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DONALD J. BACHINSKI

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HORACE WINCHELL

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FANS AND PEDIMENTS*

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ABSTRACT. Alluvial fans and pediments are discussed within the framework of an open system. Most desert piedmonts include both fans and pediments and have systems of stream channels with contrasting drainage area, discharge, gradient, and bedload. The drainage net on a piedmont includes streams that head in the adjacent highlands and others that rise on the piedmont and are tributary to the streams from the highlands. The reason for these contrasts is geologic; it is the presence of a highland that sheds coarse detritus to an adjacent piedmont where the debris is stored for a time until it is weathered and then removed both in solution and by stream erosion.

Washes in desert areas probably increase in discharge downstream only in mountains; on piedmonts, discharge may decrease rapidly downfan. Using the open-system concept, a piedmont may be considered as approaching a steady state when the rate of movement of detritus from mountain to piedmont is nearly the same as the rate at which material moves from piedmont to playa or flood plain. To maintain such a steady state requires broad areas of piedmont where erosion is the dominant process. Whether these areas of erosion are areas of more or less bare rock—pediments—or whether they are abandoned segments of fans depends upon the geometry of highland and lowland. Large highlands and small lowlands favor complex fans where half the surface area may no longer receive sediment but be subject to erosion, whereas broad lowlands and small highlands favor extensive pediments.

An open-system approach to the origin of fans and pediments encourages the study of present-day processes and opposes the current tendency to rely solely on climatic change as the explanation for features whose mode of formation may be in doubt.

INTRODUCTION

This paper is concerned with the application of the principle of dynamic equilibrium to the formation of alluvial fans and pediments (Strahler, 1952; Hack and Goodlett, 1960; Hack, 1965; Chorley, 1962). In this discussion, piedmont refers to the plain with locally complex topography that slopes from highland to playa or flood plain. The piedmont is an important part of the arid landscape of the Basin and Range province. Part of a piedmont may be a more or less bare rock surface, a pediment. Part is alluvium, and if its surface has the form of a section of a very low cone it is a fan. In the Death Valley region most piedmonts are largely coalescing alluvial fans; in parts of the Rio Grande Valley the pediment is the dominant form. Piedmonts with discontinuous gravel aprons and areas of bare rock occur also in humid regions.

The interpretation of piedmont formation under the concept of dynamic equilibrium assumes that a piedmont acquires its specific shape or morphology because it is acted on by certain processes and will maintain this morphology as long as these processes are in operation. If these processes change their character or intensity, then the piedmont changes

* Publication authorized by the Director, U. S. Geological Survey.

its morphology. Process and form are indivisible. Neither can exist without the other. In piedmont formation the energy of the system depends primarily upon the height of the mountains above the surrounding piedmont. This energy performs work through such agents as running water, weathering, and mass wasting to maintain the piedmont in its proper state as regards its size, shape, character of surface, and so on. A steady state may be maintained at different levels, depending especially upon the ratio between the rates of its "gains" and "losses". For piedmonts this point refers to the rates of movement of material from the upland to the piedmont and from the piedmont to the adjacent playa or flood plain.

In the Death Valley region, many piedmonts have large segments that do not receive detritus from the mountains. Material is being removed from these segments by local runoff. A certain amount of detritus is added to the piedmont each year, and a certain proportion of the total amount of fan debris is removed each year. The fan (part of the piedmont) grows larger year by year, but eventually the rates of supply and removal must be equal. The piedmont has then attained equilibrium; the volume of detritus on the piedmont is constant and will remain the same as long as the environment does not change. Nikiforoff (1942, 1959) devised a simple mathematical formula to illustrate the equilibrium principle as applied to soil formation, and Hack (1965, p. 7) has described how the formula can be applied to talus accumulation at the base of a cliff. It can be shown to apply also to piedmont formation when the rates of supply and removal are equal.

Desert piedmonts have two systems of stream channels, those that head in the adjacent highlands and others that rise on the piedmont and are tributary to the streams from the highlands. The reason for these contrasts is geologic. The highland sheds coarse detritus to an adjacent piedmont where the debris is stored for a time until it is weathered and then removed both in solution and by stream erosion. The highland owes its existence either to tectonic movements or to resistant bedrock.

Washes in desert areas probably increase in discharge downstream only in mountains; on piedmonts, discharge may decrease rapidly downfan. For this reason the amount of debris supplied to a desert piedmont will greatly exceed the amount removed from it unless the area of piedmont that is being eroded is large. To maintain a steady state between form of piedmont and rates of supply and removal requires broad areas of piedmont where erosion is the dominant process. Whether these areas of erosion on the piedmont include broad sloping plains or pediments or whether the areas of erosion are deeply gullied into badlands depends primarily on geology of mountain and basin.

This picture of piedmont development in the desert is an outgrowth of a study of alluvial fans in the Death Valley region made in 1956-58 (Denny, 1965; Denny and Drewes, 1965) and of earlier studies in New

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Mexico (Denny, 1941). In the preparation of this paper I am indebted to C. C. Nikiforoff for advice and encouragement. I am also particularly grateful to J. T. Hack and R. P. Sharp for their suggestions and critical discussion.

A THEORY OF ALLUVIAL-FAN FORMATION

A fan is "an accumulation of debris brought down by a stream descending through a steep ravine and debouching in the plain beneath, where the detrital material spreads out in the shape of a fan, forming a section of a very low cone" (Howell and others, 1960, p. 105). The prime requisite of fan formation, the setting of highland and lowland side by side, can be explained in various ways. In Virginia, it is produced by the differential erosion of adjacent bodies of rock of varying resistance; in the Death Valley region it is the result of tectonic movements. In common with stream channels in humid regions, it is probable that the average channel slope of a desert wash in the mountains is inversely proportional to its discharge, but for a given discharge it is directly proportional to a function of the material it transports and the resistance of the bedrock or material that encloses the channel (Hack, 1957). If the mountain is composed dominantly of resistant rock, the streams in the mountain will have much steeper gradients than those in the adjacent lowland. Where a stream reaches the mountain front it encounters these gentle slopes and deposits the part of its load that is too coarse to be moved on such subdued gradients. The wash builds a fan in the lowland and alluviates its channel in the mountain. It thus has a smooth slightly concave-upward profile from valley floor well up into the adjacent highlands.

Deposition is by no means the only process that operates on an alluvial fan. Although a small fan at the base of a Recent fault scarp may be entirely covered by water during floods, many large fans include areas that have not received sediment for a long time. The broad apron of coalescing fans that form the piedmont in Death Valley east of the Panamint Range is a mosaic of areas of desert pavement and of wash (Noble and Wright, 1954, fig. 2; Hunt and Mabey, 1966). The local relief on the fan surface near the mountain front is more than 100 feet. More than half the surface of the fan is desert pavement and gully—segments where weathering and erosion have been the dominant processes for a long time. Sedimentation is now limited to less than half the surface of the fan.

In the arid cycle of Davis (1905), fans are characteristic of the youthful stage and grow larger and larger until the mountains are considerably reduced, broad alluvial aprons slope toward extensive playas or flood plans, and the several originally enclosed basins have become integrated. This picture of the long-continued expansion of alluvial fans is not entirely consistent with the existence of large fans where more than half the surface is being eroded and deposition is limited to only a small segment. If we consider fan formation in the framework of a dynamic system, a more consistent hypothesis can be devised.

Initially, let us suppose that a graben begins to be lowered across an area of low relief. At once fans begin to form adjacent to the initial fault scarp on either side of the sinking block. If the rate of depression were exceedingly slow, perhaps the rate of erosion of the bordering fans might soon approach their rate of growth. Such fans might indeed be so small as to pass almost unnoticed.

If the rate of depression of the graben is rapid, and if the mountains are large and the lowlands are broad, fans may grow and coalesce. Assume that the volume of material supplied to these fans per year is constant. Actually, of course, the amount of detritus brought to a fan varies from year to year, and the rate can be regarded as constant only as an average over many years. The torrential summer cloudbursts in desert regions have a highly erratic distribution both in time and in space. Floods that come from the mountains and spread water only near a fan's apex are a more frequent occurrence than those due to precipitation that falls directly on a fan. Mountains induce precipitation, concentrate flow, and have channels that do not lose as much water by percolation as those on fans. On the ideal fan debris is commonly deposited near the fan's geometrical apex. Movement of debris downfan from the apex is erratic, taking place in short periods of flow separated by long intervals of dryness. An occasional flood may carry debris from mountain to playa, but floods that do not pass far beyond the apex are probably more frequent.

Many large fans are dissected near the mountain front so that their upper part no longer receives sediment from the mountain. The loci of deposition is shifted away from the mountain front, away from the fan's geometrical apex. This incision is an important step in the history of a complex fan and probably may occur for several different reasons, depending on the local geology (Eckis, 1928, p. 236-241).

