent to fashion a rock surface of sub-conical form with all radii slightly concave upward and nicely graded to the normal profile of stream transport, appears to be stream erosion. We may therefore reasonably conclude that if rock fans are found along the inner margins of pediments, the hypothesis ascribing a dominant rôle to stream action in the formation of pediments is strongly supported.

FIELD SEARCH FOR ROCK FANS.

Field observations in widely separated localities soon made clear the fact that it is not easy to find the combination of conditions which will furnish conclusive proof on the critical question as to the existence or non-existence of rock fans. Cases were observed in which ravines trenching alluvial fan forms revealed bedrock beneath the alluvium; but while it was believed the bedrock also possessed the fan form, exposures were not sufficiently abundant to exclude the possibility that more or less isolated irregular foothill spurs, buried by alluvium, had been revealed by later dissection.

Examples were encountered in which a bedrock plane appeared on the surface of the fan form near its lateral borders, as if streams following along the contact of fan margin with mountain front, in the manner so frequently observed on alluvial cones and fans, had merely removed a thin veneer of alluvium from this marginal belt. A good illustration was seen near the mouth of a small, unnamed canyon on the west flank of the Ortiz Mountains in New Mexico, east of the wagon road leading from Golden to Cerrillos. Here again one was impelled to believe that he saw partially exposed a rock fan of considerable dimensions; but it was not possible to exclude the possibility that the stream, shifting laterally on a thick alluvial deposit, had merely cut into the mountain flanks for a limited distance, giving lateral rock benches of no great magnitude, such as are apparently represented by Eckis[8] in Fig. 5 of his report on alluvial fans of the Cucamonga region in California.

On the west side of the Franklin Range north of El Paso, Texas, is a series of coalescing alluvial fans beautifully terraced toward their outer margins where stream trenching shows a great thickness of alluvium. The steeply inclined upper slope of one of these fans was found to merge with a slope developed on bedrock (Fig. 1, A), the transition from alluvium to rock taking place abruptly a short distance out from the mountain scarp. This example seemed to indicate that retreat of the mountain front by lateral corrasion may cause the fan form, fashioned wholly on alluvium farther out, to develop on bedrock as the wall of the range is cut back. But so local and so tiny an illustration could not alone bear the weight of an important theory.

Better exposures near the apex of what appears to be a fairly extensive rock fan were found not far from Golden, New Mexico, at the northern base of San Pedro Mountain. An opportunity to visit this area was afforded in 1930 through the courtesy of Mr. Herbert Brooks of Albuquerque. The igneous intrusions of the range are gold bearing, and the alluvial fans flanking its base have long been worked on a limited scale as placer deposits. Prospect holes have been sunk in the fan surfaces, apparently not only to test the richness of the deposit but also to determine the depth of alluvium (10 to 25 feet in this locality) cloaking the rock floor. Near the apex of the fan in question operations with a steam shovel have exposed, in a long trench, the contact between alluvium and bedrock (Fig. 1, B). The exposure indicates that the surface of the latter is a relatively smooth plane and slopes gently away from the range. Boulders up to 3 and 4 feet in diameter rest on the plane, which has a low gradient compared with the steep mountain front. This relationship suggests that here at least the rock plane is not the product of weathering controlled by maximum size of fragments, but is the result of stream erosion. As this part of the rock plane is distinctly higher than even the alluvial covering farther along the mountain base, one is impelled to believe that the rock surface has the form of a semi-cone or fan. Unfortunately, my efforts to

[8] Eckis, R., Alluvial Fans of the Cucamonga District, Southern California, Jour. of Geol., **36**, *224-247*, 1928. See Fig. 5.

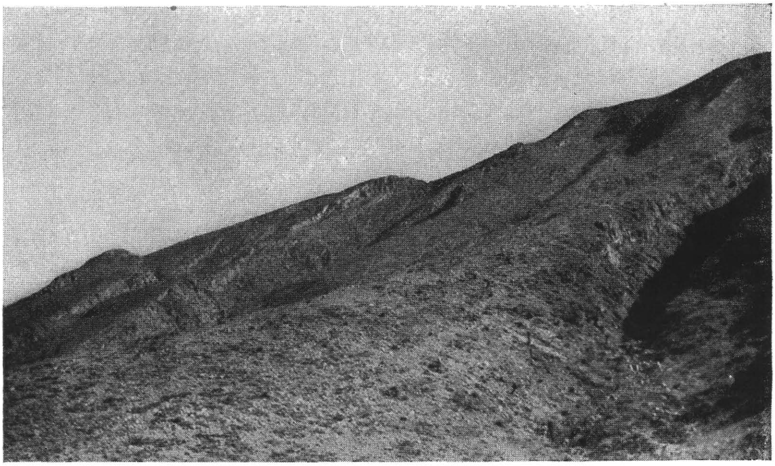

Fig. 1, A. Steep apex of fan on west side of Franklin Mountains, north of El Paso. In foreground the fan is composed of alluvium, but the upper part in right background is of bedrock, well exposed in walls of marginal ravine.

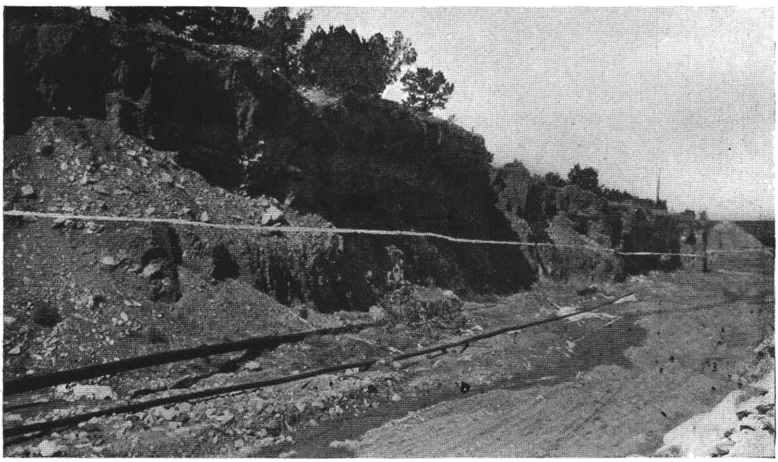

Fig. 1, B. Contact of rock plane (shown by white line) with overlying alluvium exposed in placer workings near Golden, New Mexico.

secure from the mining authorities data which would enable me to plot the depth of alluvium in a number of test pits, and so develop the form of the rock surfaces over a considerable area, have been without success.

