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LANDSCAPES OF ARIZONA

The Geological Story

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CHAPTER 11

ALLUVIAL FANS AND PEDIMENTS OF SOUTHERN ARIZONA

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INTRODUCTION

When driving across southern Arizona one is impressed by the variety and beauty of the ever visible rugged mountain ranges. Much less obvious to the traveler are the plains between the mountains. However, it is the subtle lowlands that occupy much of the State. For example, in the southwestern part of the State, mountain ranges occupy only about 10% of the landscape and plains occupy the remaining 90%. Many of Arizona's urban and agricultural areas are on such plains.

The mountain-front plains or piedmont slopes that form so much of the Arizona landscape have diverse origins, which provide clues about the past climates and internal forces of the earth. Debris washed out of the mountains may make a depositional type of plain composed of coalescing alluvial fans, which was more common in the geologic past. Stream channel and floodplain deposits laid down by the main streams flowing through the valleys form still another type of plain. Minor types of depositional plains include sand dunes and lake beds. Erosional beveling of the rocks at the mountain fronts and the planation of sediments derived from the mountains have made pediment plains that comprise much of southwestern Arizona. The pediments and fans of Arizona that are the subject of this article were studied by workers such as Tolman, 1909; Paige, 1912; Bryan, 1922, 1932, 1940; Blackwelder, 1931; Rich, 1935; Gilluly, 1937; Hadley, 1967; Howard, 1942; Miller, 1950; Tuan, 1959, 1962; Lance, 1959; Corbel, 1963; Mammerickx, 1964; Melton, 1965; Rahn, 1966, 1967; Royse and Barsch, 1971; and Moss, 1977.

An intriguing question is "Why are erosional plains adjacent to some mountains, and depositional plains adjacent to other mountains?". The answer lies in the way that streams cut and deposit, and how the past climates and uplifts of the mountains have affected the streams that flow out of the mountains. The geologist uses some of these interrelations to decipher the evolution of Arizona's landscape. The study of the geologic past, particularly the Quaternary (the last 1.8 million years) record, may also provide information that is useful to the engineer and urban planner who are concerned about surface rupture, earthquakes, and other hazards. As our cities expand toward the nearby mountains, it is desirable to know more about the Quaternary history of movements of the faults along which tectonic forces created the mountains.

PURPOSE AND SCOPE

The chief purpose of this article is to discuss two important types of plains in Arizona, the alluvial fans and the pediments. The typical features of each will be described and the changes in both types of plains that occur during geologic time will be evaluated. It will be shown that whether alluvial fans or pediments are next to the mountains is controlled by the rate of tectonic uplift of the mountain front. Lastly, the importance of alluvial fans and pediments to man will be evaluated in regard to engineering and hydrologic benefits and problems. The examples used will be from the Basin and Range Province where the pediments and fans are more distinctive than those of the Colorado Plateau. For the locations of geographic features and figures referred to in this article the reader is referred to figure 11.1.

ALLUVIAL FANS

How to Recognize an Alluvial Fan

Depositional plains commonly are made up of many coalescing alluvial fans. An alluvial fan is a deposit with a distinctive surface — a segment of a cone that radiates downslope from

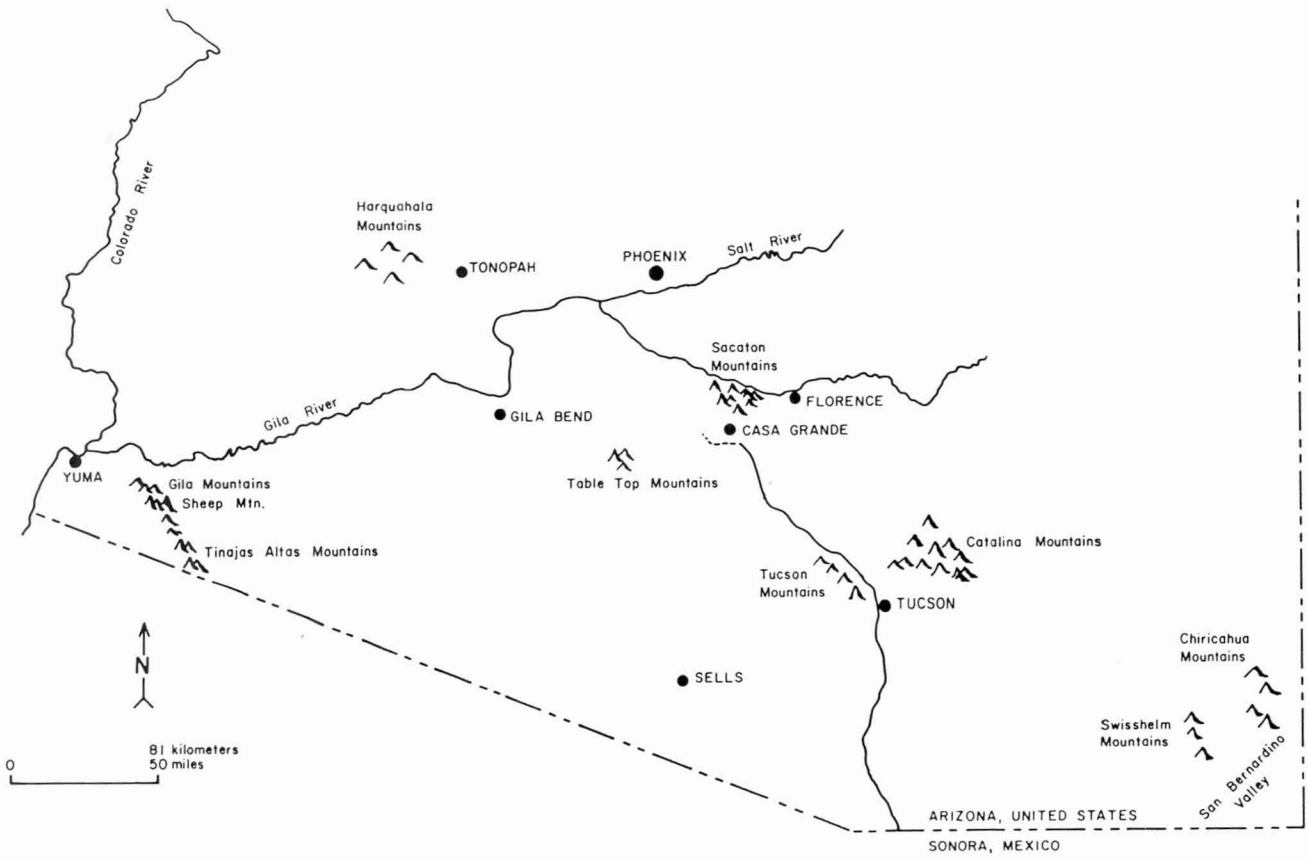


Fig. 11.1 Locations of towns, mountains, and rivers referred to in this article.

the point where the stream spreads out on the plain (figures 11.2 and 11.3). The typical fan is derived from a mountainous source area (called a drainage basin) from which a single trunk stream transports the erosional products of the hillslopes to the fan apex. The cone-shaped aspect of the deposit is revealed by topographic-map contours that bow downslope (figure 11.3) and by cross-fan profiles that are convex. In plan (or map) view, the deposit commonly has a fan shape (figure 11.3). No one criterion should be used to define a fan. Some pediments approximate a segment of a cone (a good example is the fan-shaped pediment north of Indian Butte in figure 11.8B), and many fans are not fan-shaped because they are restricted by larger adjacent fans. The above aspects of alluvial fans are fairly easy to recognize by viewing the landform from the ground, or from a mountain or airplane, or through the use of aerial photographs and topographic maps.

The thickness of alluvium indicates whether a piedmont is basically depositional (an alluvial fan) or erosional (a pediment) in origin. Because a pediment is an erosional surface one would commonly expect to find it mantled by less than 2 meters of alluvium or debris weathered from the bedrock. The minimum thickness of deposits needed to class part of a piedmont as an alluvial fan is difficult to define. Fans vary greatly in size from less than 100 meters to more than 20 kilometers in length. Thus it is not possible to assign some minimum value of thickness, such as 10 meters, as being definitive of alluvial fans. Three meters of deposits would be substantial for a small fan that is only 30 meters long from fan apex to fan toe. The same thickness on a piedmont that is 10 kilometers long would best be interpreted as a pediment mantle that could easily be removed by streams flowing down the piedmont, thus exposing the bedrock. As a general guideline, fans may be distinguished from pediments as being landforms where the thickness of deposits is more than 1/100 the length of the landform. Many large fans are thicker than 300 meters. Even the above defi-

nition of alluvial fans is hard to apply where field information about the thickness of deposits is not available. Exposures of fan deposits by a stream that has become incised in the fan are a common type of data used to determine minimum thicknesses, and some of the best information is obtained through geophysical techniques, or by the drilling of water wells or other bore-holes. Where subsurface information is not available, it is best to remember that because fans are depositional landforms, bedrock knobs rarely protrude through the alluvium. Many isolated outcrops of bedrock downslope from the mountain front are typical of pediments, not of alluvial fans (see figures 11.7 and 11.8). Where one is unsure of whether or not a landform is a fan or a pediment, the term "alluvial slope" is appropriate.

Some of the characteristics of alluvial fans are shown in figures 11.2 and 11.3. The individual nature of the component fans of the piedmont is readily apparent. A marked change in the size of the debris deposited on a fan can be seen in figure 11.2C. The largest boulders have an intermediate diameter of 350 centimeters at the mountain front but only 15 centimeters at the toe of the fan.