Faulting may cause fan-head trenching. Most active fans in the Death Valley region have a smooth, slightly concave upward profile from the central playa or flood plain well up into the adjacent highlands. A relative sinking of the valley floor, expressed by a fault scarp on the fan a short distance below the apex, like some of those that cross fans in Panamint and Death Valleys (Jennings, 1958), may cause a steepening of the slope of the fan-building wash for a short distance upfan from the scarp, perhaps to a point inside the mountain front. Thus the depositional apex of the fan is shifted downfan to the scarp. Probably the stream channel above this new apex will soon be regraded to another smooth slightly concave upward profile similar to that present before faulting. Regrading would probably involve a slight downcutting along the entire length of the stream channel in the mountains and the deposition of this debris downfan from the new apex.

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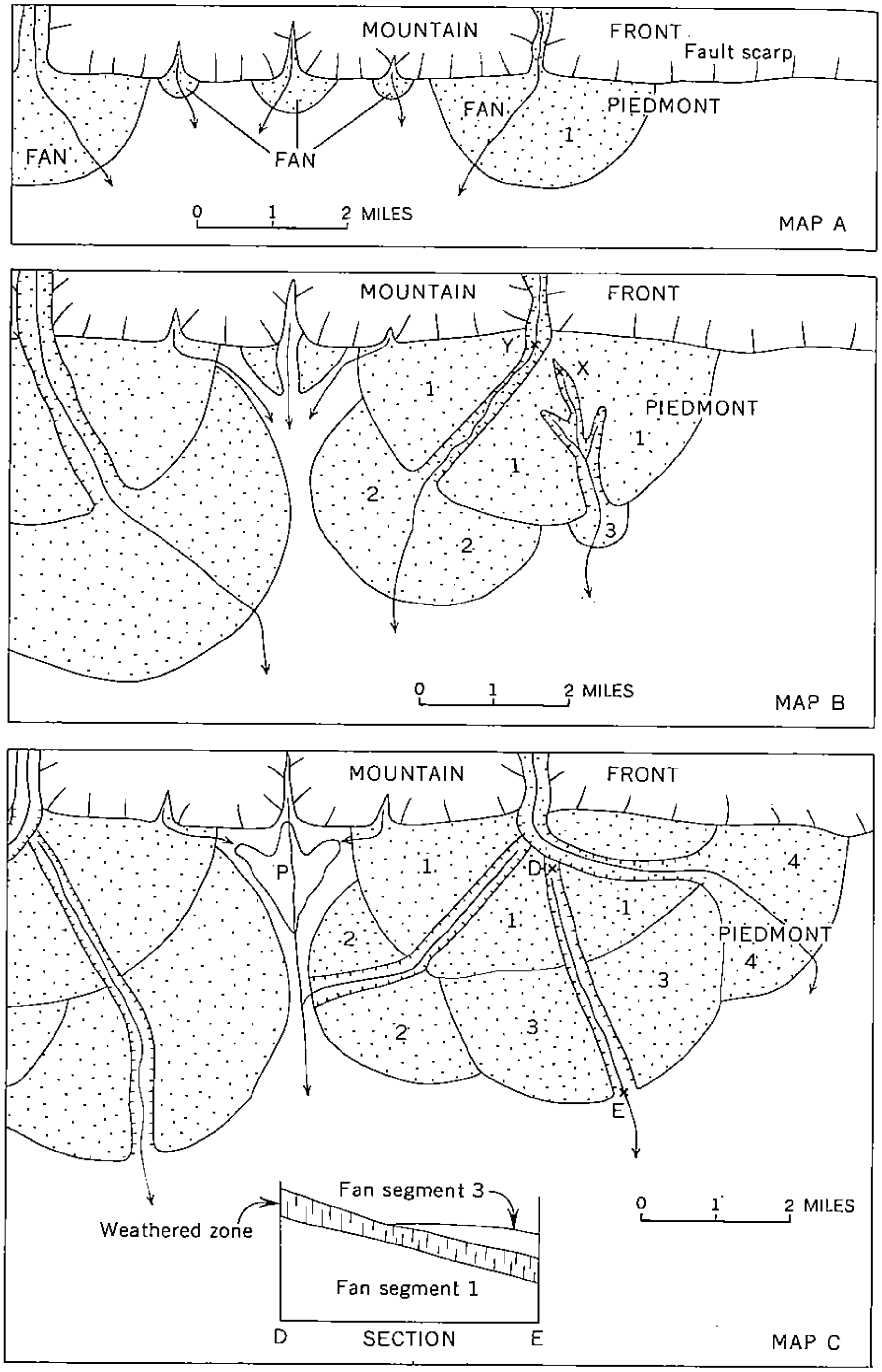
Fan-head trenching may be the normal consequence of large variations in flood discharge. That is, during a long period of time a fan will have a tendency to grow at its apex, but occasionally an exceptionally large flood will trench the fan near its apex and deposit near its toe.

Consider the hypothetical example shown in figure 1. Map A shows several fans at the base of a fault scarp. Map B (fig. 1) shows the hypothetical fans after fan-head trenching has taken place. Detritus from the mountain bypasses segment (1) by way of a narrow trench and is deposited as fan segment (2) which laps up over a part of the outer edge of segment (1). Weathering and erosion by local runoff and by wind become the dominant processes on abandoned segment (1). Gullies are carved in it by local runoff—one is shown in map B—and desert pavement develops on the interfluves. These gullies that head on the fan—the fan washes—erode the fan and deposit their load either on the adjacent playa or flood plain or further downfan. Thus, fan washes are to be contrasted with those from the highland—the mountain washes—that are primarily agents of deposition. Near its headwaters at point x, the floor of the gully may be below the level of the adjacent large wash at y. If the mountain wash erodes its left bank at y, the wash may cut through its bank and spill down into the meandering gully at x. This piracy leads to the abandonment of segment (2) and the enlargement of (3) (map C).

The area of the fan that no longer receives detritus from the mountain, or the area where weathering and erosion are dominant, is now greater than before piracy took place. This increase in the area being eroded causes an increase in the rate of removal of material from the fan. Because we have assumed in this hypothetical analysis that the volume of material deposited on the fan per year is constant, any increase in the area of erosion requires a decrease in rate of growth of the fan. Other drainage diversions will take place; one such event is suggested in map C. These changes will cause further shifts in areas of deposition and corresponding increases in total area being eroded. This ideal fan is approaching a time when the amount supplied to it per year will equal that removed by erosion. The fan will then be in a steady state of fan formation. Thereafter the fan will not grow larger either in area or in volume, but the geographic position of active and abandoned segments will be continually changing. Mountain washes deposit, and fan washes erode; an equilibrium between them is maintained by piracies.

Requirements of the theory.—The interpretation of piedmonts as the steady state of an open system requires a shift from time to time in the loci of deposition and of erosion. Otherwise part of the piedmont's surface would grow higher and higher while the remainder would be reduced to lower and lower elevations. The transformation of the surface of an abandoned segment of a fan (part of the piedmont) into



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desert pavement is a part of the process of removal and is discussed later. Changes in area of deposition take place because washes with differing gradient and load occur side by side and lead to drainage diversion or piracy. The juxtaposition of contrasting washes is caused by a variation in geology and hydrology between mountain and fan. The mountain may be made of resistant rock that yields coarse detritus which is carried on a steep gradient out onto the piedmont and deposited as a fan. The small, commonly meandering gully that heads on the piedmont has a fine-grained bedload because it comes from unconsolidated material, in part from weathered debris—the pavement and the weathered zone beneath it. The slope of the gully is less than that of the fan-building wash to which it is tributary. The difference in profile is commonly so great that the wash from the mountain crosses the fan at higher elevations than its own downstream tributary, the meandering gully. The gradient of the gully can be low because its bedload is fine grained and because rapid runoff on adjacent pavements tends to increase gully discharge. It is the erosion by meandering gullies, caused by local runoff on the piedmont, that is continually removing debris from the fan.

Piracy on piedmonts, related to lithologic contrasts between highland and lowland, has been noted by several authors (Rich, 1935; Mackin, 1936; Hunt, Averitt, and Miller, 1953; Knechtel, 1953; Hack, 1960). The Shadow Mountain fan in the Amargosa Valley, California, is described below to illustrate the part played by piracy in the maintenance of the steady state of fan or of piedmont formation.

Shadow Mountain fan as an illustration.—A piedmont extends from the west base of Shadow Mountain, east of Death Valley Junction, California, for 3 to 6 miles to the flood plain of Carson Slough, a tributary of the Amargosa River (fig. 2), which lies about 3000 feet below the mountain top. (See map of Shadow Mountain fan, pl. 1 in Denny, 1965). The piedmont is largely coalescing alluvial fans; there are but two small areas of pediment, K and L, that cut across deformed Tertiary(?) rocks (Denny and Drewes, 1965, pl. 1).

The Shadow Mountain fan heads in a reentrant on the north slope of Shadow Mountain. The fan is concave upward in an east-west direction, the average slope being about 700 feet per mile near the mountain front, decreasing to less than 100 feet per mile near Carson Slough. The fan is built of fragments of quartzite and other resistant rock.