In portions of New Zealand alluvial fans have a very striking development, and along some of the precipitous coasts of the region these are occasionally cut into by waves in such manner as to give cross-sections of fans and underlying bedrock. As observed from a boat some distance off the coast west of Wellington, the bedrock appears distinctly to rise in

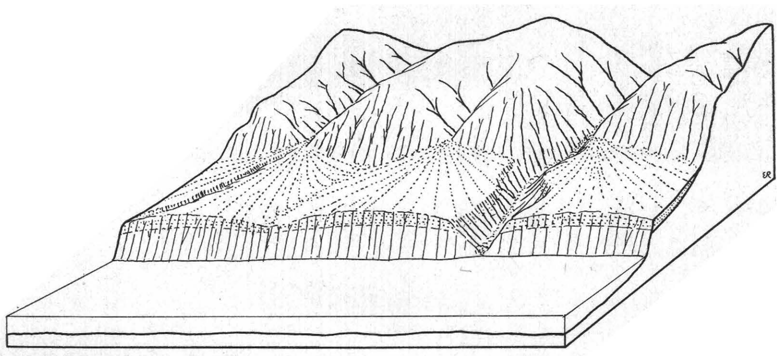

Fig. 2. Truncated fans of the New Zealand coast. Generalized sketch.

convex swells under the somewhat steeper convexities of the alluvial surface, as shown in Fig. 2. It was believed that the convexities of the bedrock profile have the same origin as those of the alluvial surface; that they result from sectioning, parallel to the mountain front, a series of coalescing rock fans. But the writer was unable to examine critical areas on the ground, and realizes the danger of error in long range observations.

Southeast of Tucson, Arizona, at the base of the Tanque Verde Mountains, is found an excellent pediment (Fig. 3, A) slightly covered with alluvium in some of the places examined, but often showing bedrock both on the surface of the plane, and in the walls of streams which trench it to a slight depth. This pediment appeared to have the form of a low, flat cone near the mouth of an adjacent canyon; but the faintness of the slopes and the large size of the form made one hesitate, in the absence of a good contour map, to trust implicitly one's visual impressions.

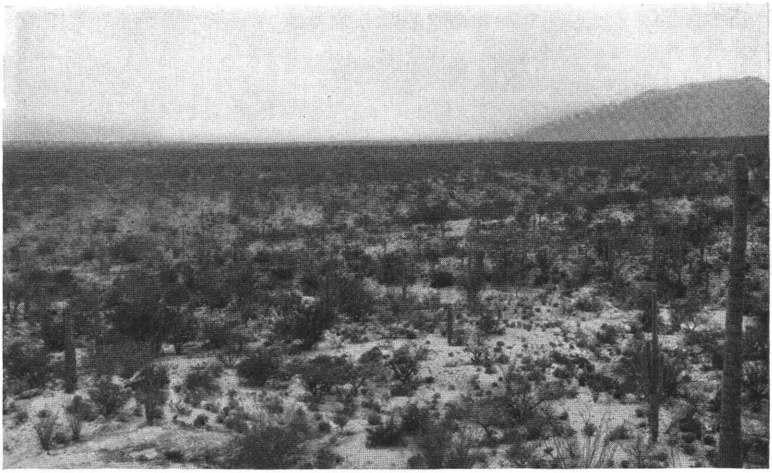

Fig. 3, A. Broad pediment, apparently fan-shaped near mountains and slightly dissected, at base of Tanque Verde Mountains, Arizona.

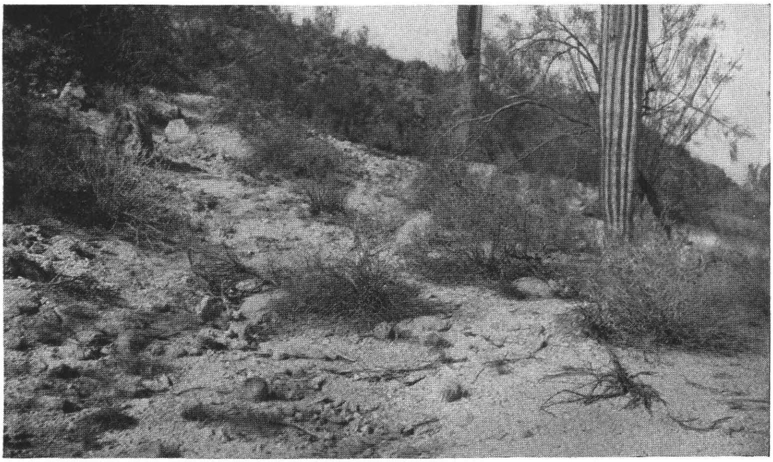

Fig. 3, B. Small and imperfect rock fan formed by rill, Sacaton Mountains, Arizona.

In the Sacaton Mountains of Arizona, on the road from Sacaton to Casa Grande, the writer had an opportunity in 1930, thanks to the courtesy of Professor J. W. Hoover of the Tempe Normal School, to examine portions of the contact of mountain scarp with the excellent pediment described by Kirk Bryan[9] in his Papago report. The angle between the two surfaces is very marked, suggesting that the two were developed under very different conditions or by different forces. The immediate angle is locally rounded, and an examination of the rounded zone revealed the presence of what appeared to be very small and imperfect rock fans, developed by small rills (Fig. 3, B). The channels of the latter sometimes followed the contact between mountain front and fan margin, in the manner frequently observed on alluvial fans. It is believed that the work of these countless rills, swinging from side to side on their miniature rock fans and repeatedly impinging against the mountain front, must in the aggregate play an important rôle in mountain front retreat. Bryan recognizes rills as a factor in desert erosion, but seemingly limits them to the previously formed pediment at the base of the mountain slope, where they tend "to reduce the height of interstream areas."[10] In the writer's opinion erosion by rills on the mountain scarp itself is an important factor in causing scarp retreat, and miniature rill-carved rock fans bordering major stream-carved rock fans are an expectable feature at the inner borders of pediments. But he realizes that the small and imperfect examples observed in the Sacaton Mountains would scarcely be convincing to one who doubts the validity of the theory of lateral corrasion.