Types of Deposition on Alluvial Fans

Streamflow spreads out where it leaves the end of a channel on a fan. As the flow spreads out, the depth and velocity of flow decrease, causing the stream to deposit part of the sediment that it has carried from the mountains. Part of the water sinks into the underlying sand and gravel, a process that also tends to cause deposition of sediment entrained in the streamflow.

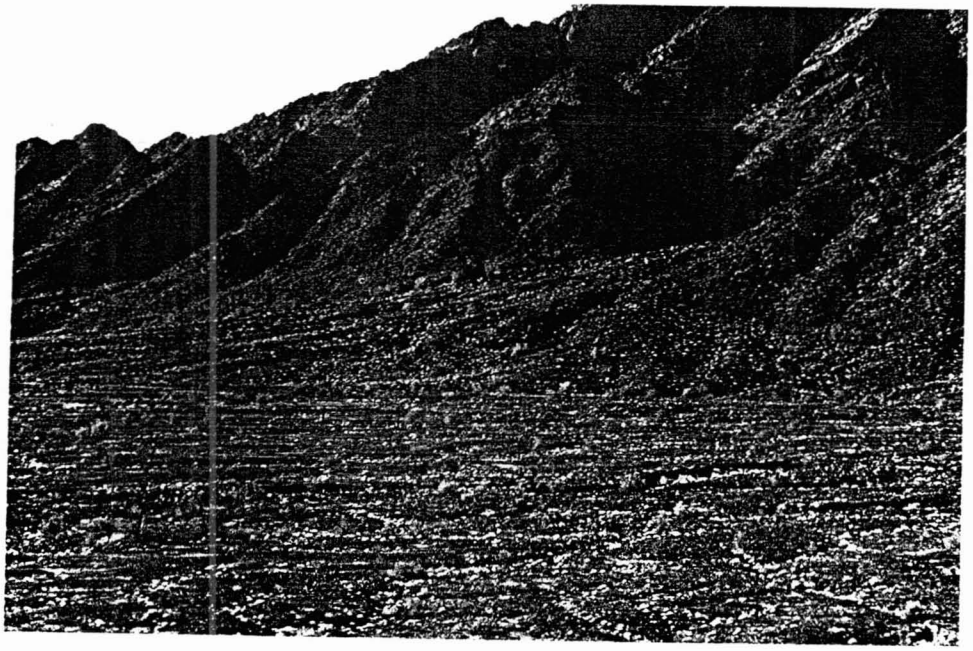
Flow on alluvial fans varies from clear water to viscous mud, and the resulting deposits vary from well sorted sand to poorly sorted debris that can include boulders weighing many tons. Both debris flows and water-laid deposits are common in the Quaternary alluvial-fan deposits of Arizona.

Two types of water-laid deposits occur in most fans. Most water-laid sediments consist of sheets of sand, silt, and gravel deposited by a network of shallow channels that repeatedly divide and rejoin, thus forming a braided stream pattern. The second type of deposit occurs as fillings of channels that were temporarily incised into the fan.

The sheets of sediments are deposited by surges of sediment-laden flood waters that spread out from the channel. Depths of water generally are less than half a meter. Shallow distributary channels fill rapidly with sediment and then shift a short distance to deposit their load at a lower location. The resulting deposit is a sheet-like expanse of sand, or gravel, that is traversed by shallow channels that repeatedly divide and rejoin. The deposits commonly consist of gravel, sand, or silt that contains little visible clay. In general they are moderately well sorted and may be crossbedded, laminated, or massive.

The deposits that backfill stream channels temporarily entrench into a fan generally are coarser grained and more poorly sorted than the sheets of water-laid sediments deposited by networks of braided distributary channels. Bedding of channel-fill deposits is poorly defined, and the thickness of individual beds ranges from less than 1 centimeter to more than 2 meters. Bed thicknesses of 5 centimeters to 1 meter are the most common in Arizona fans.

During those infrequent occasions when a streamflow incorporates enough sediment that sediment entrainment becomes irreversible, it becomes a debris flow or mudflow. A mudflow is a type of debris flow that consists mainly of sand-size and finer sediment. Debris flows have a high density and viscosity compared to water flows, can selectively deposit only the bouldery part of their load, and have a matrix that moves as a mass — after sand is incorporated into the matrix, it cannot be deposited separately. Because of these characteristics, debris-flow deposits are poorly sorted, have lobate tongues extending from sheetlike deposits, have abrupt well defined margins, and are capable of transporting boulders weighing many tons. The boulders shown in figure 11.2C probably were deposited on the fanhead by debris flows, as is indicated by the presence of debris-flow levees on the fanhead and adjacent to the channel in the mountains. Factors that promote debris flows are abundant water over short periods of time at irregular intervals (in Arizona for example, heavy rainfall from thunderstorms), steep hillslopes having insufficient vegetative cover to prevent rapid erosion, and abundant source material on the hillslopes that contains



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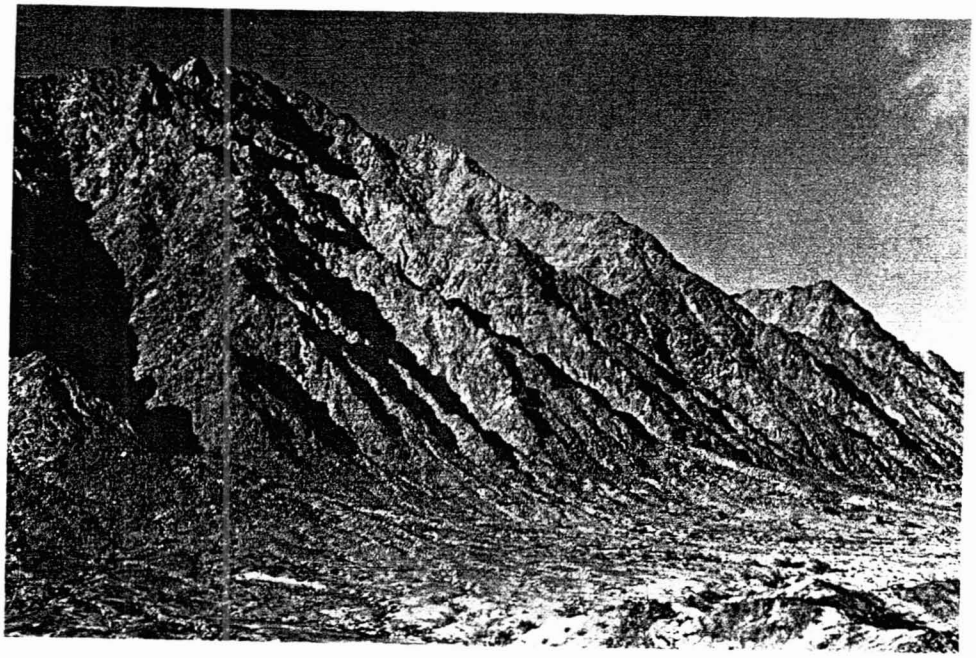


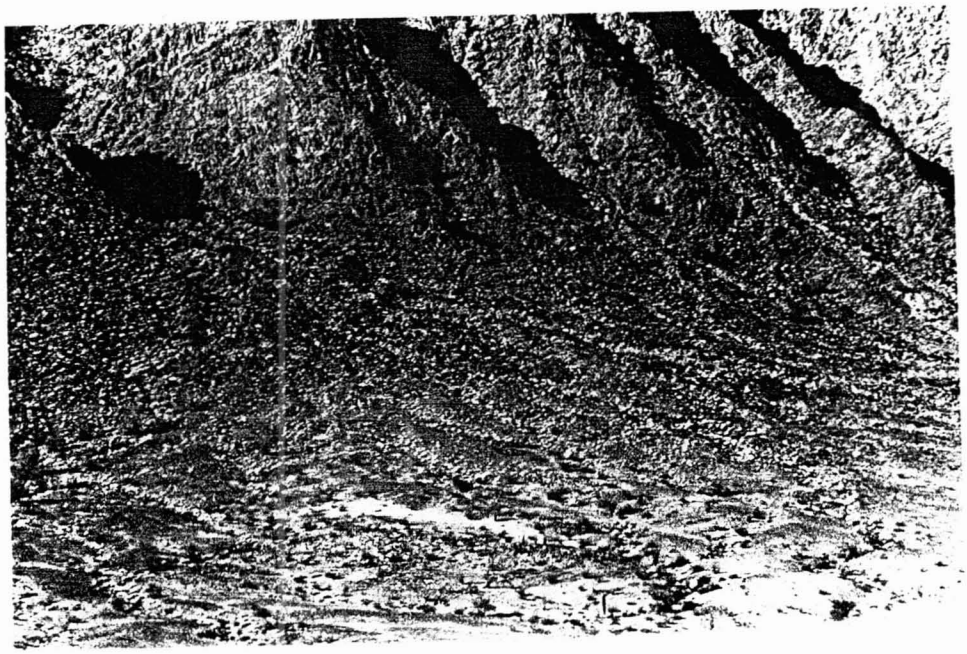
B

Fig. 11.2 Alluvial fans northeast of Sheep Mountain, Arizona.

(A) Small, steep alluvial fan that coalesces with a much larger fan in the foreground.

(B) Small alluvial fans that have been deposited at the base of an eroded fault-bounded mountain front. The fan at the left side of the photo is shown in more detail in figure 11.2(C) (page 287).

(C) (next page) Small fan that has a visible decrease in the size of the coarsest surficial material in the downfan direction.