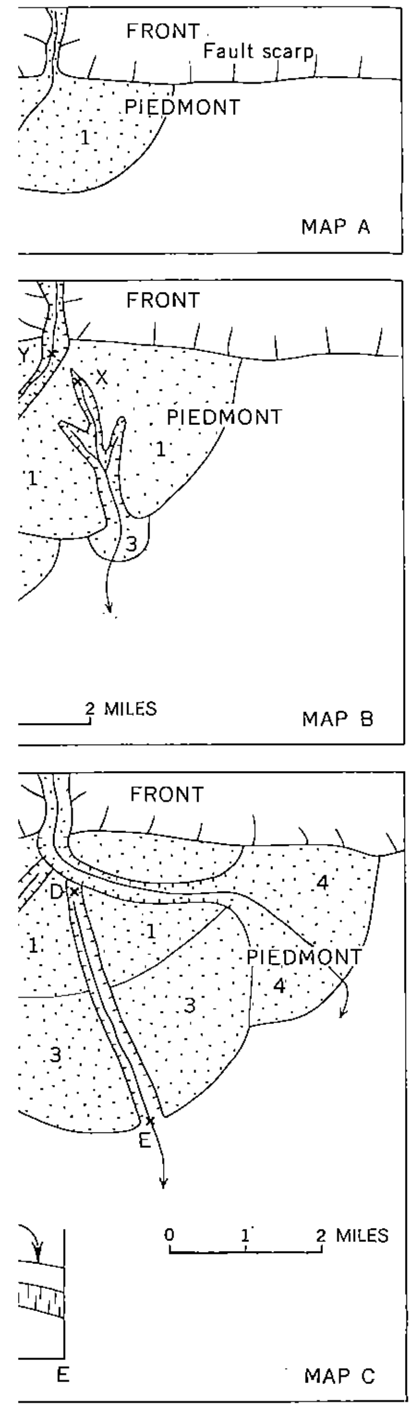

Fig. 1. Maps showing development of alluvial fans. Scales approximate. Map A, small fan at base of recently elevated mountain. Map B, wash from mountain has dissected original fan, segment (1), and is building a new fan, segment (2). Another wash, heading in abandoned segment (1), is building a new fan, segment (3), at its mouth. Map C, two drainage diversions have taken place causing wash from mountain to abandon segments (2) and (3) and to build new segment (4) at its mouth. Section D-E, stratigraphic relations betweens fan segments (1) and (3) as they are exposed in wall of gully D-E.

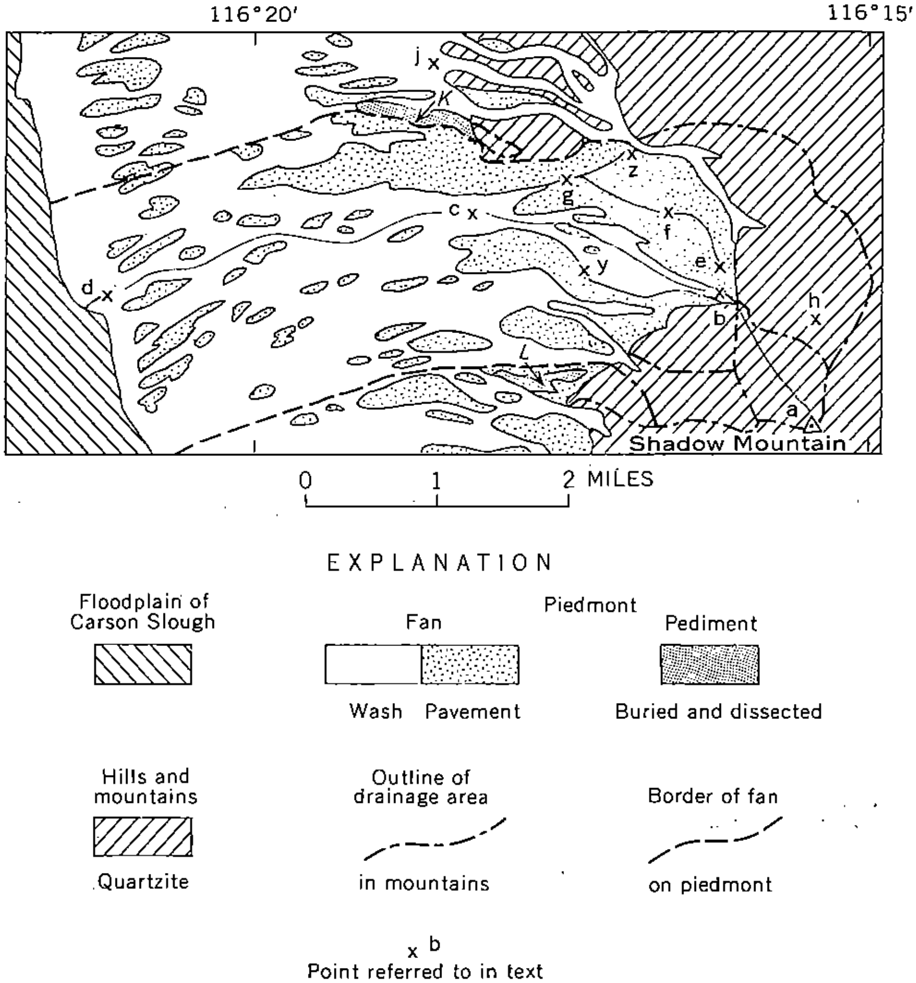

Fig. 2. Map of Shadow Mountain piedmont on east side of Amargosa Valley near Death Valley Junction, California.

Near the mountain front the material is pebble and cobble gravel; near the toe the gravel fraction is finer grained, and more than half of the fan debris is sand and silt.

The fan is a complex mosiac of desert pavements and of washes with a total surface area of about 9 square miles. The desert pavements that cover about one-third of the fan are smooth, gently sloping surfaces composed of closely packed angular fragments of rock. All the large areas of pavement are dissected by steep-sided gullies (most are not shown on fig. 2). Pavements are described later. Washes that cover the rest of the fan consist of braided channels and gravel bars. About one-

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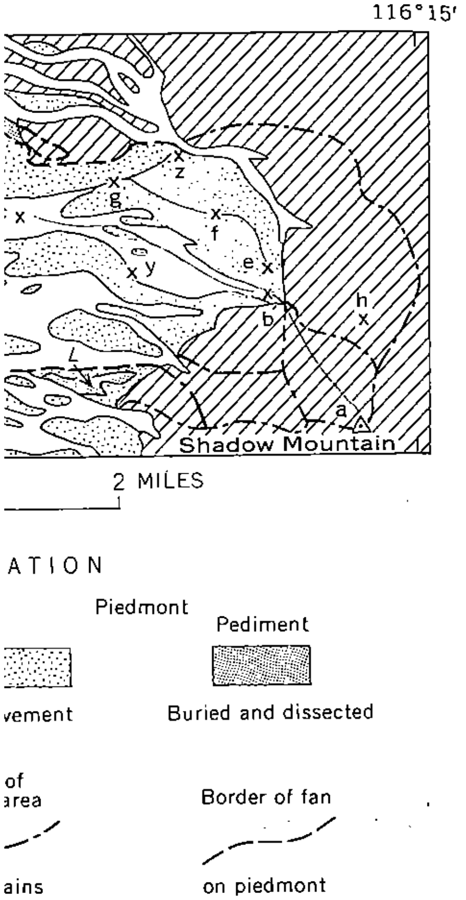

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third of the area of washes is floored with unweathered gravel that is moved by present-day floods; the remaining washes have their surface material coated with desert varnish and have been dry for a long time, perhaps for 2000 years (Hunt and Mabey, 1966). The local relief between pavement and wash ranges from about 40 feet near the fan's apex to only 1 or 2 feet near the toe.

On Shadow Mountain fan, the juxtaposition of washes with contrasting gradient and bedload has led to piracy. One of the principal fan-building washes heads at the mountain summit and runs northward and westward to Carson Slough. In figure 2 the course is roughly a-b-c-d. A second wash heading in the pavement on the north side of the fan at point e runs through the pavement for about $1\frac{1}{2}$ miles (e-f-g) to join the large wash at c. At points approximately a mile up each wash from where they join, the gradient and size of bedload of the large wash are about twice that of the small one. Throughout much of its length the bed of the large wash lies below the adjacent pavement, but at some points, such as y, the wash's bed is even with the pavement, and unweathered detritus laps onto a floor of varnished stones.

Another large wash skirts the northeast edge of the fan, draining a large area on the north slope of Shadow Mountain; the headwaters are near h. This wash passes north of the fan by way of several channels that reach the piedmont near j. In actuality, runoff from the north slope does not reach j because the upper part of the large wash has been diverted westward at z, in the northeast part of the map area, and now drains to the Shadow Mountain fan (z-g-c). Before piracy took place, the bed of a small west-flowing wash heading on the pavement near z lay about 10 feet below that of the large wash to the northeast. Apparently the large wash cut through its south bank near z to empty into the adjacent, small, low-lying channel.

On the bed of the large wash near the elbow of piracy the new west-flowing channel is separated from the older northwest-trending one (trending toward j) by a gravel bank only 2 or 3 feet high. Clearly this drainage diversion was initiated but a short time ago. A high flow of water down the large wash could still supply the water to both channels at z. Because of this piracy, the amount of water and detritus reaching the Shadow Mountain fan in time of flood will increase whilst that supplied the piedmont to the north will decrease. This shift in the equilibrium between form and process will probably cause alluviation of the narrow gully in the pavement (z-g) and the gradual building of a low cone of detritus near the mouth (c).