I have deemed it worth while to present the foregoing illustrations of the difficulty of securing wholly convincing field evidence of the existence of rock fans, both to emphasize my conviction that these forms are much more widespread than is at first apparent, and to explain why they should long remain so little known despite their abundant development. Fortunately excellent examples, beautifully exposed and of undoubted authenticity, do exist. Let us now turn our attention to some examples in southern Arizona which leave no room for doubt as to their origin and their significance for the student of desert erosion planes.

[9] Op. cit., pp. 52-58.
[10] Op. cit., pp. 55-57.

A ROCK FAN IN THE DRAGOON MOUNTAINS.

Twelve miles east of Benson, Arizona, is a broad low pass between the Dragoon Mountains and the Little Dragoon Mountains. Through this gap runs the highway known as Route 81. As the west-bound traveller emerges from the western portal he finds himself looking downward into the San Pedro Valley across the smoothly sloping rock plane

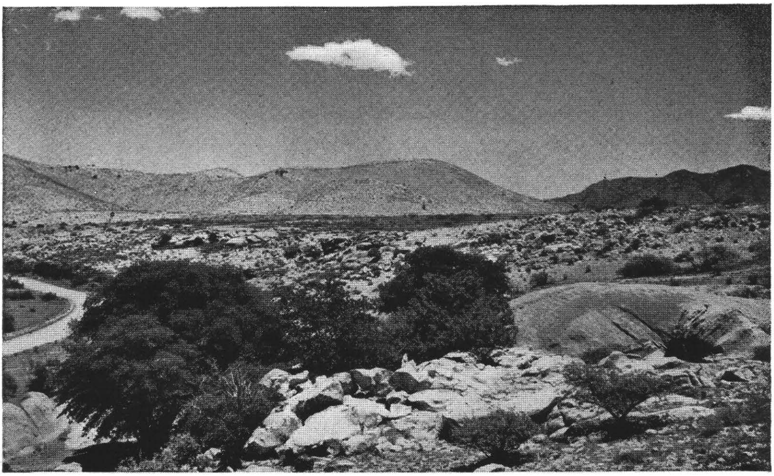

Fig. 4. Rock fan cut on granite, western side of Dragoon Mountains, Arizona. Stream trench at left, followed by road, is cut 50-75 feet below fan surface. View near apex. Compare with Fig. 5.

shown in Fig. 4. Granite is abundantly exposed over the surface of the plane for a mile or more out from the mountain scarp, while a stream trench cut 50 to 75 feet into the rock enables one to see how neatly the surface bevels the granite and how devoid it is of alluvial cover.

It was my privilege recently to inspect this plane in company with Professor F. J. Wright of Denison University. A short walk southward was sufficient to show us that at the mouth of the pass we were well above the country to the south, as well as above that to the west. In other words, the fact that we were on the high apex of a broad rock cone was clearly apparent. One may look southward (Fig. 5) over the rounded surface of bedrock, down into the inter-fan depression, and beyond this to the more distant fans of the main Dragoon range. The northern slope, not being visible from near the auto route, was not observed by us.

The contrast between rock fan surface and mountain front was very pronounced, the two very different types of slopes meeting at an angle which, although rounded at the immediate junction, was nevertheless very marked. Westward the rock fan gradually disappears under alluvium which in the San Pedro Valley is beautifully dissected to depths of 100 feet or

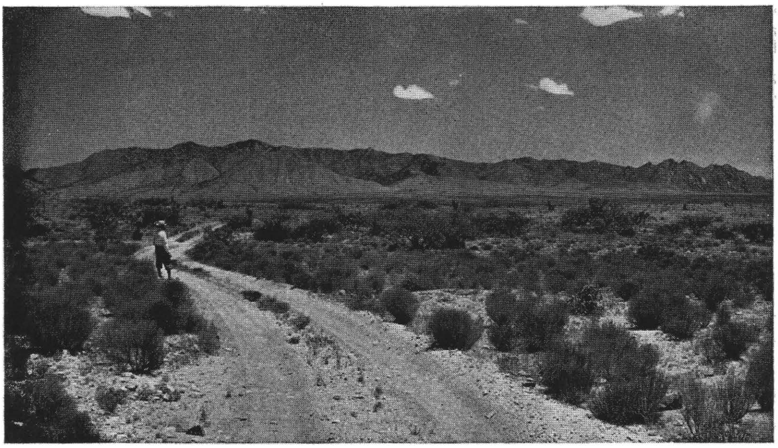

Fig. 5. Looking southward over rounded surface of same rock fan shown in Fig. 4, to more distant fans of Dragoon Mountains. Bedrock is abundantly exposed over this surface.

more without revealing the rock floor. In this case, therefore, we seem to have a good example of a rock fan, but one which cannot be traced into continuity with any extended rock pediment farther out from the range.

ROCK FANS OF THE SIERRITA MOUNTAINS.

Some 25 to 30 miles southwest of Tucson in Arizona lie the Sierrita Mountains. Bryan and Waibel have each drawn attention to the fact that this range is bordered by a broad rock plane, one of truly astonishing perfection. To Professors

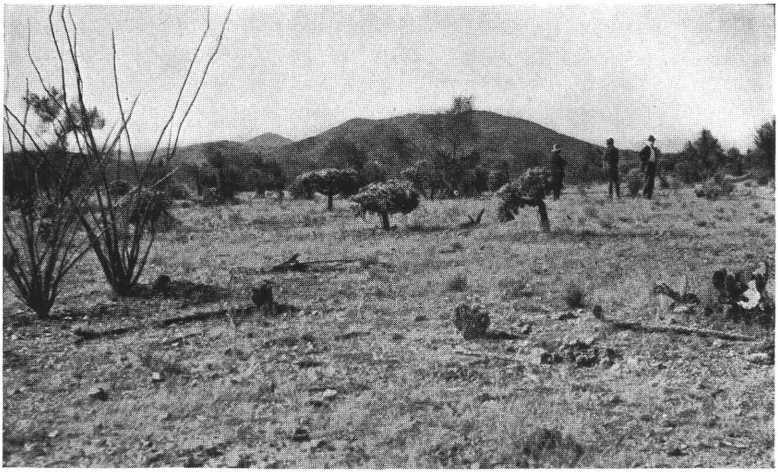

Fig. 6, A. The Sierrita pediment, Arizona, where the rock surface is undissected. Compare with 6, B.