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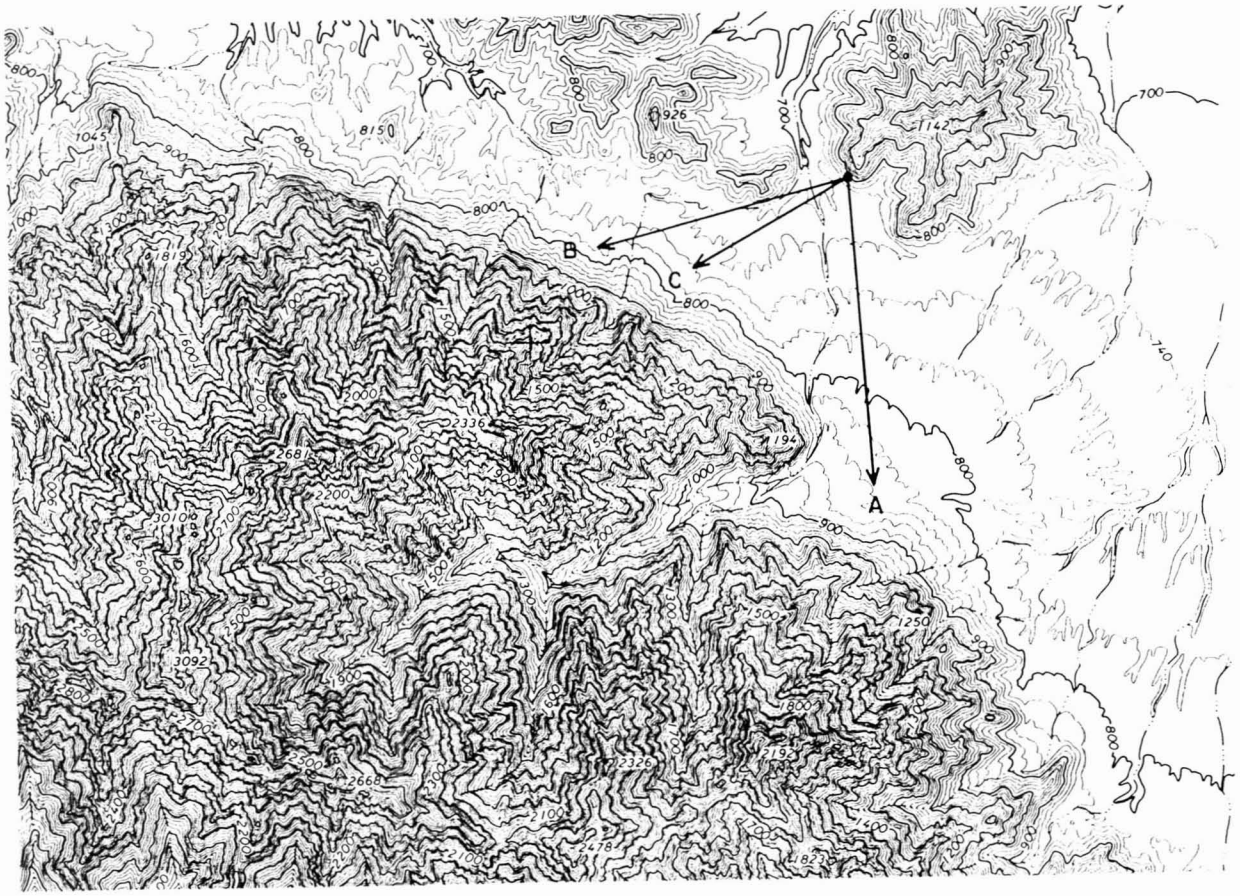


Fig. 11.3 Topographic map of the alluvial fans and their source areas northeast of Sheep Mountain in southwestern Arizona. The arrows and letters refer to the directions from which the photographs were taken that are shown in figures 11.2(A), 11.2(B), and 11.2(C). From the United States Geological Survey Wellton Hills topographic quadrangle.

enough sand, silt, and clay to provide a matrix of mud for the debris flow. Not all these conditions need to be present in order for a debris flow to occur. Because of their high viscosity, debris flows may not flow as far down the fan as do water flows.

The proportions of water-laid and debris-flow deposits vary greatly from fan to fan. Where source-area conditions are not conducive for the production of debris flows, the fan deposits consist almost entirely of water-laid deposits. Other fans consist mainly of debris flows. Most fans whose drainage basins produce debris flows also have less intense flood events that result in the deposition of water-laid deposits. Thus the depositional sequence of many fans consists of interbedded deposits of debris and water flows in varying proportions.

The types of deposits laid down on alluvial fans in Arizona have been affected greatly by changes in the climate during the Quaternary. At the present time stream channels are entrenched into the fans more than they were during the late Pleistocene and early Holocene, and the most common type of deposit is water-laid sediments. Although historic debris flows have been noted in some areas, such as on the hillslopes of Camelback in Phoenix and the Tucson Mountains near Tucson, debris flows rarely occur on hillslopes or fans as compared to the frequency of debris flows during the early Holocene. The hillslopes of most of the desert ranges are steep, have a sparse vegetative cover, and are subjected to intense cloudbursts during the summer rainy season. Conditions seem ideal for the stripping of debris from the hillslopes to form debris flows. The general lack of modern debris flows may be the result of such frequent erosional events that insufficient fine grained debris remains on most hillslopes to make the clayey matrix needed for debris flows. The present rate of weathering of the rocks apparently is much less than the rate of erosion of the weathering products. Thus although the annual precipitation at present is less than during the late Pleistocene, the effect of intense rainfalls on barren hillslopes is to make flash floods of water that transport chiefly sand and gravel.

Debris flows have been common in Arizona during the geologic past. Most mountain ranges have many bouldery levees that were formed by debris flows on the hillslopes and along the smaller valleys. These levees are at least 4 to 6 thousand years old as is indicated by the dark desert varnish coating the boulders, and thickly pitted and weathered nature of the boulders. The fan deposits exposed by the mid to late Holocene trenching of the stream channels also commonly contain flows.

The change in climate that occurred during the transition from late Pleistocene to Holocene may have produced conditions favorable for debris flows. Van Devender concluded that the climate in western Arizona became warmer, and that the mean annual precipitation decreased about 50% between late Pleistocene and early Holocene times. Brakenridge believes that annual precipitation did not change much but that a substantial increase in temperature occurred at the beginning of the Holocene. The change in climate was sufficiently large to decrease the amount of vegetation on the hillslopes, and to reduce the rate of weathering of the rocks. Although the frequency of intense rains may have decreased during the early Holocene, the relatively unprotected hillslope debris was available to furnish an abundant supply of soil and loose rocks for the debris flows. The amounts of available soil and the frequency of debris flows probably have continued to decrease during most of the Holocene.

The Internal Structure of an Alluvial Fan

The internal structure of an alluvial fan reflects the accumulation of vast numbers of beds of differing extent and thickness as well as the history of changes in the locations of deposition caused by repeated entrenchment and backfilling of the trunk stream channel leading from the mountains. The typical situation is shown diagrammatically in figure 11.4. The area portrayed is one where recent uplift along a fault has favored rapid accumulation of deposits adjacent to the mountain front. The truncated ends of spur ridges extending out from the mountains form triangular-shaped facets similar to the ones shown in the right side of figure 11.2B. The surface of the fan in figure 11.4 is not entrenched and is traversed by a network of braided distributary streams, some of which are associated with the most recent episode of deposition.

Considerable differences can be noted in the radial and cross-fan sections shown in figure 11.4. Along the radial section, individual beds