This piracy is but the most recent one. The gravel beneath the broad area of pavement on the fan's north edge was derived in part from the north slope of the mountain (Denny, 1965, fig. 16). A later diversion of water away from the fan established the northwesterly drainage (z-j) that has only just now been beheaded.

Piracy is what maintains the balance on the piedmont between the processes of erosion, deposition, and weathering. The shifting from time to time of the loci of these processes places a constraint on long-continued fan-building. That is why the surface area of many fans, regardless of their past history, bears a simple functional relation to the area of their highland sources. Weathering and erosion have been for a long time the dominant processes on the large pavement near the northeast edge of the fan, while deposition has been dominant on the piedmont to the north, near j. As a result of the recent piracy, a reduced amount of debris now reaches the piedmont northwest of the fan where I would now expect stream channels to be incised and the material on the interfluves to weather. Meanwhile the rate and area of sedimentation on the fan itself will increase because its source area has been doubled. Some of the small areas of pavement on the lower half of the fan are only a foot or two above adjacent washes and may in time be buried under detritus.

It is interesting to note that these examples of localized deposition or dissection on the Shadow Mountain fan and in the adjacent mountains are the same sort of features that in Deep Springs Valley, California, are believed by Lustig to be indicative of climatic change (Lustig, 1965). Shifts in loci of deposition from within the mountains to points far down the fan, fan-head trenching, abandoned channels (channels no longer connected to mountains), and hanging tributary fans in the mountains are all features of Deep Springs Valley that have their counterparts on the Shadow Mountain fan.

Desert pavement, an example of a steady state.—The abandoned segments of many fans that have not received sediment from the mountain for a long time are traversed by gullies that head in the abandoned segment (map A, fig. 3). The gullies, many of which have meandering courses, range in depth from a few feet to many tens of feet. Near its headwaters the floor of a gully lies well below the bed of the adjacent wash (section B-B′) although the gully empties onto the wash farther downfan. On most fans, except those composed of granitic detritus (R. P. Sharp, written communications, 1963), the gullies are separated by flattish areas of desert pavement.

On most abandoned segments, the area of pavement is considerably greater than the area of meandering gully, suggesting, at first glance, that a once more extensive pavement is now being dissected. This suggestion implies that pavement-forming processes were dominant during some interval in the past, but that now dissection is the sovereign process. The absence of ungullied pavements, the ubiquity of meandering gullies, and the presence of pavements on the walls of many gullies leads me to wonder if pavements on fans are not always dissected, that the processes of pavement formation and dissection go hand in hand (Sharon,

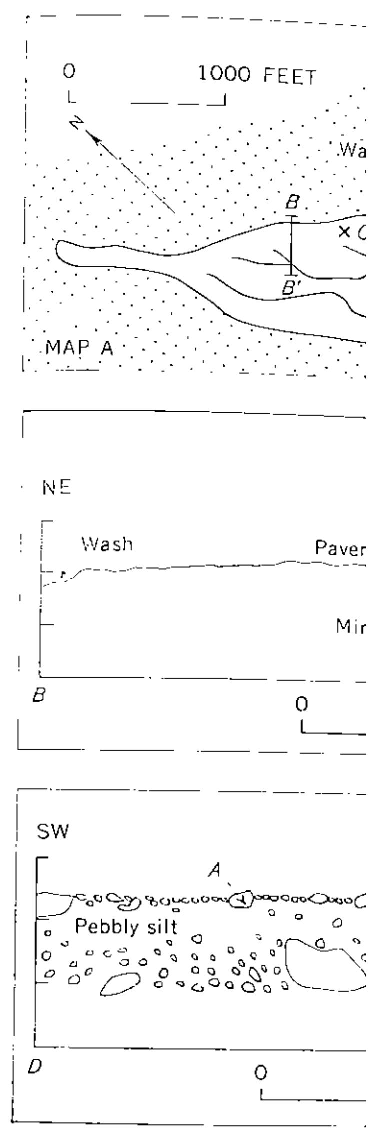

Fig. 3. Map, profile, and sectio
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Death Valley Junction. Meandering
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ıe balance on the piedmont between the and weathering. The shifting from time processes places a constraint on long- is why the surface area of many fans, ıry, bears a simple functional relation urces. Weathering and erosion have been processes on the large pavement near the le deposition has been dominant on the . As a result of the recent piracy, a re- reaches the piedmont northwest of the t stream channels to be incised and the weather. Meanwhile the rate and area of will increase because its source area has ll areas of pavement on the lower half of above adjacent washes and may in time

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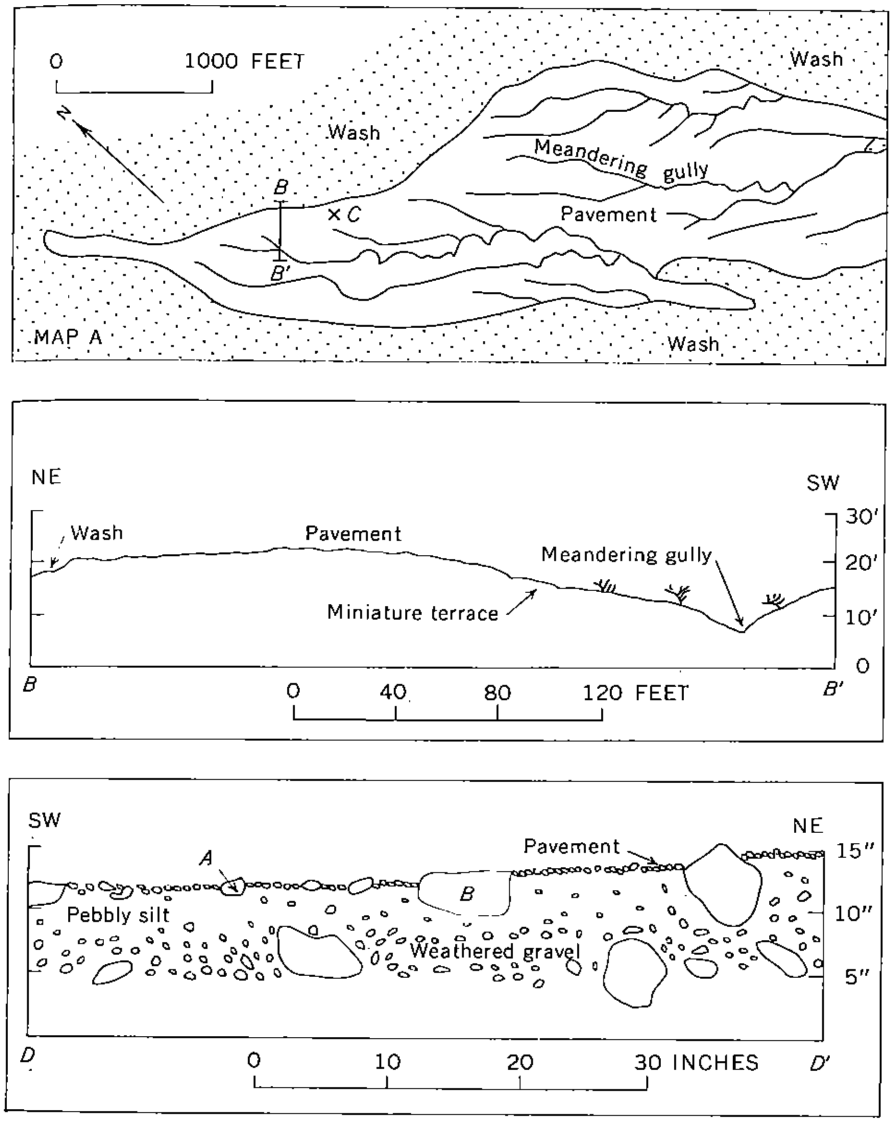

Fig. 3. Map, profile, and section of pavements on fans in Amargosa Valley, near Death Valley Junction, California (Denny, 1965, pl. 2, figs. 8 and 11). Map A, map of pavement and surrounding washes on Bat Mountain fan about 4 miles northwest of Death Valley Junction. Meandering gullies head in pavement. B-B′, profile across parts of pavement and wash showing miniature terraces. Floor of gully lies nearly 10 feet below bed of adjacent wash. For location see map A. D-D′, section of pavement on Shadow Mountain fan (near g, fig. 2). Armor of stones rests on pebbly silt that is transitional downward into weathered gravel. Large stones are risers of miniature terraces.

1962, p. 133). Doubtless there are places where pavement dissection reflects some tectonic or climatic event. Nevertheless I believe that many "dissected" pavements are approaching the steady state of an open system within the broader system of the piedmont as a whole. Pavement dissection tends to balance pavement formation. The pavement on a fan is dependent for its existence on the shifts in the locus of deposition caused by piracy.