Fig. 6, B. The Sierrita pediment (same as 6, A) where slightly trenched by recent erosion.

W. M. Davis and B. S. Butler I am indebted for an opportunity to visit the eastern margin of this pediment in the winter of 1930, in their joint company. I then gained a first acquaintance with the manner in which the remarkably even bedrock surface (Figs. 6, A and B) appears to emerge imperceptibly from the thinning wedge of alluvium that blankets its outer slopes. At the time of this visit I remarked what I believed might be a series of rock fans at the base of the range, some miles west of the portion of the plane examined by us. But the opportunity to study at close range the critical zone where plane and mountain meet did not present itself for more than a year.

In the summer of 1931 with the aid of my brother, S. G. Johnson of Tucson, I returned to this interesting region to test the long-distance surmises of the earlier visit. Approaching the mountains by a new route, we again noted what appeared to be a wedge-like thinning out of the alluvium and a gradual rise to the surface of the bedrock plane, the latter seemingly buried under alluvium farther east. While we made no careful study of this transition zone, which lies some four or five miles out from the base of the range, we believe the relations are identical with those reported for the partially buried pediment of Bryan, or the suballuvial bench of Lawson.

Continuing southwestward past Mineral Hill and Helmet Peak the observer journeys for some miles over the great expanse of bedrock plane, which here bevels granite for the most part, but occasionally highly metamorphosed sediments. Over broad areas the plane seems little affected by stream erosion post-dating its formation. The small wet weather streams flow on the surface of the plane, or in shallow depressions sunk but five or ten feet below its surface. Elsewhere, and especially near the mountains, the arroyos have channelled the pediment to depths of 50 feet or more, giving abundant opportunity to study both the plane surface and the rock on which it is cut.

As one nears the mountain base he notes that it is bordered by a series of very perfect fans, which to the casual observer offer no features of particular interest. In form and position they appear identical with thousands of alluvial fans seen elsewhere. Each fan has the apex of its flat semi-cone opposite the mouth of a canyon or major ravine, the fans opposite the largest canyons normally being flatter and lower than those apexing in smaller drainage basins.

At the base of the highest central peak (possibly Samaniego Peak) an unusually prominent fan (Fig. 7), heading high on the slope of the range, is extensively dissected by radial ravines; and even from afar the careful observer may note that the slopes of these ravines do not have the angle of repose with which he is familiar in channelled alluvium. One begins to suspect that the fans, like the pediment over which he is travelling, are cut on solid rock. Yet the illusion of an ordinary alluvial fan is hard to dispel. On the south side of

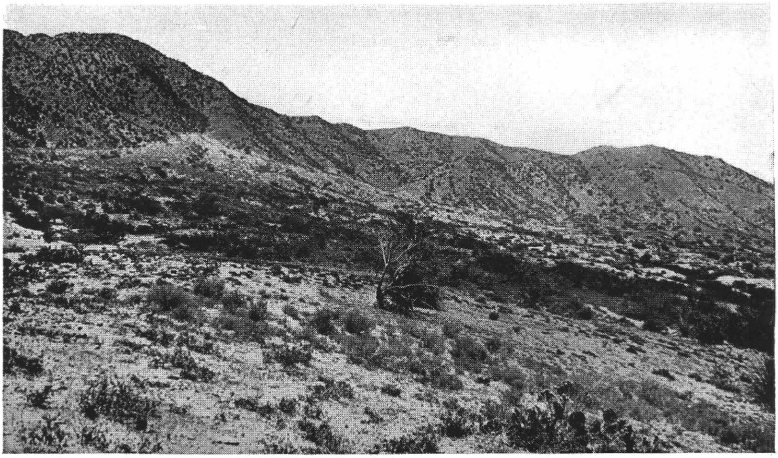

Fig. 7. Rock fan at the eastern base of the Sierrita Mountains, Arizona. Granite is exposed on all parts of the surface, now moderately dissected by recent erosion. The negative was retouched to emphasize outline of the fan, but the view correctly represents the essential relations.

the fan (left of view, Fig. 7), along the mountain base, one even notes distinct evidence of the presence of a marginal stream following the contact of fan surface and range front, and truncating the basal spurs of the peak, a phenomenon often observed on alluvial fans.

A closer approach leaves no doubt of the fact that the prominent fan at the base of Samaniego? Peak is carved out of solid rock. Ledges of granite (Fig. 8, A) outcrop frequently in the radial ravines which trench the fan. Rock in place is often exposed over undissected remnants of the fan surface; but here it is usually weathered, and one is not always sure of bedrock until he finds structures locally characteristic of the granite (such as jointing and sheeting with directions corresponding to similar structures in the unaltered ledges) traversing the weathered mass. From the lower part of the fan out across the pediment, and up the steepening cone to its very apex, rock in place is abundantly exposed. Alluvium was looked for, but with the exception of doubtful material in some of the ravines none was found. Whatever debris may have been left on the fan surface by the shifting stream which carved it, time and the elements have effectually removed.

In form this rock fan is very symmetrical. The apex rises 100 feet or more above the outer margins where these meet the mountain base, while the breadth of the fan, measured along the mountain base, is something less than a mile,—both these figures being mere estimates and subject to correction. The profile along any radius is concave upward, the slope becoming sufficiently steep near the apex to make walking something of a task. Away from the range the slope decreases, and merges imperceptibly with the sloping plane of the typical pediment. There seems no room to doubt that rock pediment and rock fan are an indivisible unit, and that both owe their development to the operation of a single process. The only process which will produce both is, so far as I can see, lateral corrasion by a heavily laden, shifting stream.