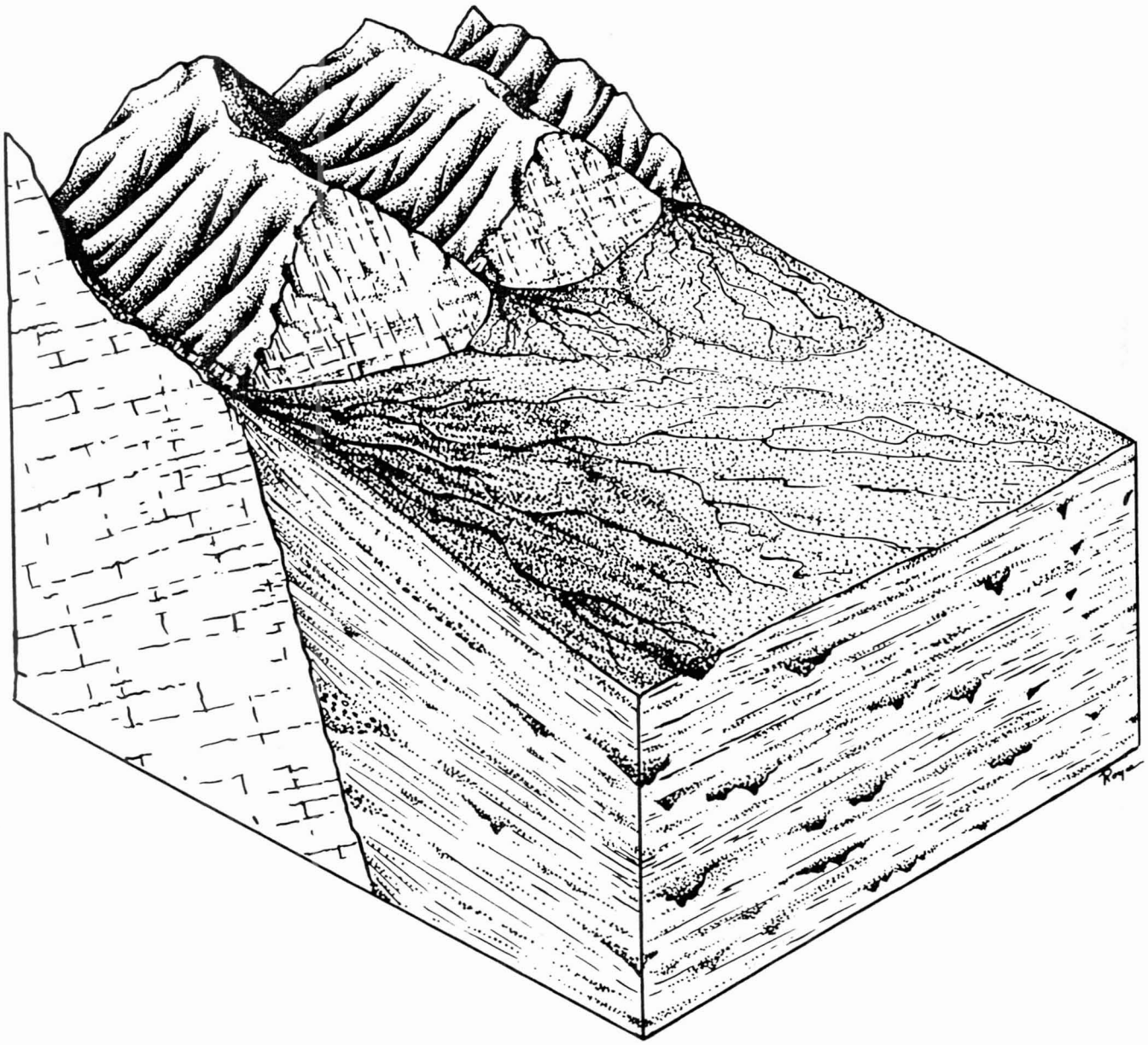
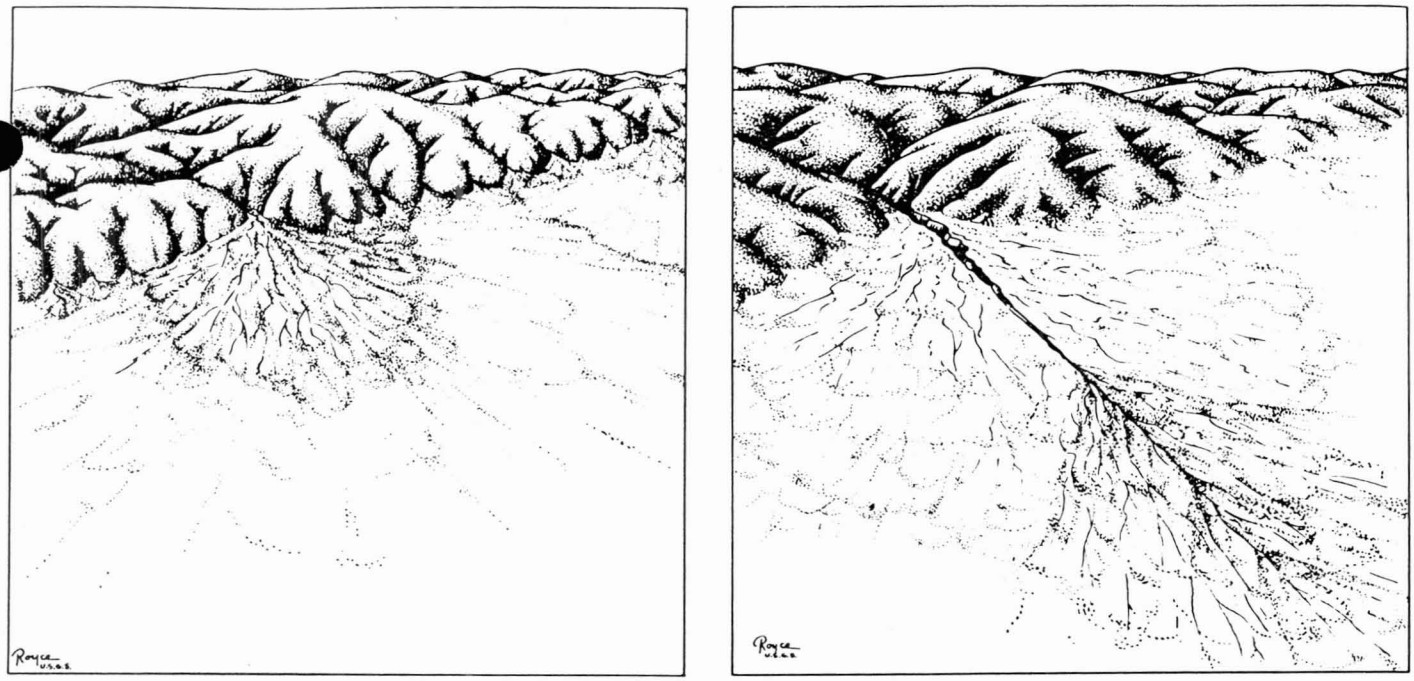


Fig. 11.4 A diagrammatic sketch showing the internal structure of a typical alluvial fan.

may be traced for long distances, and channel-fill deposits are rare. In contrast, the cross-fan section reveals overlapping beds of limited extent that are interrupted by backfilled stream channels. Because some channels were entrenched only a short distance downslope from the fan apex and others were entrenched into the midfan area, the backfilled channels are most common near the fan apex and are rare or absent near the toe of the fan. The thick deposits portrayed in figure 11.4 were typical of the stages of the development of the Arizona landscape during the mid-Cenozoic, but actively accumulating thick fans are rare in the State today.

Types of Alluvial Fans

Two basic types of alluvial fans are shown in figure 11.5. In figure 11.5A, the area of deposition is near the mountain front. In figure 11.5B, the area of deposition has shifted downfan as a result of stream-channel en-



A B

Fig. 11.5 Two types of alluvial fans.

(A) Unincised fan with the area of present deposition next to the mountains.

(B) Alluvial fan with the area of present deposition downslope from the mountains due to stream-channel entrenchment.

trenchment. If the entrenchment is temporary (such as that caused by climatic variations), the channel will be backfilled and deposition will occur near the mountain front again. If the entrenchment is permanent, the deposits upslope from the end of the stream channel will be weathered and eroded by local streams that head on the fan. The erosional parts of the fan surface will be characterized by dendritic stream channels and strongly developed weathering profiles. Permanent channel entrenchment of the upslope part of a fan may result from either uniform or accelerated downcutting of the trunk stream channel, but in either case it is associated with a decrease in the rate of uplift of the mountains.

PEDIMENTS

How to Recognize a Pediment

The preceding section might lead the reader to assume that desert mountain ranges are islands surrounded by a sea of alluvium. Such is not the case. Many desert plains have been carved out of the rock of the mountains during the course of erosion of the mountains. Rock plains are very common, and the term "pediment" was first used by McGee to describe these erosional surfaces in Arizona.

A pediment is an erosion surface formed by retreat of an escarpment and by the continued planation of rocks and sediments downslope from the escarpment. Most Arizona pediments have formed downslope from mountain fronts. Some workers prefer to restrict the definition of pediment to only erosional piedmonts cut in rock. However, the inclusion of the term "rock" means that in order to recognize a pediment, different workers must be able to use a common method to separate in the field those materials that are weakly indurated rocks from those moderately cemented alluvial materials that one arbitrarily chooses not to call rock.