Desert pavements are smooth, gently sloping surfaces composed of closely packed rock fragments commonly coated with desert varnish or faceted by solution. The stones range in diameter from a fraction of an inch to several feet and are slightly rounded to angular. Many of the latter are broken fragments of an abraded pebble, cobble, or boulder. The pavement is an armor that promotes runoff and protects the underlying material from removal by water or wind. Pavements rest on and in a layer of silty material ranging from about one to several inches thick that is transitional downward into weathered gravel (sec. D-D′, fig. 3). R. P. Sharp (written communication, 1963) states that in many places the silty layer is less than an inch thick and rests with sharp contact on underlying material.

The silty layer beneath the armor of stones appears to be a concentrate formed in part by weathering and in part as a consequence of the processes that produce the stone armor, processes that transform an initial surface of channels and gravel bars into a smoth pavement. Some of the silty material may be the result of the weathering in place of gravel similar to that which underlies it. Under some pavements, the gravel is strongly weathered to depths of several feet, and some of the stones crumble in the fingers. However, in many places the gravel beneath pavements appears to be little weathered, and the silt between gravel and pavement must have been introduced. Perhaps in such places the silt was deposited by the wind, and the stones became set on and in it by lateral movements when the silt was wetted. Lateral movement of a saturated surface layer, as explained below, might also move stones upward to the pavement from beneath the silt.

The overall slope of a pavement is downfan; in map A of figure 3 this would be to the southeast. The local slope is generally toward the adjacent wash or meandering gully (sec. B-B′) and may be nearly at right angles to the overall slope. Most pavements are broken by miniature terraces with risers less than an inch high which trend at right angles to the slope of the pavement for tens of feet. The treads of some of these terraces are composed of small fragments and coarse sand forming discontinuous bands across the pavement. In many cases the treads are indistinguishable from the adjacent pavement in surface form or in varnish coating, and it is only the riser that can be distinguished.

These miniature terraces apparently form by downslope flow when the underlying silty material is wetted to depths of 2 to 3 inches. The are places where pavement dissection re- : event. Nevertheless I believe that many roaching the steady state of an open sys- ı of the piedmont as a whole. Pavement ement formation. The pavement on a fan on the shifts in the locus of deposition

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risers are miniature scarps formed at right angles to the pavement slope. It is this downslope movement, aided by surface wash and by wind action, that gradually transforms the channels and gravel bars of an abandoned wash into a smooth pavement.

Observations over several years led Hunt and Washburn (1960, 1966) to postulate that miniature terraces in Death Valley are not forming at present but are largely relics of a moister climate. In the Amargosa Valley, miniature terraces are forming at the present time. I observed a pavement after a heavy rain and found that the upper 2 inches of the silt layer was wet, whereas the material below was dry. When I removed a stone such as A in section D-D′ of figure 3, the surrounding silt and its stone shell tended to flow down into the hole formerly occupied by the stone. In section D-D′ the pavement is broken by two rock-defended terraces with risers about an inch high. When the surface layer of saturated silt moves downslope (to the left in D-D′), it piles up behind large stones such as B that are anchored in firm dry ground beneath. Smaller stones in the pavement, such as A, rest on the wet silt and are carried along with it.

Apparently pavements are born dissected. Once a segment of a fan ceases to be an area of sedimentation it begins to be gullied by local runoff while the interfluves between gullies are gradually smoothed. The smoothing of the interfluves involves the movement of fine debris down into an adjacent gully, both from the pavement itself and from the weathered zone beneath the pavement. This movement, which tends to fill up the gully, is opposed by the transporting power of local runoff down the gully. The stream in the gully deposits its load where it emerges downfan onto a broad wash. Pavement formation and gully erosion may tend to balance each other, to approach a steady state. Thus a pavement once formed may persist for some time. Although the actual stones forming it are gradually comminuted by weathering, they are replaced by others as the surface is gradually lowered by lateral movement of a surface layer, by rainwash, and by deflation. The appearance of a pavement may thus remain much the same. Similar pavements may be of diverse ages.

The deeper that gullies are cut below adjacent pavements the smaller the areas of pavement become, until they are finally completely consumed. On the Shadow Mountain fan the areas of pavement near the apex have the form of long fingers separated by narrow gullies. Some of the fingers have rounded tops, all areas of essentially smooth pavement having been destroyed. An area of pavement will ultimately be destroyed by erosion or buried beneath new increments of fan debris.

Discussion.—Thus far I have discussed fan formation only in terms of a steady state, but I do not mean to imply that all features of fans or of the piedmonts of which they are a part are in or approaching a steady state. Some features are probably relics of past conditions. The

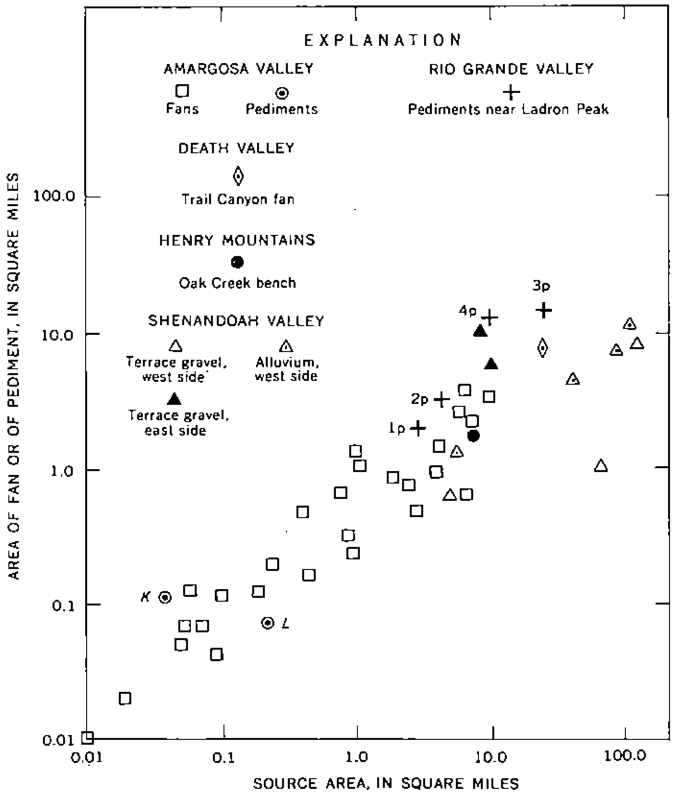
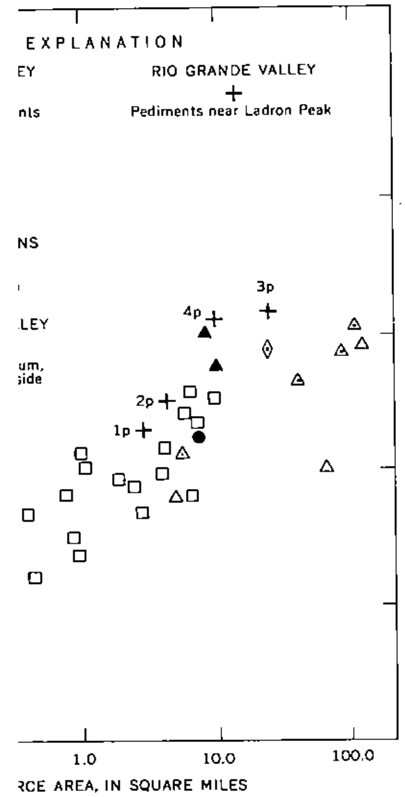


Fig. 4. Logarithmic graph showing the relation between the area of a fan or pediment and its source area in adjacent mountains. Data for Amargosa Valley from Denny (1965), for Shenandoah Valley from Hack (1965).

matter hinges on the rapidity with which landscape features adjust themselves to changes in the rates of the processes that act on them (Chorley, 1962, p. 6). Lustig studied alluvial fans in Deep Springs Valley, California, and concluded that climatic changes best account for their characteristics, their form tending toward an equilibrium with each successive climatic episode (Lustig, 1965). As already noted, many of the features cited by Lustig from Deep Springs Valley as evidence of climate change can, on the Shadow Mountain fan, be explained as the result of piracy. Without doubt, climatic changes have occurred and have influenced fan morphology, but the changes involve only the rates at which the processes operate. Changes in rates cause changes in the steady state, not a change in the nature of the system as a whole.

The example of a steady state described earlier involved equal rates of sediment supply and removal from a fan or piedmont. We have no data on what the actual rates involved may be, but we can compare the area of a fan with that of its source. Figure 4 shows that the size of fans



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in the Amargosa Valley, California, is an exponential function of the size of the source area. As we are dealing with fans of contrasting size, lithology, and geologic history, this relationship indicates a steady state between form and process.

Lustig believes that the surface areas of the alluvial fans in Deep Springs Valley, California, do not show a relation to their catchment areas in the adjacent mountains. He attributes this discrepancy to the fact that planimetric measurement of surface area may not accurately reflect the volumes of sediment that have been either removed from the catchment area or deposited in the fan (Lustig, 1965, p. 134). However a study of the topographic map of Deep Springs Valley indicates a fan area-source area relation in Deep Springs Valley similar to that in the Amargosa Valley if most of the southwest-sloping floor of the valley northeast of the playa is included as part of the fan with the largest catchment basin. It seems clear that the areas of fans will soon adjust to geologic changes caused by faulting or tilting and to changes in stream regimen due to piracy or climatic change.