Looking northward from near the apex of the fan just described, one sees in profile another rock fan. The immediate contact of fan surface with mountain front appears somewhat softened or rounded in places, as if long free from erosion by shifting streams. Elsewhere the contact is notably angular, and the evidence of lateral stream corrasion in such localities is often very clear (Fig. 8, B). But even where the contact appears rounded, the zone thus affected is a narrow one. There still remains a sharp contrast between the far-extended slopes of the steep mountain front on the one hand, and the even farther-extending gentle slopes of the combined fan-and-pediment surface on the other. My observations are thus not wholly in accord with those of Waibel[11] who cites the Sierrita Mountains as a case where the angle between mountain front and pediment is missing, the "mountains being seen to rise with gentle slope and a gradual transition from the surrounding pediment." It should be noted, however, that Waibel fully

[11] Waibel, L., Die Inselberglandschaft von Arizona und Sonora, Sonderband der Zeitschrift der Gesellschaft für Erdkunde zu Berlin Hundertjarfeier, 1828-1928, 68-91, 1928, p. 88.

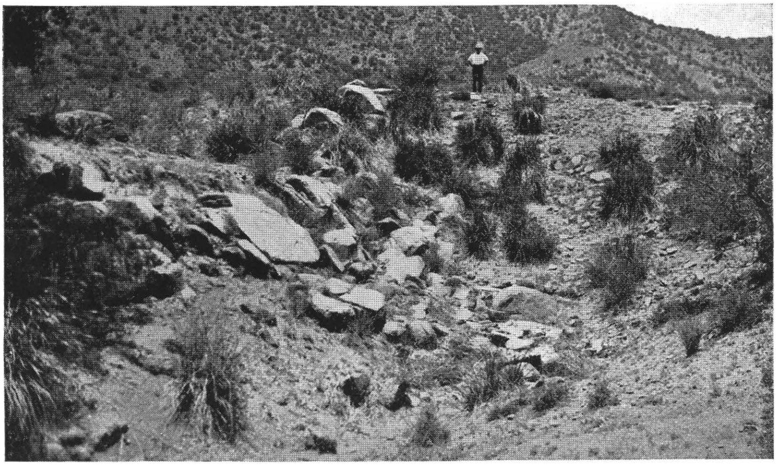

Fig. 8, A. Ledges of granite exposed in radial ravine dissecting rock fan at base of Sierrita Mountains. Rock in situ is exposed clear to surface of fan which is devoid of alluvial cover. The man is standing upon bedrock, on fan surface.

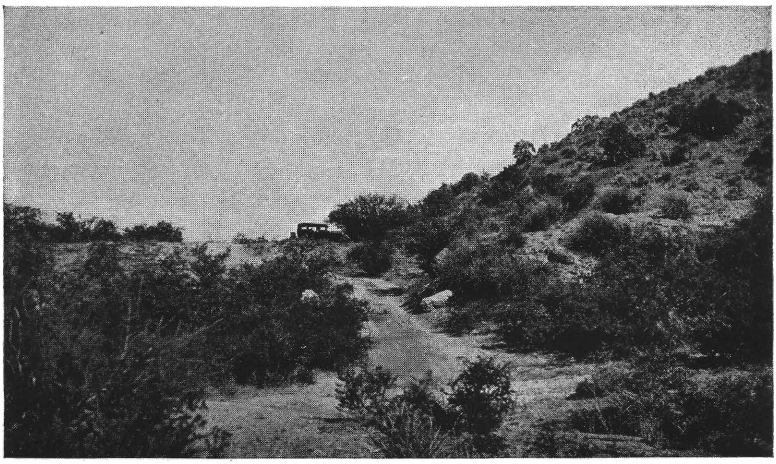

Fig. 8, B. Apex of rock fan north of Magee's Ranch, Sierrita Mountains. The automobile is on the rock surface of the fan at the base of the mountain front. Stream erosion has trenched the fan in the foreground.

recognizes the presence of this angle as a characteristic feature of desert ranges in general, and seeks to explain it as the result of "transportation of debris in rills (*Flächenspülung, Rinnenspülung*)." I am in doubt as to the precise manner in which debris transportation by rills is supposed by Waibel to create this angle, for apparently the rôle assigned to the rills is primarily the relatively passive one of removing debris. Waibel states that "the essential process (in pediment forma-

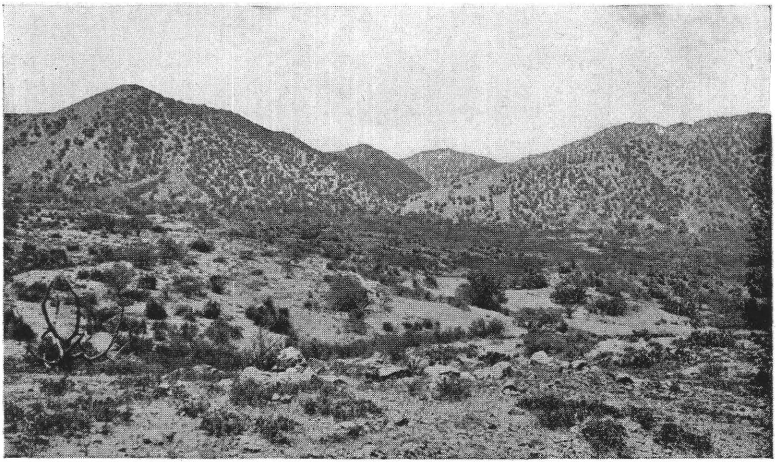

Fig. 9. Apex of low and relatively flat rock fan at mouth of large canyon just south of area shown in Fig. 7. The bedrock surface of the fan is moderately trenched by later stream erosion.

tion) is the comparatively swift recession of the escarpment by weathering of the exposed rock walls and removal of the debris from the plains."