In working with desert plains, the easiest

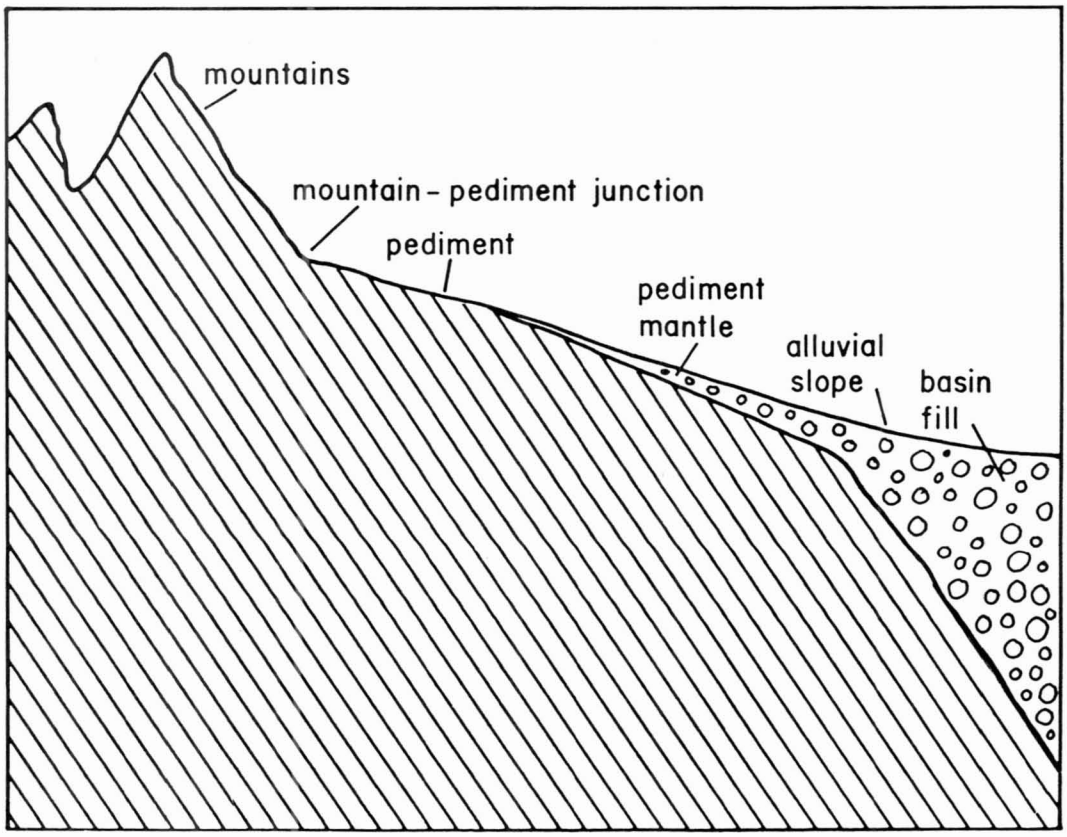
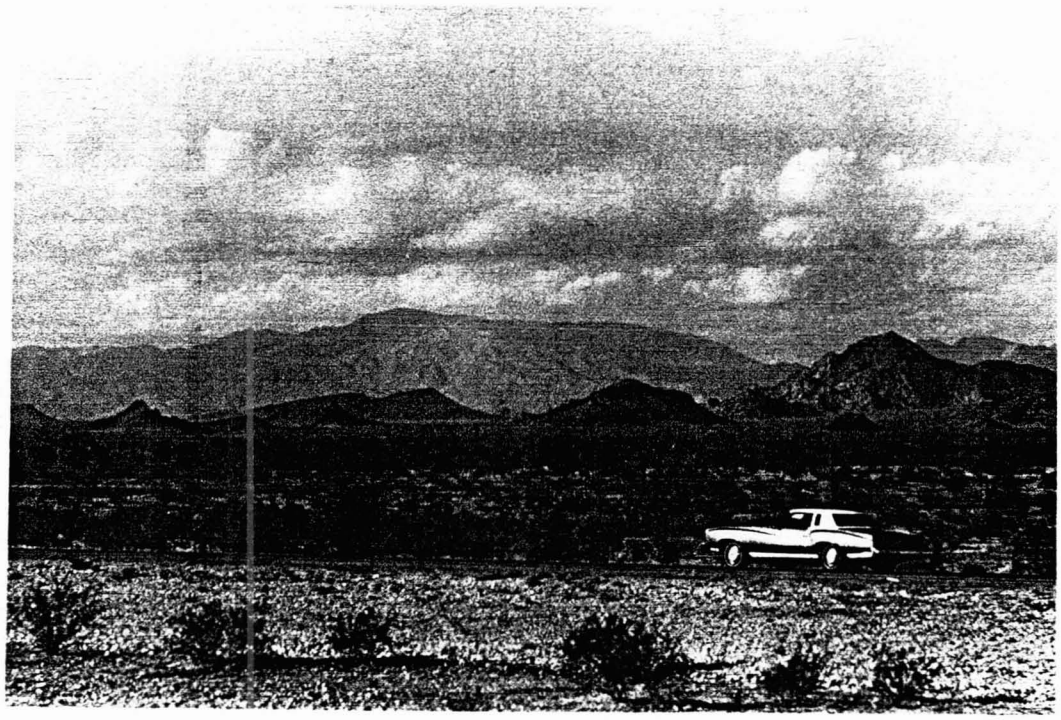


Fig. 11.6 Diagrammatic cross section showing the types of landforms associated with pediments.

approach is to emphasize the dominant process responsible for a landform. Depositional landforms next to mountains generally should be considered alluvial fans, and erosional surfaces should be considered pediments. The term "pediment" thus includes exceptionally smooth surfaces cut on granitic rocks, gravel-mantled surfaces cut in soft materials, which European geomorphologists have called "glacis d'erosion" (Joly, Dresch, Mensching, Royse and Barsch) and the surfaces cut in the subhorizontal strata of the Colorado Plateau (Cooley) and South Africa (Fair). It would also include the wide strath or cut terraces described by Cooley and by Royse and Barsch, and the miniature pediments of badlands described by Bradley and by Schumm.

The names of landforms associated with pediments are outlined in figure 11.6, and a three-dimensional view of a pediment association is shown in figure 11.11. The mountains can be large or small, because the size of the mountain mass has little bearing on the size of the adjacent beveled surface. The areal extent of a given pediment surface is largely the result of the amount of time that has passed since the last uplift of the mountains along the fault bounding the mountains, the processes acting to erode the pediment and mountain front, and the erodibility of the materials of the remaining mountains. The mountain-pediment junction commonly is abrupt, and in arid regions may appear angular when viewed from a distance. A pediment may be mantled either temporarily or permanently with weathered colluvium and/or alluvium. The typical situation in Arizona during the Quaternary has been for the area covered by a pediment mantle to expand and contract with climate-controlled variations in the sediment and water yielded from the hillslopes of the source area. As in the case of alluvial fans, where one is not certain whether an erosional or a depositional slope is present, it is best to refer to the landform as an alluvial slope. The basin fill is the alluvium downslope



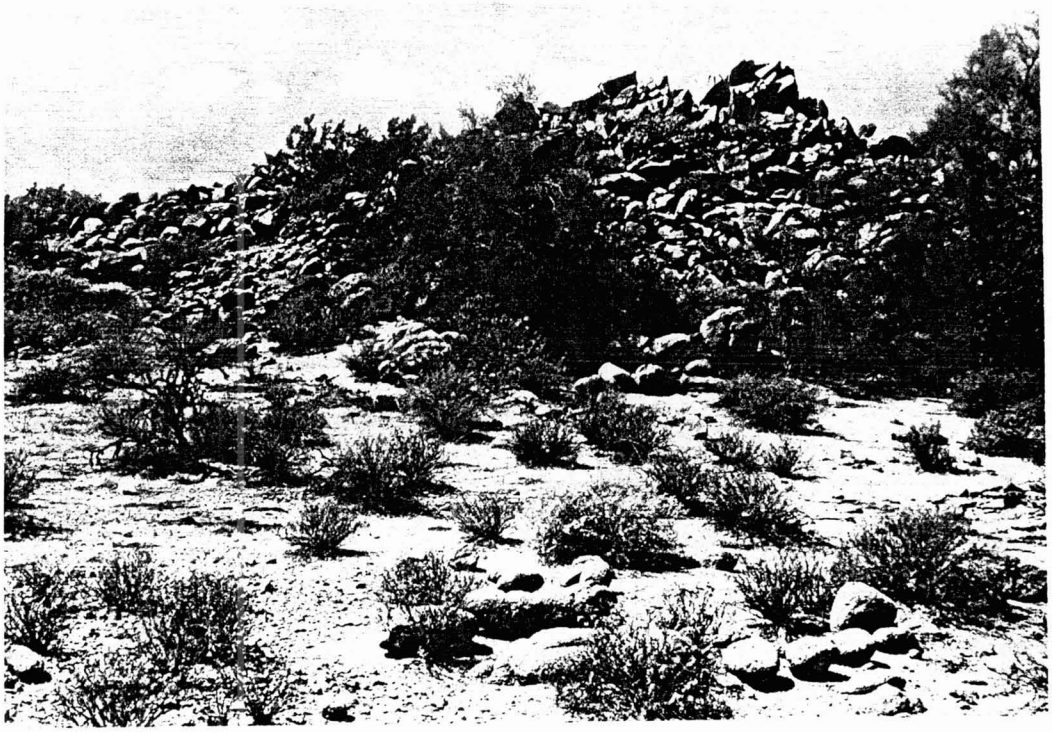
A

Fig. 11.7 Typical Arizona pediments.

(A) View of pedimented landscape southeast of the Harquahala Mountains, from Interstate Highway 10 about 19 kilometers west of Tonopah.

(B) Surface of pediment next to outcrop of granitic rock. The blocks of rock between the joints (cracks) weather into rounded boulders that litter the outcrop and the surface of the pediment (see Chapter 17). Sacaton Mountains about 16 kilometers north of Casa Grande.

(C) Pediment exposed by Interstate Highway 10 about 16 kilometers north of Casa Crande. The smooth surface of the pediment is capped with a veneer of weathered rock. A mountain remnant rises behind the pediments. Sacaton Mountains.



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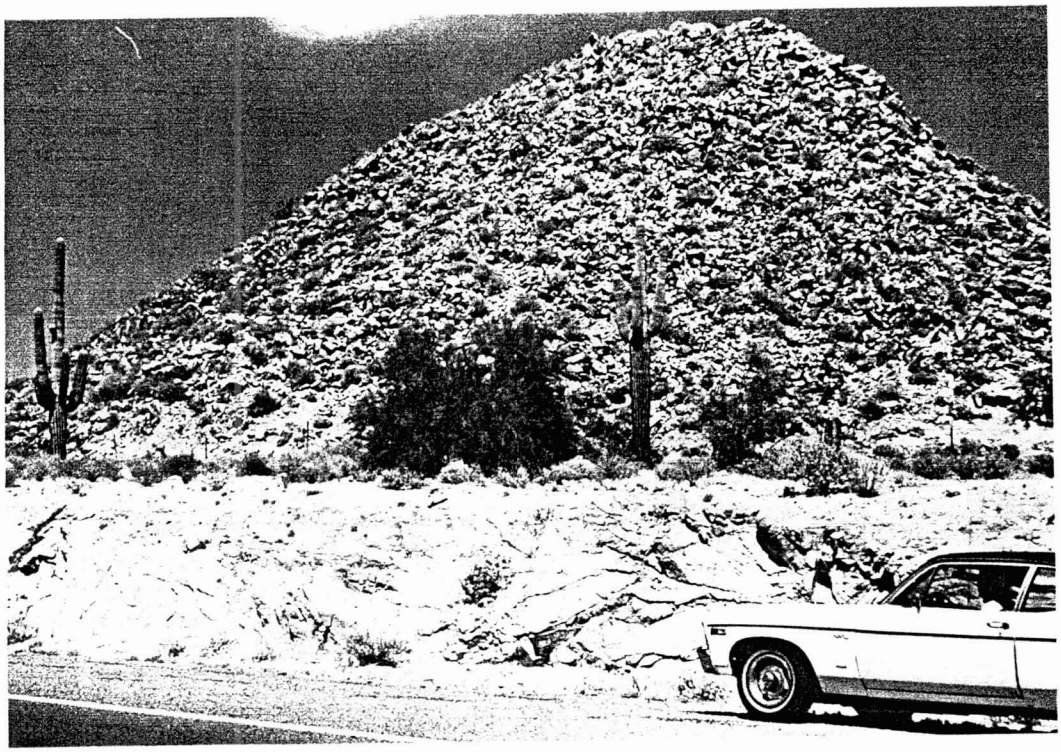