The contrast in surface area between the small fans on the east side of Death Valley and the large fans on the west side does not reflect the volume of sediment the adjacent mountains have contributed to this basin. The source areas to west and to east are about the same size. The mountains to the west (Panamint Range) are about 3000 feet higher than those to the east (Black Mountains). This difference doubtless causes sedimentation on the Panamint Range fans to be faster than on the Black Mountain fans and will, in itself, cause the fans to be larger on the west side of the valley. However, the small surface area of the eastern fans is due also to eastward tilting of the valley floor, which causes more rapid deposition on the playa at the toes of the Black Mountain fans than at the toes of those to the west. To maintain the surface of the playa in a horizontal position, the eastern fans are being buried more rapidly than those to the west.

Another difficult problem is the exact nature of climatic change. What is the range in variability in the rates at which various processes operate from time to time within a given time interval? Could the features cited by Lustig as indicative of climatic change be merely the result of variations in magnitude and frequency of floods during the last few hundred years? I know of no actual measurements that might have a bearing on this point and offer only an analogy with features in a humid region, specifically the valley of Little River in the Appalachian Mountains in Virginia, described by Hack and Goodlett (1960). There, over a 7-year period, floods of various intensities produced terraces and dissected alluvial fans analogous in many respects to features in desert mountains. The features in Virginia do not record a climatic change.

Implications for stratigraphy.—The interpretation of fan stratigraphy under an open system differs from one based on a cyclic approach. Under Davisian theory, a dissected fan, such as most of those in Death Valley region, is the product of one or more depositional episodes separated by erosional intervals. The historical interpretation suggests that such a fan was built largely during glacial epochs and was weathered and dissected during parts of interglacial intervals. Under dynamic theory, the processes of erosion, weathering, and deposition are all in operation at the same time. It is only the relative intensity of these processes from place to place that has changed since the fan first came into existence. The concept of time independence of a fan requires the continued maintenance or renewal of the factors that brought it into being, such as relative position of mountain and basin, rate of sedimentation, and so on. In a tectonically active region such as Death Valley these factors may have obtained for a long time.

The difference in stratigraphic interpretation can be illustrated by an example based on the ideal fan described earlier. In figure 1 each segment is about the same size, but such perfect equilibrium is unlikely. One segment probably grows larger than another and partly buries the older one. In map C of figure 1, for example, segment (3) buries the lower edge of segment (1). An exposure along the bank of the gully that dissects both segments, section D-E, records first deposition of segment (1), then weathering of segment (1), and finally deposition of segment (3).

Under Davisian theory, this cross section could be the result of a series of episodes that affected all fans in the area. Perhaps deposition took place in a fluvial episode followed by weathering at a time when flooding was infrequent. Under dynamic theory, this section is interpreted as indicating that two episodes during which sedimentation was the dominant process at this place were interrupted by an interval during which weathering and erosion were the dominant processes at this same point in space. While segment (1) was being weathered, other segments of the fan were being eroded, and still others were receiving sediment.

The concept of simultaneous deposition and weathering on the surface of a fan was clearly expressed by Rollin Eckis (1934, p. 101):

> A consideration of the processes at work upon the present alluvial surfaces suggests the mode by which the complex series of alternating residual clays and unweathered deposits has accumulated on the piedmont slopes. Portions of the alluvial cones (fans) that are undergoing active deposition are being covered by unweathered gray deposits. Simultaneously, on the portions of these same cones remote from active deposition the gravels at the surface are breaking down to form red-brown soil clays. During the long and complex history of alluvial deposition in this area, accumulation of detritus has not been continuous over the whole cone, consequently red soil clays have developed on different parts of the cones at different periods, later to be buried by fresh deposits, and thus alternate with unweathered or partly weathered deposits in vertical section.

It may well be true that climatic change alters the rates of the processes that control alluvial-fan formation, but stratigraphic sections such as described above do not prove that this is so. Under dynamic theory, erosion, deposition, and weathering operate concurrently; they

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vary in relative intensity from place to place, not from time to time. In the absence of independent evidence, the presence of similar stratigraphic sequences on adjacent fans is not proof that the fans are contemporaneous, nor does it demonstrate that the sequences are climatically controlled. Perhaps they are, but this kind of evidence does not prove it.

ORIGIN OF PEDIMENTS

As used in this paper, the term pediment (Bryan, 1922, p. 88) refers to the part of the piedmont that is a more or less bare rock surface. Although pediments are commonly veneered with alluvium, the underlying surface on the bedrock—the pediment— is visible in many places. Where the veneer of alluvium is smooth and not gullied, it is sometimes difficult to decide whether the landform is pediment or fan.

Many geologists have speculated about the manner in which erosion fashions a pediment and about the origin of the sharp break in slope between mountain and pediment (see summary in Tuan, 1959). I will consider only the geometry of fan and pediment in areas where the mountains are of resistant rock and the valleys are of weak rock, a situation that leads to stream piracy and changes in areas of erosion and deposition. The mountains may be the result of faulting or of differential erosion, and the climate may be humid or arid. Examples are drawn from the arid Amargosa Valley, from the semiarid Henry Mountains and Rio Grande Valley, and from the humid Shenandoah Valley.

Shadow Mountain piedmont.—The pediments on the piedmont near Shadow Mountain in the Amargosa Valley illustrate the development of such surfaces in areas of high relief and active deformation. In this valley the areas of pediment are small. The climate is arid; precipitation is about 3 to 4 inches per year. The mountains are of resistant quartzite and limestone and furnish a coarse detritus to the piedmont.

On either side of the Shadow Mountain fan, weakly consolidated and deformed beds of sandstone, claystone, and fanglomerate are exposed in shallow gullies. These Tertiary rocks are overlain unconformably by a few feet of gravel. The unconformity at the base of the gravel is a buried pediment. These pediments (areas K and L, fig. 2) are in reentrants between large alluvial fans. They were eroded, buried, and reexposed by washes tributary to the large fans which thus act as a local base level.

The area of pediment at K is larger and that at L is smaller than the size of fans with comparable source areas (fig. 4). This difference is perhaps related to differences in the washes that formed the pediments. The wash at K has a low gradient because its source is an area of weak Tertiary rocks that yields a fine detritus. The wash at L has a coarse bedload and steep gradient because its source is in resistant limestone. The gradient and bedload of the wash at L more nearly resemble those of the adjacent fans than those of the wash at K.

The washes in which these pediments are exposed head in small segments of the adjacent hills, commonly meander, and resemble the meandering gullies in areas of pavement. Both types of gully have small drainage areas, low gradients, and fine bedloads. The only distinction between them is that some have cut down through the unconsolidated fan deposits into the underlying deformed bedrock. Because these gullies and the large washes from the mountain join downfan, adjacent segments of the two systems are at different levels and invite piracy. The gullies in pediment area L (fig. 2) lie 10 to 20 feet below the wash to the north and are separated from it by a low narrow ridge of gravel capped by desert pavement. If the wash should erode its south bank, it will spill down into the gullies and bury the pediment under fan gravel.

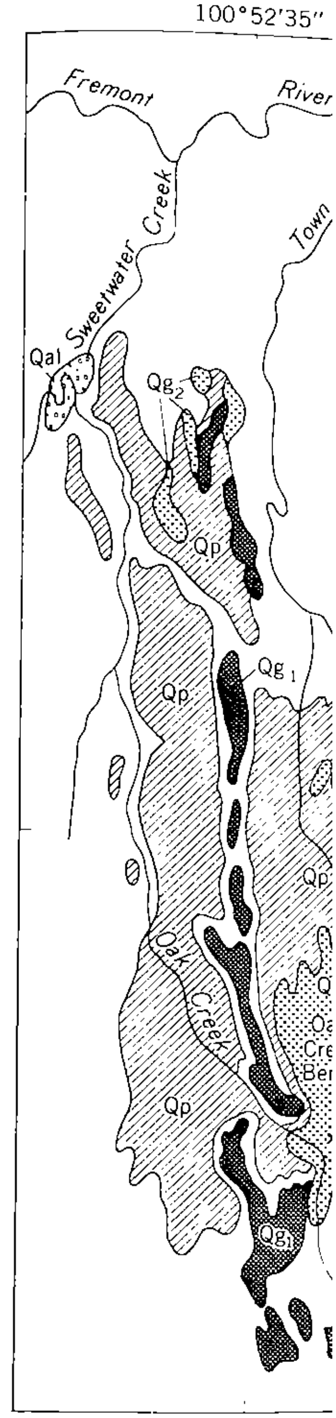
From the point of view of process the areas of dissected fan and gullied pediment are the same. They are both areas where gully erosion is the dominant process. The only real difference between the gullies is that those of the pediment, as commonly recognized, are eroded in the rocks of the mountain block or in deformed sediments of the adjacent depositional basin, whereas the gullies in the abandoned segments of a fan are flowing in alluvial materials that have a fan-shaped surface and have undergone little or no deformation.