The marked contrast in slopes referred to above strongly suggests that the two types of surface have developed under control of different forces. The steep slopes of the mountain front are like those determined by the forces of weathering when operating upon scarps of any origin; the gentler slopes of fan and pediment are like those being carved by heavily laden streams in arid regions. It is difficult to see how weathering could produce two sets of slopes each of great areal extent and differing profoundly from the other in degree of inclination, the two meeting at a sharp angle or in an angle but little rounded. Had any one force produced the rock slopes, they should not be obviously separable into two distinct types, but should merge imperceptibly one into the other.

If one passes south along the mountain front, descending the southern slope of the high rock fan at the base of Samaniego? Peak (Fig. 7), he soon begins to ascend the rock surface of another fan which has its apex at the mouth of a large canyon (Fig. 9). This fan, like its neighbor described above, has granite in situ abundantly exposed over its surface. But it is much flatter than the fan to the north, and its apex is considerably lower. This is what we should expect if the fans are the product of laterally corrading streams; for the stream of greater volume, debouching from the larger canyon, will normally attain the graded condition on a slope more gentle than that of its smaller neighbor. Similar relations were observed in the fans near Golden, New Mexico, and in those of the Dragoon Mountains. While Bryan did not recognize rock fans as an element of pediment topography, his carefully recorded observations of field facts strongly suggest their presence in areas studied by him, and show the same relations of steepness of slope to size of canyon described above. Bryan[12] writes: "The angle of slope of pediments ranges from about 50 feet to 200 feet to the mile. It is noticeable, however, that in any one mountain range the slope is steeper opposite the smaller canyons and very much flatter opposite the large canyons." He notes certain exceptions, already quoted in an earlier section of this paper, where unusually steep slopes opposite the mouths of (larger?) canyons are associated with the presence of especially resistant (large?) boulders, to which latter he attributes a protective action. If the boulders are large, as seems to be implied though not directly stated in his text, even the exceptions agree with the expectable consequences of rock fan formation by lateral corrasion of streams, since a large stream heavily laden with big boulders will attain the graded condition on a relatively steep slope. It seems difficult to account for the observed nice adjustments of pediment slopes to sizes of associated streams and stream load by any theory which does not attribute to stream corrasion the major rôle in pediment formation.

Further progress toward the south along the base of the Sierrita Mountains is difficult, the rock fans close to the mountain face giving the undulating or corrugated effect which

[12] Op. cit., pp. 53-54.

Blackwelder[13] believed to be characteristic of alluvial fans alone, while dissection of the rock fans increases the ruggedness of the topography. But one may return eastward to the originally smoother and still less dissected part of the pediment, then turn south a few miles, and again approach the base of the range near Magee's ranch. Here he finds himself once more traversing a series of coalescing rock fans, so badly dissected by recent stream erosion that fan remnants appear as mesas, or as "peninsulas" connected with the mountain base by narrow strips of the original fan surface. The apex of one of these fans is shown in Fig. 8, B, where the adjacent mountain slope has been distinctly trimmed by a lateral ravine following the contact of fan surface and mountain front. If the reader will place a straight edge tangent to the upper part of the mountain slope shown in this figure, he may readily note some trace of oversteepening of the lower part, a feature much more prominent in the field. The canyons debouching from this part of the range show inner gorges 50 feet or more in depth, presumably due to the same incision of streams which trenched the fans.

The major fan of this region has its apex more deeply re-entrant into the mountain mass than does the smaller example shown in Fig. 8, B, and is located just to the south, with Magee's ranch on a part of its surface. Bedrock is sufficiently exposed to leave no doubt as to its character; but unlike the parts of other rock fans examined in the Sierrita district, this individual is partially cloaked with alluvium. Arroyos five or six feet deep in places showed as much as four feet of angular stream gravel and sand overlying the bedrock floor; and it is probable that a more thorough inspection than we were able to give would show even greater thicknesses of alluvial cover.

The dissection of certain of these rock fans, coupled with their varying altitude opposite different canyon mouths, prompts the reflection that attempts to correlate fan remnants, where these appear as benches along the mountain front, may lead to erroneous deductions. There seems to be no reason why the upper levels of different fans produced at the same time should not show ranges of altitude amounting to some hundreds of feet. To correlate such remnants either as parts of the same erosion surface warped by differential earth move-

[13] Blackwelder, E., Desert Plains, Jour. of Geol., **39**, 133-140, 1931, pp. 136-137.

ments, or as parts of successive erosion surfaces formed in different epochs, would be equally wrong. As I have already indicated,[14] we should consider the possibility that certain reported peneplanes in the western mountains, including the Rocky Mountain peneplane in central Colorado (Fig. 10), may be parts of ordinary pediments the inner borders of which

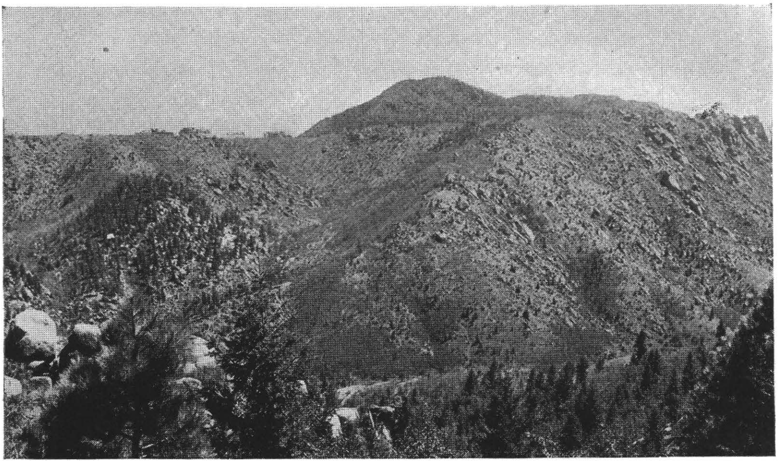

Fig. 10. "Rocky Mountain peneplane" west of Palmer Lake, Colorado, with monadnock rising above and canyon cut below its even surface. The marked eastward slope of this erosion plane, the apparent former perfection of its surface, and the "inselberg" character of some of the monadnocks, suggest that it may be a dissected high-level pediment, formerly continued across and bevelling the tilted strata of the Great Plains.

presumably, on the theory of lateral corrasion, consisted of rock fans, perhaps developed on a grand scale. May it not be that some of our difficulties in correlating remnants of these supposed peneplanes is due to the great variation in altitude of the original forms consequent upon the diverse local conditions under which they developed? And may not some of the slopes attributed to tilting, as possibly in the case of the Rocky Mountain peneplane just cited, represent the original relatively steep inner portions of extended rock pediments? If so, both the uplifts and the tiltings these forms are supposed to register may prove to be non-existent.