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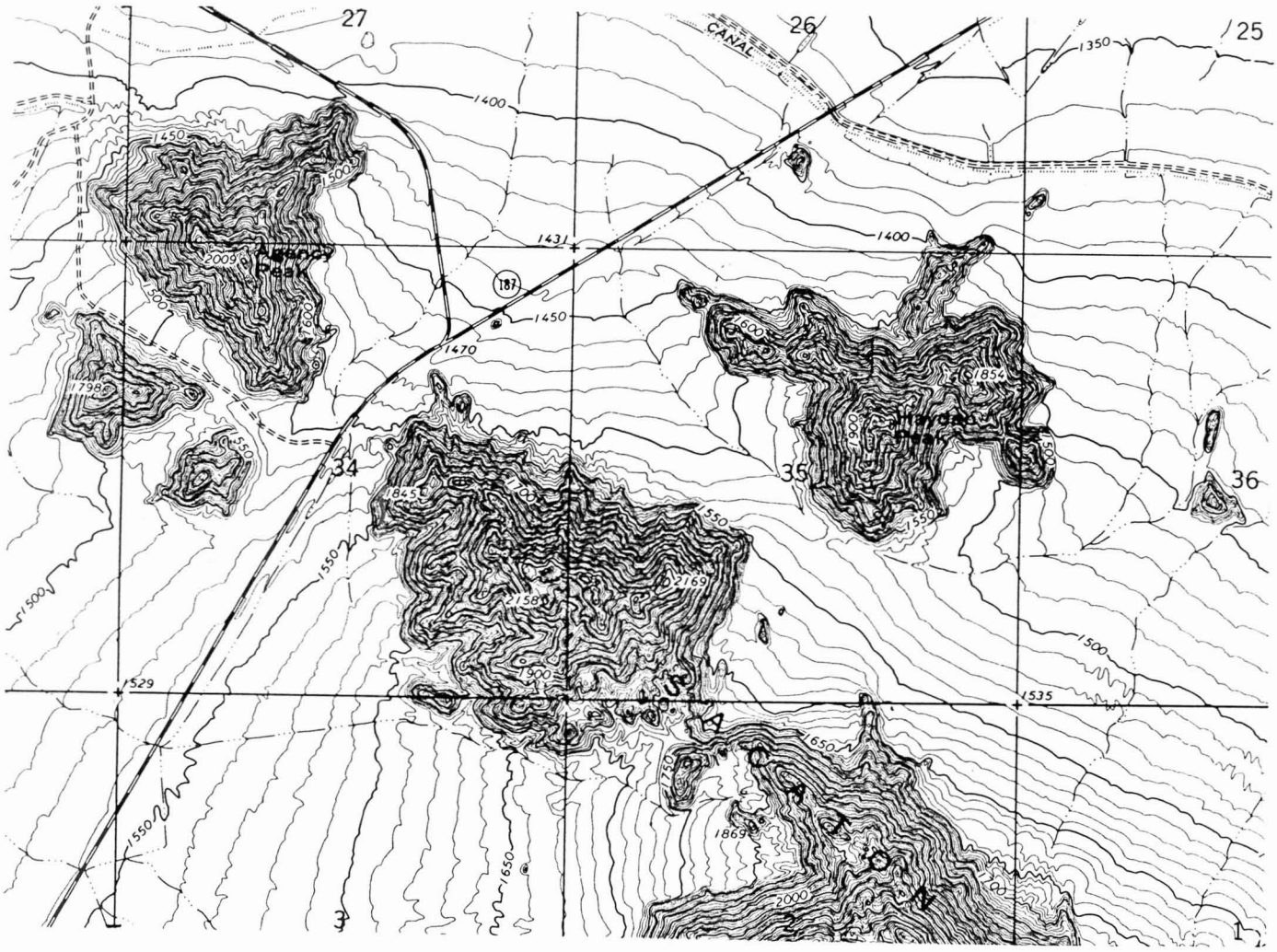
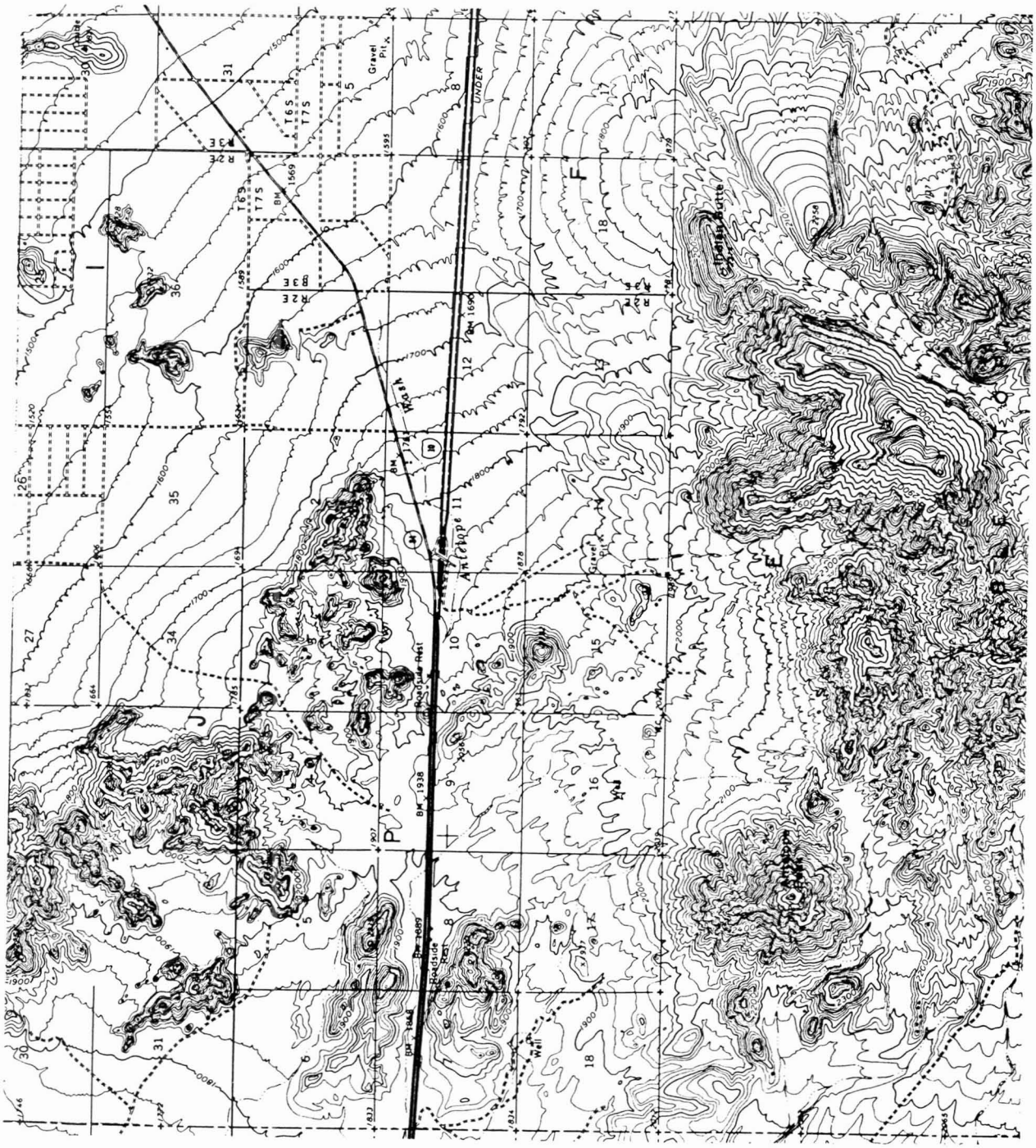


A

Fig. 11.8 Topographic maps of pedimented landscapes

(A) Topographic maps of pedimented landscapes. The Sacaton Mountains pediment. Sacaton quadrangle.

(B) Pedimented landscape north of the Table Top Mountain. Antelope Peak quadrangle. Inselbergs (I), rock fan (F), mountain-pediment junction (J), pediment embayment (E), pediment pass (P).


Antelope 11
Wash
Gravel Pit
UNDER
Roadside Rest
Well
Indian Butte

B

from the original mountain front. The basin fill commonly consists of fanglomerates (gravelly fan deposits that have been cemented into rock) that have been so eroded and beveled that no vestige of the original fan surface remains. In such a case a continuous pediment is beveled across bedrock near the mountains and beveled across cemented alluvium downslope from the original position of the mountain front.

The highways of Arizona pass through spectacular pedimented landscapes (see figure 11.7A). Instead of having straight mountain fronts and well developed drainage basins such as were illustrated in figures 11.2 and 11.3, the pedimented landscape consists of remnants of mountains. Erosion has largely destroyed the larger drainage basins. Most of the water flowing onto the pediment comes from small hillslope rills and streams and as sheetwash. A rock pediment surface veneered by weathering products and alluvium does not look greatly different from an alluvial slope when viewed from the ground (figure 11.7B) or from an airplane. All similarities to a depositional landscape cease when one views a subsurface exposure of a pediment. In figure 11.7C one can readily see how thin is the coating of surficial detritus as well as the abrupt mountain-pediment junction at the base of the remnant of what was once an extensive mountainous mass of granitic rock. The boulders littering the surface of the hill have been weathered from the blocks of rock between widely spaced joints (cracks).