The areas of pediment in the Amargosa Valley, controlled by the level of the adjacent fans, will remain small as long as the high relief between mountain and basin maintains large fans. Piracy may cause changes in location of areas of pediment but not in their relative proportion to the area of piedmont as a whole.

Henry Mountains piedmont.—The piedmont around the Henry Mountains, Utah, shows how the relative size of mountain and basin may influence the development of pediment and fan. The mountains are small and the surrounding lowlands are large. The piedmont north of the mountains, shown in figure 5, is about twice as long, from Table Mountain to Fremont River, as that west of Shadow Mountain. This contrast in size is one of the reasons why pediments are more extensive than fans on the Henry Mountains piedmont. The mountains are a group of isolated peaks produced by differential erosion of small bodies of resistant porphyry and indurated sedimentary rocks surrounded by broad areas underlain by shale. The climate is semiarid; precipitation ranges from about 7 inches on the piedmont to perhaps as much as 15 inches on the mountains.

On the piedmont north of the mountains (fig. 5), gravel (Qg_1 and Qg_2) composed chiefly of fragments of porphyry and indurated sedimentary rocks is deposited by streams heading on or near Table Mountain, while washes heading on the piedmont are continually removing gravel and carving valleys bordered by bare rock surfaces or pediments. The loci of erosion and deposition shift from time to time because of piracy.

Fig. 5. Map showing gravel deposits, areas of pediment, and the loci of stream piracies on a small segment of piedmont north of Henry Mountains, Utah (Hunt, Averitt, and Miller, 1953, pls. 18 and 20).



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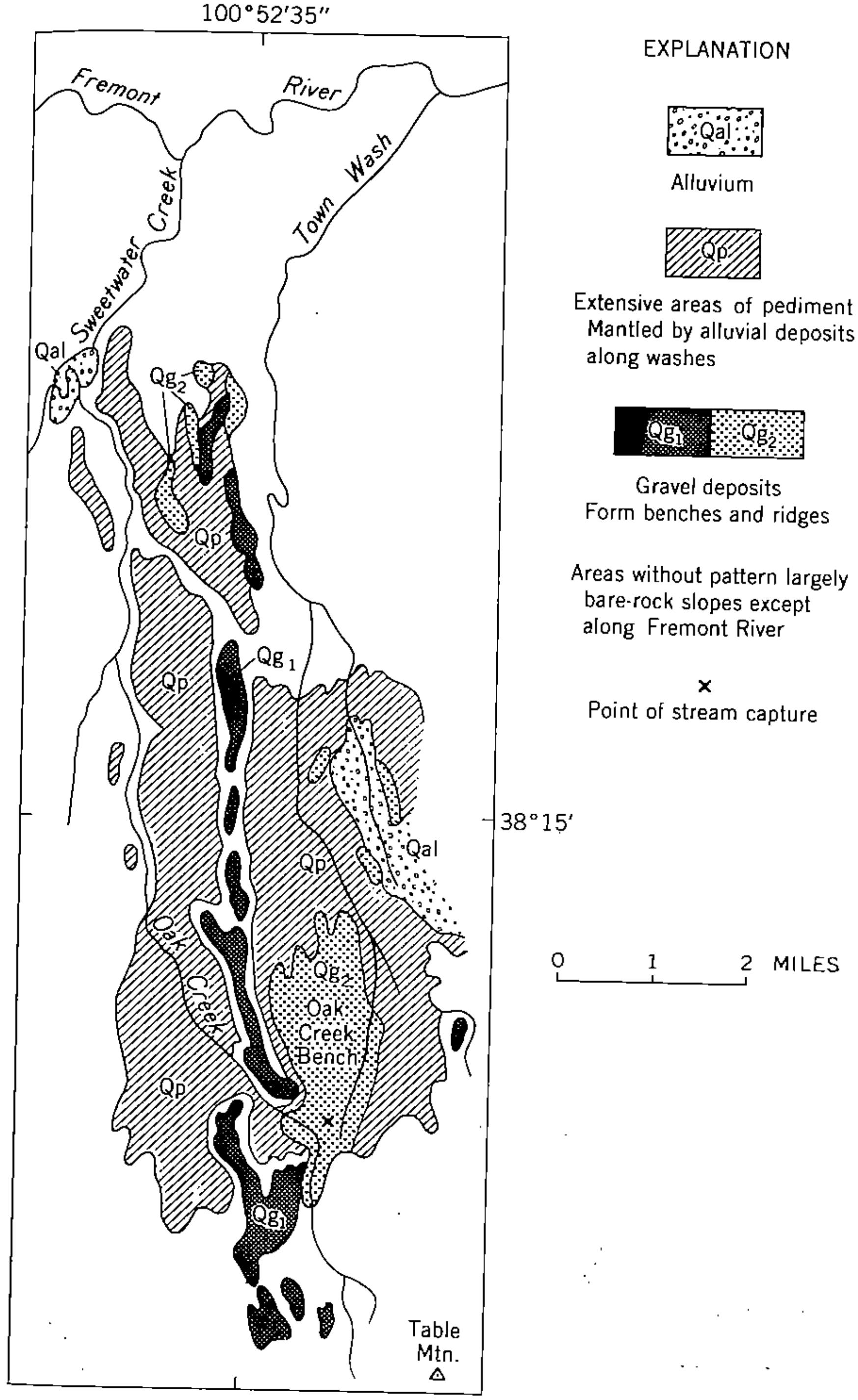

posits, areas of pediment, and the loci of stream
dmont north of Henry Mountains, Utah (Hunt,
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The gravel (Qg_2) of Oak Creek bench was deposited by the ancestral Oak Creek on a surface, probably a pediment, cut on the Blue Gate Shale. At present, Oak Creek flows in a shallow channel across the head of the bench to point X (fig. 5) where it turns sharply west and flows down into a broad valley. This broad valley was eroded by the stream that captured the ancestral Oak Creek at point X. Oak Creek is now aggrading the broad valley but is threatened with imminent capture by a tributary of Town Wash which has its headwaters close to point X. The divide between Oak Creek and Town Wash is only 10 feet high (Hunt, Averitt, and Miller, 1953, p. 195).

The piedmont north of the Henry Mountains is twice as long as that west of Shadow Mountain. If the systems of which these two piedmonts are a part are nearly in equilibrium, the present rate of supply of detritus to the larger piedmont is nowhere near enough to cover it. The size of Oak Creek bench relative to its source area on Table Mountain falls at the bottom of the field of scatter of the points in figure 4 representing fans in Amargosa Valley. In semiarid southern Utah one might expect a greater area of sedimentation for a given source area than in arid southern California (Langbein and Schumm, 1958). The discrepancy may be due to erosion that is removing the gravel that underlies Oak Creek bench.

Rio Grande Valley.—The following discussion of the Rio Grande Valley illustrates piedmont formation under a semiarid climate where the piedmont is graded to a through-flowing river. Changes in the master stream can affect the piedmont in various ways, depending upon the geologic setting of the valley.

The piedmonts of the Rio Grande Valley in central New Mexico are largely pediments cut across weak rocks and are veneered with gravel from the adjacent highlands of resistant rock. The valley is semiarid although slightly more humid than the Henry Mountains. Precipitation ranges from 10 inches on the piedmont to 20 inches in the highlands. The pediments are extensive relative to the size of the adjacent mountains, and their gravel veneers are in places thick enough to obscure the underlying bedrock. The pediments rise steplike above the river and were described by Bryan and others (Bryan, 1932; Bryan and McCann, 1938; Denny, 1941; Wright, 1946) as primarily stream-eroded surfaces graded to a successively lowered base level, the Rio Grande.

North of Ladron Peak, which lies about 15 miles west of the junction of the Rio Puerco and the Rio Grande, are the remnants of three pediments that slope northward and eastward toward the Rio Puerco about 5 miles east of the eastern limit of the area shown in figure 6. (Denny, 1941, fig. 2). The small remnant of the Tio Bartolo pediment is a steeply sloping, fan-shaped mass of bouldery gravel resting in part on pre-Tertiary rocks. The profile on top of the gravel was thought (Denny, 1941) to be graded to a level about 400 feet above the Rio Grande. The Valle de Parida pediment, a gravel-covered and slightly dissected plain,

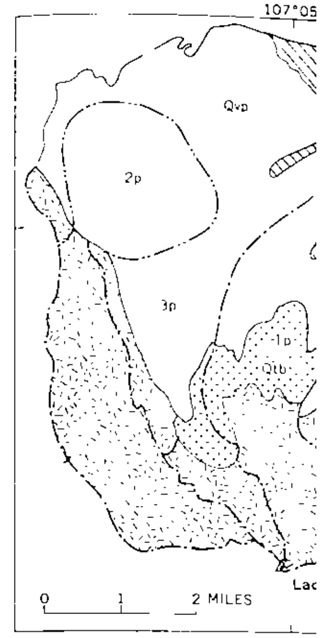

Fig. 6. Map of pediments
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5) where it turns sharply west and flows
; broad valley was eroded by the stream
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is threatened with imminent capture by
ich has its headwaters close to point X.
k and Town Wash is only 10 feet high
3, p. 195).