Whatever may be the answers to these questions, the pri-

[14] Johnson, Douglas, Planes of Lateral Corrasion, Science, **73**, 174-177, 1931.

mary significance of the rock fans of the Sierrita Mountains lies in this fact: they provide an unusually beautiful illustration of a landform the existence of which was recognized by the writer not in the ordinary course of routine field observation but solely as the result of deducing the reasonable (but in this case unexpected) consequences of a theory. The finding of these forms, following the purely deductive conclusion that they ought to exist, inevitably inspired an added measure of confidence in the theory that rock pediments, or suballuvial benches, owe their development chiefly to the corrading action of heavily laden, frequently shifting streams.

ROCK FANS OF THE COYOTE MOUNTAINS.

Thirty-five miles southwest of Tucson, Arizona, lie the Coyote Mountains, a small mass at the northeastern extremity of the great Baboquivari range. The writer has never visited this region, but an excellent view of a portion of the Coyote Mountains is appended to W J McGee's classic paper on "Sheetflood Erosion."[15] No discussion of rock fans is given in the main text of McGee's paper; nor is there any reference to such a feature, unless an obscure passage on page 104 describing deltas and fans containing fragmental debris varying in thickness from nothing to 40 or 50 feet and resting on bedrock, and another equally obscure at the bottom of page 109 and the top of page 110 referring to the building of alluvial fans which are later planed "into gentle curves blending with the adjacent baselevel," were intended by McGee to describe alluvial fans overlying fans formed on rock. But the plates at the end of the article are accompanied by long descriptive texts, and that relating to the view of Coyote Mountains contains this short but clear and highly important observation:

> "Several low fans are shown . . . . these have the form of alluvial accumulations, but actually consist of sharply carved mountain rocks, veneered thinly with granitic loam and gravel littered with great boulders."

The fans in question are very perfectly developed as shown in the full-page plate, evidently reproduced from a good photograph. The wording of the text indicates close range, first-

[15] McGee, W. J., Sheetflood Erosion, Bull. Geol. Soc. Amer., **8**, 87-112, 1897. See Plate 12, and descriptive text on page 112.

hand observation on the part of a competent investigator, and it therefore seems reasonably safe to include the Coyote Mountains among the localities exhibiting rock fans having a high degree of perfection.

Interest also attaches to McGee's descriptive text of Plate 13 in his report, reproducing a photograph of the eastern side of the valley of Rio Magdalena, north of Imuris, Mexico. It is there stated that "the great aprons forming the background have the appearance of alluvial fans, ... yet analogy with all of the plains examined indicates that they are in greater part baseleveled mountain rocks thinly veneered with alluvial deposits. They were not visited." Reasoning from analogy is altogether unsafe in this problem, and we now know that McGee greatly over-estimated the extent of rock pediments in the southwest, and similarly under-estimated the extent of true alluvial deposits which frequently have enormous thickness. But if we must hesitate to follow this author in regarding the fans in question as necessarily composed of rock, the quotation has value in emphasizing how completely he visualized the existence of this type of desert topography.

In view of these clear statements regarding rock fans in the descriptions of McGee's plates, it seems most remarkable that his classic paper otherwise takes no account of such novel forms. Possibly the difficulty of satisfactorily explaining them as a product of sheet-flood erosion caused him to postpone discussion of this particular phase of the problem until further evidence of the precise manner of their shaping should be secured. However that may be, there remains to be explained my own failure to recall McGee's reference to rock fans in a paper which I have read more than once in the last thirty years. I can only infer that the reference (assuming I ever read the plate descriptions carefully) made no particular impression on me at a time when I saw no special significance in fan forms developed on rock; while I certainly failed to read through the long plate descriptions in later years when the significance of the reference would have appealed to me. I am indebted to Professor Davis for bringing the lapse to my attention following my discussion of rock fans at the Pasadena meeting of the American Association for the Advancement of Science. Let me add that chagrin at my remissness has been quite over-balanced by the pleasure experienced upon independent discovery of the Sierrita rock fans. Perhaps there was, after all, advantage in discovering anew field facts which met the requirements (originally unanticipated) of a theory, rather than fashioning a new explanation expressly to account for features found described in the literature.

DISSECTED ROCK FANS.

We have seen that in the case of the Sierrita fans stream dissection has already begun its work of destroying their symmetrical cone forms. When once the eye is accustomed to detect these features it will find in the foothill topography of many ranges abundant indication of former rock fans. Sometimes these will be reduced to a maze of rolling hills and ravines which still preserve distinct indications of the earlier

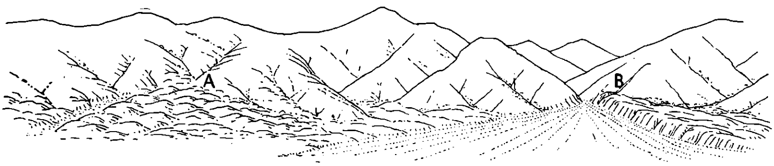

Fig. 11. Types of dissected rock fans:
A. Sub-conical mass of hills partially blocking canyon mouth, the stream escaping by marginal gorge following contact of fan and mountain front.
B. Inclined rock bench preserved on one side of canyon mouth, representing marginal portion of rock fan largely removed by planation at lower level where new fan of more gentle gradient has been formed.

conical shape. Occasionally the mouth of a canyon appears partially blocked by such hills, and the stream turns to one side, taking a passage which strongly suggests the course of a fan distributary following the contact of fan surface and mountain front (Fig. 11, A). Elsewhere the only trace of the former rock fan will be a dissected rock bench on one or both sides of, and sloping away from, the canyon mouth (Fig. 11, B). Here planation at a lower level has consumed most of the earlier fan, and a new cone, either of alluvium or carved on rock, may be the most conspicuous feature. Every stage of dissection has been noted, down to that of a mere rudely conical arrangement of foothills, of doubtful significance. All these forms are of interest to the student of desert morphology; but the question of origin of such forms must first be decided on the basis of those which are best preserved.