A topographic map of part of the Sacaton Mountains pediment is shown in figure 11.8A. Although the map does not provide clues as to the former extent of the mountains, one gets the impression that Hayden and Agency Peaks are mere remnants of granitic rock left from what may have been a range of substantial height and area.

Interstate Highway 8 between Casa Grande and Gila Bend passes through a variety of pedimented landscapes, part of which are shown in figure 11.8B. This is one of the few areas in Arizona where a large drainage basin discharges onto a pediment. The result is a rock fan which has contours that are similar to those of an alluvial fan. The rock fan, however, is underlain by beveled bedrock instead of thick accumulations of sand and gravel. The outliers of bedrock are called "inselbergs" and commonly represent the remnants of former ridges that have survived the long-term erosional planation of the adjacent parts of the mountains. Pediment passes are the extensions of pediment embayments that have resulted in the joining of two valleys on opposite sides of a range into a continuous pedimented surface. Despite the extent of the erosion, the abruptness of the mountain-pediment junction is characteristic of this and other Arizona pediments.

Weathering and Erosion of Pediments

The literature on pediments abounds with hypotheses about how pediments are formed, but little field work has been done to determine the relative effectiveness of weathering and erosional processes on pediments.

Pedimented landscapes generally require more than a million years to form and some pediments may be relicts from mid-Cenozoic times of wetter climates. As in the case of alluvial fans, one has to consider the factors influencing the source of runoff in the mountains as well as on the pediment. In 1915 Lawson postulated parallel retreat of the mountain fronts as a result of the combined action of weathering of the rock and removal of the weathering products by water flowing in rills and as sheets. Stream action is the most competent process operating in the desert landscape, so it is only natural to assume that lateral planation by streams has resulted in the beveling of large areas of rock and other materials. Lateral planation has been described by Gilbert, Bryan, and Rahn and was emphasized as being the chief process forming pediments by Johnson. Johnson maintained that little deposition or erosion occurred on pediments and that the chief process was the transport of debris across the surface. During the course of stream transport the channels shifted sideways, and lateral cutting occurred where they impinged on the bedrock bordering pediment embayments. Although lateral cutting by streams occurs, Sharp and Lustig have pointed out that a stream cannot flow out of the mountains, make a right angle turn, flow along the mountain front, and cut laterally on the upslope side of the stream channel.

Sheetfloods were first described in Arizona by McGee, and Davis considered rillwash and sheetflood as being important processes in forming pediments. However, as has been pointed out by Lustig, a smooth surface must

exist before a sheetflow can occur. Although sheetflows may flow over smooth pediments and may be capable of extending them, some other process or combination of processes formed the smooth surface initially. Rillwash and sheetwash probably are important processes for the erosion, reworking, and deposition of the pediment mantle.

The slow processes described above suggest that pediments are formed slowly and that expansion of pediments occurs over millions of years at the expense of the mountain ranges. The coalescence of pediments may make widespread erosional surfaces of great extent that King has called pediplains.

Many aspects of Arizona's landscape are interrelated, and the great length of time needed to form an extensive pediment suggests the probability of the pediment being affected by other parts of the landscape. The larger streams such as the Gila, Santa Cruz, and Salt Rivers are parts of the landscape that change rapidly during geologic time because a stream is a highly competent geomorphic agent that can either downcut or backfill its valley. Both backfilling and downcutting of the river valleys have occurred during the Quaternary in Arizona, but the long-term trend has been net downcutting of the river valleys. Times of prolonged backfilling along main streams may have been times of pedimentation of the mountain front and of accumulation of pediment mantles on the downslope parts of the erosion surface. During the times of prolonged downcutting of the river valleys, the tributary streams cut down into the pediments. The effect of fluctuating but overall net lowering of the altitudes of river valleys has been to preserve older pediments as dissected but distinct surfaces above the younger surfaces. Southeast of Table Top Mountain, Roger Morrison (United States Geological Survey, Denver, Colorado, oral communication, July, 1971) has found five different levels of pediments, which may have been affected by the type of river-valley fluctuations noted above. Royse and Barsch (1971, figure 11.2) described five erosion surfaces in the basin fill along Tonto Creek. Where a river is close to the area being pedimented, the erosion surfaces of different ages tend to be linear and parallel to the streams tributary to the river. Such pediment terraces have been described by Royse and Barsch, and by Cooley.

Most pediments probably are formed by several processes that vary in importance from one location to another. Mabbutt's hypothesis of mantle-controlled planation emphasizes the roles of both weathering and erosion. Granitic rocks, in particular, vary in their susceptibility to weathering. They weather more rapidly where buried by a cover of colluvium (weathering products) or alluvium than where exposed to the drier micro-environment of the atmosphere. Runoff from the mountain front or other outcrops frequently is concentrated at the base of the hillslope and thus provides sufficient moisture to sustain a zone of accelerated weathering that maintains the sharpness of the mountain-pediment junction. Any protrusions of the bedrock into the mantle are weathered in the same manner. Different weathering rates caused by differences in soil moisture remove some of the irregularities of the bedrock surface and transfer the smoothness of the mantle to the bedrock. The smooth pediment surface is exposed to view when conditions are favorable for the temporary stripping of the mantle. Prolonged exposure, however, generally results in a decrease of the smoothness of the pediment as stream channels become incised into the pediment. Lateral planation by larger streams probably is important, but by rills is negligible.

TECTONIC ENVIRONMENT OF ALLUVIAL FANS AND PEDIMENTS

The landscapes of Arizona are not static. They have been shaped by the internal forces of the earth, and by the processes of erosion and deposition. The relative importances of the different processes have varied with time, and the landscape continues to change. Pedimentation is a widespread and common process forming the desert plains now, but the geologic record shows that plains formed of alluvial fans were more common several million years ago. The change from fans to pediments has been the result of changes in the rates of uplift of the mountains.

In figure 11.9 a diagrammatic cross section shows the accumulation of thick alluvial-fan deposits. Two processes tend to cause entrenchment of the channel into the fanhead — downcutting of the stream channel in the mountains and the deposition of more fan deposits next to the mountains. One process — uplift of the mountains — tends to offset the effects of the two processes that tend to cause entrenchment, because uplift tends to keep the stream

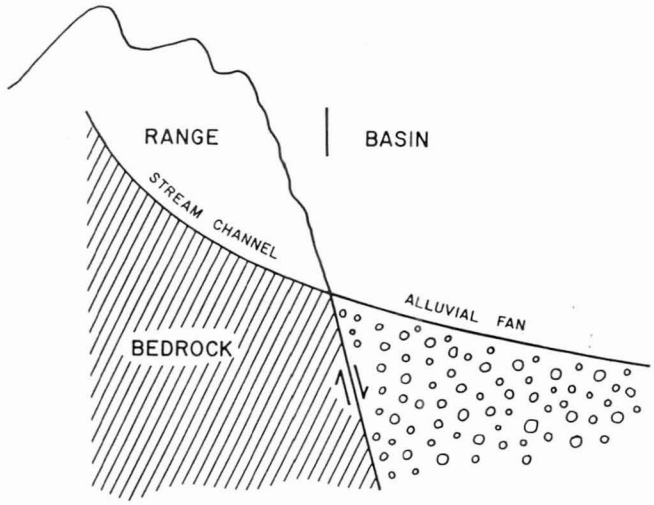


Fig. 11.9 Diagrammatic cross section showing the accumulation of alluvial-fan deposits next to the mountains.

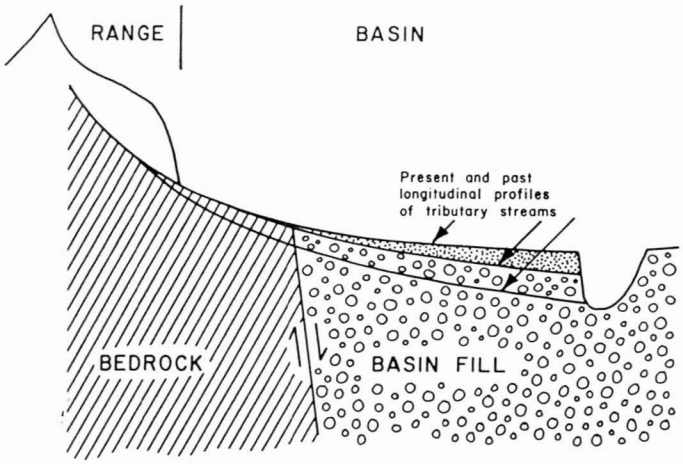


Fig. 11.10 Diagrammatic cross section showing the development of pediments that are incised by stream channels.

at, or above, the apex of the fan. Thus whether or not the fan deposits continue to accumulate next to the mountains is determined by the relative rates of uplift, channel downcutting, and fan deposition. The interrelations between these processes can be expressed in an equation as follows:

uplift rate $\geq$ channel downcutting rate + fan deposition rate.

As long as the rate of uplift equals or exceeds the sum of the rates of downcutting and deposition, fan deposits will continue to accumulate next to the mountains. In Arizona, thousands of meters of uplift of ancestral mountains is shown by the presence of thousands of meters of fan deposits. In figure 11.9 the mountain front coincides with an active tectonic structure — a fault.