ıe Henry Mountains is twice as long as
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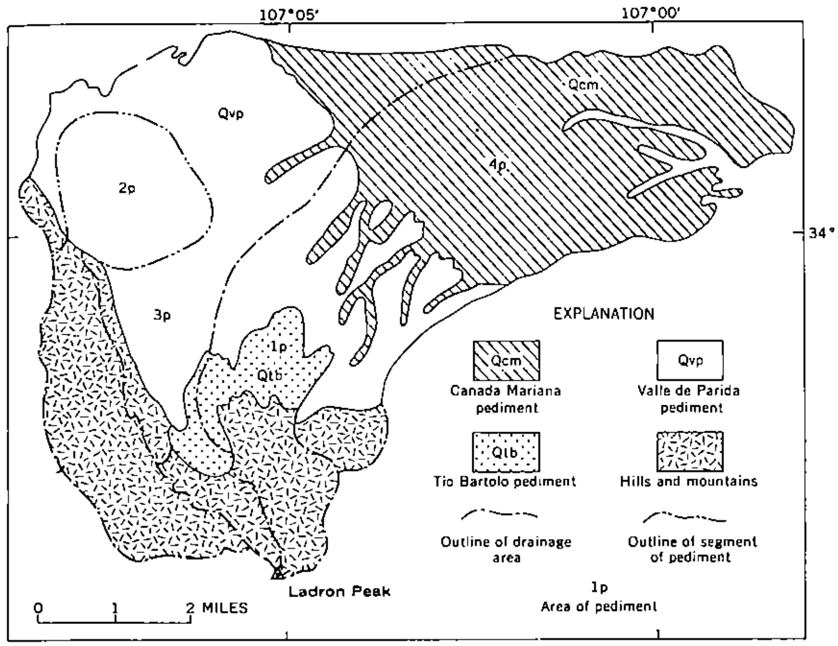

Fig. 6. Map of pediments north of Ladron Peak, Socorro County, New Mexico. Map generalized from figure 2 in Denny (1941) and from Riley and Mesa Aparejo 15′ quadrangles, U. S. Geological Survey.

slopes northeastward to a level about 150 feet above the Rio Grande. At a lower level and separated from the higher pediment by a gently sloping dissected escarpment lies a third pediment, the Cañada Mariana, graded to a level about 50 feet above the Rio Grande.

On figure 6, I have measured the area of these dissected pediments, or parts of them, and also the areas that drained to them and supplied their gravel cover. Plotted on figure 4, the points that represent these pediment remnants fall on the upper side of those for the Amargosa Valley fans but show a similar exponential relation to the size of their source areas.

In 1941, I stated, under Davisian theory, that these three pediments were primarily the result of lateral planation by streams from Ladron Peak. The grade of these streams was successively lowered because the Rio Grande, the local base level, periodically lowered its channel. The scarps between the pediments were said to have retreated headward parallel to themselves.

Under dynamic theory the formation of these pediments may be thought of as a continuous process, not dependent solely on successive lowerings of the Rio Grande separated by long intervals when the river's grade was stabilized. It would be surprising to have a relation between size of pediment and its source if the lower pediment is enlarging itself at the expense of the higher one. Rather it is probable that these three pediments near Ladron Peak, although their initiation may have been related to changes in the level of the Rio Grande, are now in equilibrium with present processes. Their variation in size and shape may be related to the local geology.

The Tio Bartolo pediment is cut across resistant pre-Tertiary rocks and shows evidence of local piracies. It resembles in form the areas of pavement on the upper part of the Shadow Mountain fan. This pediment is now bypassed by streams from Ladron Peak, and the gravel that caps it is old but has no necessary relation to any pause in the downcutting of the Rio Grande. It may well stand above the Valle de Parida pediment because of differences in the underlying bedrock that cause differences in the bed load of the streams which traverse these pediments. Differences in bed load lead to differences in gradient between the two pediments. That the size of the two lower pediments is also related to the local geology rather than to changes in the level of the Rio Grande is suggested by their area-source relations as shown in figure 4. Perhaps the northwest-trending break in slope between Valle de Parida and Cañada Mariana pediments reflects a change in the underlying bedrock from more resistant older Cenozoic or pre-Tertiary rocks on the west to less resistant later Cenozoic continental sediments on the east. The more resistant rocks may act as a local base level and retard the dissection of the Valle de Parida pediment.

The Rio Grande Valley pediments illustrate, as have those in Utah and California, the overall importance of the local geology in pediment formation. Isolated areas of pediment such as those near Ladron Peak do not necessarily have historical significance. They can be related to bedrock differences or to piracy. This does not mean that an extensive pediment in the Rio Grande Valley, such as the Ortiz pediment (Wright, 1946, pl. 10), does not record a long period of stability for the Rio Grande. Probably it does.

A second characteristic of many of the broad areas of pediment in the Rio Grande Valley is that such surfaces are smooth. This is due at least in part to their extensive gravel covers which in places are so thick that parts of these pediments should be classed as fans. The fan-shaped area of the Valle de Parida pediment, area 2p, is an example. The area-source relations (fig. 4) show that this fan is as much a part of the equilibrium of the piedmont north of Ladron Peak as are the associated pediments where slightly deformed older rocks are visible beneath a gravel cap. In places outside the area shown in figure 6 where the pediment surface beneath the gravel cap is well exposed, the pediment has a much greater local relief than the top of its gravel cap.

The smooth gently sloping gravel surfaces of the Rio Grande Valley contrast with the steeper and more irregular gravel surfaces in the Amargosa Valley. Although the major differences between these arid and semiarid piedmonts are due to geologic factors, it is probable that the ne. Rather it is probable that these three although their initiation may have been of the Rio Grande, are now in equilibrium variation in size and shape may be related

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greater rates of erosion and deposition on the semiarid piedmont favor gentle gradients and extensive gravel blankets.

Shenandoah Valley.—The gravel-covered footslopes of the Shenandoah Valley, Virginia, are an example of piedmont development in a humid region where the relief between mountain and basin is due to differential erosion of rocks of different resistances, rather than to faulting. The only tectonic requirement is that the region be maintained at an altitude sufficient to cause vigorous erosion for a long time. In the Shenandoah Valley solution is an important process, not only as a major factor in basin formation but also in the degradation of fans and pediments.

The rocks of the Shenandoah Valley region include a thick sequence of limestones, dolomites, and shales that form lowlands, and resistant quartzites and igneous rocks that form highlands. Alluvial terraces occur in the lowlands where a large stream enters from the adjacent mountains. These terraces and the adjacent flood plains have the form of fan-shaped, gravel-covered, and dissected pediments (Hack, 1960, 1965). Piracies take place where streams heading in the carbonate rocks are tributary to fan-building streams and have lower gradients than the main streams.

The area-source relationship of the gravel-covered piedmonts of the Shenandoah Valley is similar to that of the Amargosa Valley fans. In both regions the juxtaposition of hard and soft rocks leads to the formation of piedmonts alike in form in spite of great differences in climate. The Shenandoah Valley piedmonts are comparable in size with those on the west side of Death Valley in California. For comparison I show the area-source relation of the Trail Canyon fan in figure 4.

Although the overall extent of the gravels in the Shenandoah Valley is roughly proportional to the area that supplies the coarse detritus, in detail it is the modern, gravel-covered flood plains that have the most orderly area-source relation. Points representing the flood plains of four streams on the west side of the valley are shown in figure 4. Gravel-covered terraces that are remnants of abandoned flood plains of these same streams are smaller than their modern counterparts (fig. 4) and are no longer in equilibrium with the streams that deposited the gravel. The gravel of the terraces is being eroded by local runoff and by weathering. Gravel aprons east of the valley are larger and perhaps thicker than those on the west (fig. 4). The eastern aprons are now subject to both deposition and erosion and probably are in a steady state.

CONCLUSIONS

Many piedmonts are storage areas for coarse detritus in transit from highland to adjacent basin. If the basin is small the detritus builds alluvial fans that may completely cover the adjacent piedmont. Where a large basin adjoins highlands of resistant rock, fans may form only a part of the neighboring piedmont; on the remainder of the piedmont streams will carve broad pediments veneered with gravel. Piracies occur because of contrasting gradients between mountain and piedmont streams and cause shifts in loci of erosion and deposition, leading to the establishment of a steady state. Such systems exist in both arid and humid regions in spite of differences in the rates of erosion, of deposition, and of weathering.

A Davisian approach to the origin of piedmonts fosters a search for features having historical significance. It leads to an overreliance on climatic change as an explanation for features whose actual mode of origin may be in doubt. A buried soil, for example, under the historical approach suggests a past climatic change, whereas in the equilibrium concept this feature is regarded as part of a single system in equilibrium.

An analysis of the origin of piedmonts as an open system emphasizes both the geometry of a piedmont and the processes that act upon it. This does not exclude the recognition of features having historical significance, but it does force one to investigate present-day processes. Only from an understanding of the results of the forces at work today can we hope to recognize and explain relict forms.

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