SUGGESTIONS FOR FURTHER STUDY.

It is believed that the rock fans of the Sierrita pediment are alone sufficient to raise grave questions as to the validity of the theory which would account for the formation of pediments or suballuvial benches through retreat of mountain fronts chiefly by weathering, although it is fully recognized that every rock surface exposed to the air suffers some weathering effects. Neither does the process of sheet-flooding seem to offer a satisfactory explanation of these forms. They are not merely explained by, they are required by, the theory of lateral corrasion. But the theory of lateral corrasion is too important, and its implications are too far reaching, to rest on the testimony of a few localities, however clear that testimony may appear to be. Hence the need of further evidence, gathered by other students of desert forms. As a possible aid to further study I append a few notes on localities which I have had no opportunity to examine carefully, but where casual observation suggests that proper scrutiny may yield data of critical value.

Along the base of the Rocky Mountain front range, six miles north of Colorado Springs, there is a series of good fans, in part composed of alluvium but in part also of rock, to judge from distant views. In high fans near the Modern Woodmen's Sanatorium bedrock was observed in several places, alluvium 50 feet thick in others. Whether we have here a rock fan covered with alluvium, a rock fan dissected and the valleys later filled with alluvium, or a combined alluvial and rock fan, the rock having an irregular surface with projecting high points planed off tangent to fan surface, was not determined. Two miles east of the Sanatorium soft white and yellow sandstones, now carved into "hoodoo" forms, appear to have once formed part of a rock pediment capped by granite debris from the mountains. Distant views suggest that this pediment is a prolongation of the high fan at the Sanatorium, while streams trenching the high fan have opened out another partial pediment at a lower level. Both surfaces can be traced a few miles out from the mountain base, gradually approaching each other due to the fact that the later surface has a more gentle gradient than the earlier. The foregoing observations were made under wintry conditions, with snow on the ground, and are subject to correction. They merely suggest that a careful examination of the critical zone along the base of the Front Range might be fruitful.

Between Benson and Vail, Arizona, the Southern Pacific Railway is bordered on either hand by typical desert ranges. From the rapidly moving train I observed high level benches or terraces, in part undoubtedly alluvial, but in part having the appearance of remnants of high level pediments or rock fans. My notebook mentions the bases of the Rincon, Empire, Whetstone, and Little Dragoon Mountains as localities which deserve careful examination by anyone interested in the problem of rock fans.

Approaching Rodeo, not far from the Arizona-New Mexico boundary, the east-bound traveller on the Southern Pacific Railway observes to the right of the track a range of mountains exhibiting a very remarkable high-level bench sloping steeply toward the plain, to which it drops off abruptly at the mountain border. The bench is of rock deeply trenched by canyons, and appears to be the inner portion of a once far-spreading pediment, the outer portion of which has been removed by erosion of weaker beds or alluvium, or dropped by faulting. A few miles farther on, the observer notes to the left of the track a wonderful series of fans, one of which rises nearly half-way to the summit of the range it borders. This high-level fan is deeply trenched, with its apex strongly re-entrant in the range. More recent, flatter fans are developed at lower levels, and appear to be alluvial. But the high-level fans suggest by the contours of their eroded surfaces that bedrock may be present, while outlying rock hills may be remnants of greatly eroded rock fans. Still farther on (ten minutes by rail), and several miles to the right of the track, a high mountain range has a broad zone of foothills which appear to represent a high-level rock pediment or series of rock fans, which rise nearly half-way to the top of the mountain scarp. The relations resemble those in the first range discussed in this paragraph, except that the bench is more thoroughly dissected and the pediment character therefore less obvious. This whole region seems a promising one for study.

Just west of Sierra Blanca, Texas, on the north side of the highway known as Route 80, is a circular group of mountains (Sierra Blanca) bordered by high-level dissected fans and later fans showing little dissection. From a distance it appeared that rock was outcropping extensively in one of the high-level fans on the western side of the range; and the contours of neighboring high fans suggest that they should all be examined carefully with a view to determining whether or not true rock fans form an important element of the range border topography. Other ranges in this general region show varying aspects of fan topography, and deserve investigation.

North of Victorville, California, Silver Mountain is bordered by a beautiful rock pediment trenched by the Mojave River and its tributaries. As observed at long range the surface of this plane seems to show frequent outcrops of bedrock, and to merge, at the base of the range, into low, relatively inconspicuous rock fans. A close range inspection would verify or correct these impressions gained at a distance.

When ten miles west of Casa Grande, Arizona, the westbound traveller on Route 84 approaches a range of mountains near the southern end of which is a conspicuous high-level plane, apparently the remnant of a fan, below the surface of which a broad valley has been opened. Whether this fan surface was developed on rock or on alluvium could not be determined from our distant view of it; but other bench-like surfaces on the face of the range, obviously developed on rock, suggest the former existence of high-level erosion planes about these mountains. From Hammock's filling station on Route 84 the traveller can probably reach the high fan remnant, not far to the south; but the urgency of a hasty journey prevented us from satisfying our curiosity regarding its true nature.

Probably not all, and possibly none, of the areas cited above, will exhibit good rock fans. They are indicated merely as "hunting grounds" which looked promising to the writer. If any reader already possesses knowledge of the existence of rock fans in any of the localities cited in this paper, or is able to secure definite information on future field excursions, the data would make a welcome contribution to the study of rock fans and their significance in the morphology of arid regions. Pending further investigation the theory of lateral planation is presented as a working hypothesis which seemingly has much to commend it to the careful consideration of geomorphologists.

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