A different situation is depicted in figure 11.10. The mountain front does not coincide with the former mountain front indicated by the location of the buried inactive fault. The processes of pedimentation have caused the mountain front to retreat from its original location. Mountain uplift has ceased, but erosion continues. The mantle on the pediment portrayed in figure 11.10 is partly removed at times, so long-term gradual erosion of the pediment is continuing. The trunk stream shown on the right side of figure 11.10 has cut below the level of the erosion surface. The tributary stream is downcutting more rapidly than is the erosion surface. The interrelations between these processes can be expressed in the equation:

uplift rate $<<$ channel downcutting rate $>$ pediment downcutting rate.

The uplift rate is essentially zero, and because the channel downcutting rate exceeds the pediment downcutting rate the pediment is incised by the streams tributary to the trunk stream. If the rates of channel and pediment downcutting were the same, the pediment would not be incised and the streams would flow across the pediment, instead of in small valleys cut into the pediment.

Figures 11.9 and 11.10 show some of the reasons why alluvial fans are associated with tectonically active mountain fronts, whereas pediments are characteristic of tectonic stability. The fact that pediments instead of alluvial fans are the dominant type of desert plain in Arizona indicates that much of Arizona has been inactive tectonically during most of the Quaternary. The typical situation in the Basin and Range Province of Arizona is shown in

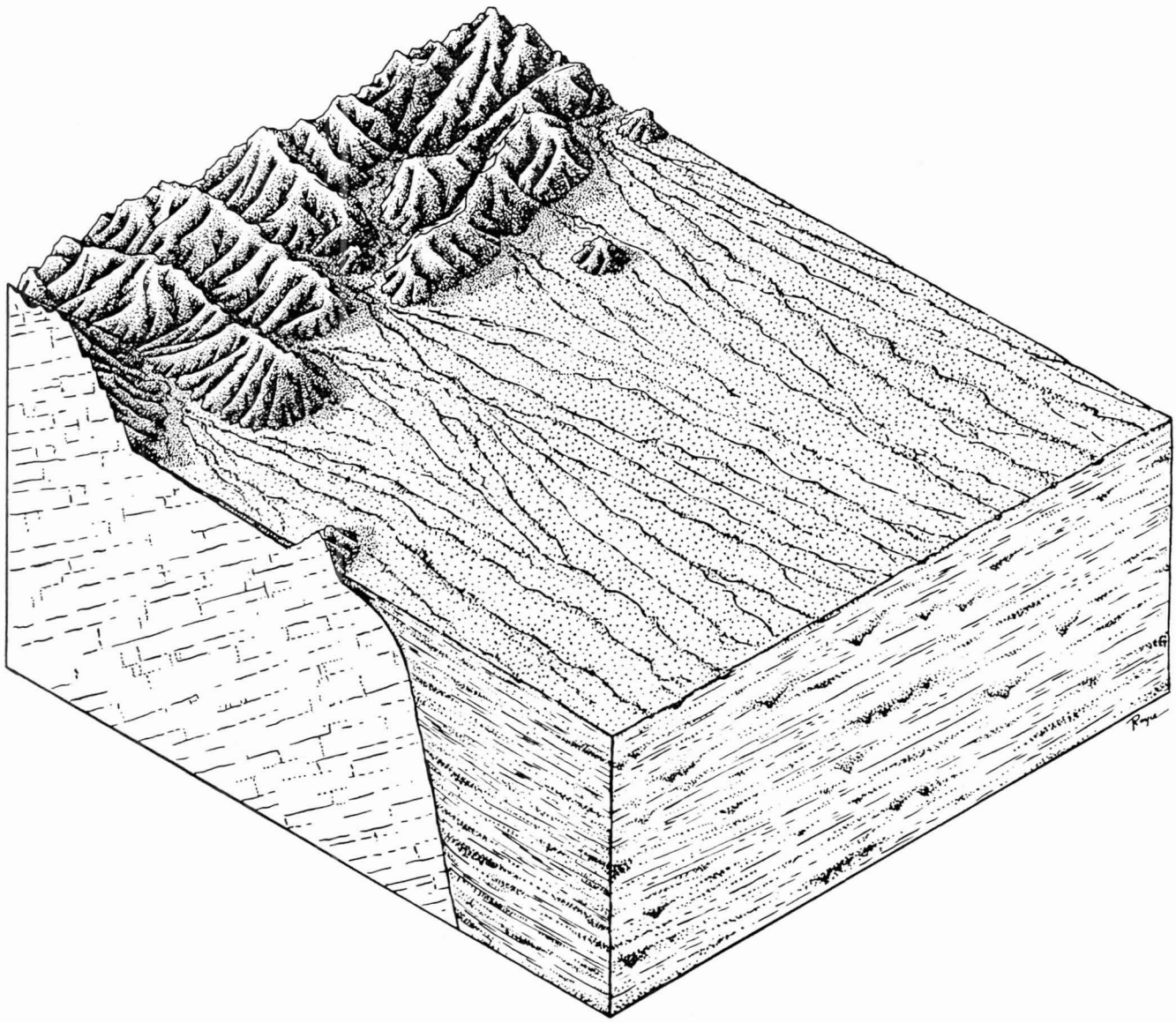


Fig. 11.11 Diagrammatic sketch showing a tectonically stable terrain with a single erosion surface that truncates the rock of the mountains, the fault, and the alluvial fans that had been deposited in the basin.

figure 11.11. A highly eroded mountain front has retreated from its original location at the buried fault scarp. Remnants of the former mountain mass now rise above a pediment mantle that is traversed by shallow unincised streams. These streams transport debris newly derived from the mountains, the weathering products from the pedimented surface, and alluvium that had been deposited previously in those areas. Downslope from the buried fault is a thick sequence of basin-fill deposits, whose upper part has been eroded so that the alluvium has an erosional surface that is an extension of the erosional surface cut on bedrock. The beds of the basin fill continue for long distances in the downslope direction, but an exposure parallel to the mountain front reveals overlapping beds of limited extent that are interrupted by numerous backfilled stream channels — features that indicate that the basin fill was deposited as alluvial fans and then was eroded into a pediment. The landscape history in much of Arizona has consisted of deposition of alluvial fans during times of active mountain building followed by tectonic quiescence and pedimentation that has removed more than 100 meters of fan

deposits and has caused uneven but extensive backwearing of the mountains.

IMPORTANCE OF ALLUVIAL FANS AND PEDIMENTS TO MAN

The alluvial fans and pediments of Arizona include important urban and agricultural areas. Knowledge about the characteristics and locations of fans and pediments is useful to scientists, engineers, and planners.

Alluvial Fans

Tectonic stability is important for most engineering structures and especially for nuclear generating plants. The presence of rapidly accumulating thick alluvial-fan deposits next to a mountain front should be a warning sign to those who are looking for sites free of potential surface rupture and distant from geologic structures that may generate earthquakes.

The locations of earthquake epicenters in Arizona during the last century are shown in figure 11.12. In comparison with the Rocky Mountain and Pacific Coast states, Arizona is surprisingly free of earthquakes. Most of the epicenters are in the northern half of the State. Southern Arizona has few, except for its south and west borders. These two areas are also the areas of best developed alluvial fans. Parts of the Gila Mountains (figures 11.2 and 11.3) have thin fans that have maintained their form during the Quaternary, but have not undergone rapid accumulations of new deposits.

In the southeastern corner of Arizona alluvial fans occur next to the Swisshelm and Chiricahua Mountains and in the San Bernardino Valley. On most of the fans deposition is occurring downslope instead of immediately adjacent to the mountains. Stream-channel entrenchment appears to be more pronounced on the west than the east sides of the mountain ranges, which indicates that the east sides of the ranges are being uplifted more rapidly than the west sides. Thirty to sixty meter scarps are present on the east side of the Swisshelm Mountains, but extensive pedimentation occurred between the times of major scarp formation. Fault scarps also occur on the east side of the Chiricahua Mountains.

The fans in the southeastern and southwestern corners of the State may indicate a slight to moderate degree of tectonic activity during the late Tertiary. These areas are not as tectonically active as the mountains associated with the alluvial fans along the east side of the Sierra Nevada and in Death Valley, California or much of Nevada. However, the likelihood of infrequent but large fault movements is greater than in the south-central part of the State.

Arizona is highly dependent on underground water supplies, and the deposition of alluvial fans in the geologic past has benefited us. Alluvial-fan deposits form much of the ground-water reservoirs of the basin fills, and much of the recharge of the ground-water reservoirs is through the coarse-grained fan deposits that fringe the basins. For example, much of the water used in Tucson is pumped from alluvial-fan deposits laid down by the ancestral stream of Sabino Canyon, which flowed out of the south side of the Catalina Mountains.

The weathered sandy deposits on fans, particularly on the downslope parts of the fans, provide some of the better agricultural soils in Arizona. Of equal importance is the fact that these soils occur above the sands and gravels of the fan deposits that furnish well water in sufficient abundance to support agriculture. The amount of water that can be pumped from the deposits varies not only with the original texture but also with the degree of cementation of the deposits. Some of the oldest fan deposits contain so much calcium carbonate cement ("caliche") that little water can be pumped from them.

Not all aspects of alluvial fans are beneficial. The basin fills of Arizona — the deposits of alluvial fans, through-flowing rivers, and lakes — are areas that are subject to land subsidence. Pumping of ground water decreases pore-water pressures and increases the forces squeezing the basin-fill deposits. As water is pumped the thickness of the ground-water reservoir becomes less and the surface of the land sinks (subsides). More than 2 meters of subsidence has been measured in Arizona, but these amounts are much less than in areas of similar deposits in California. The occurrence of earth fissures in Arizona, such as those described by Robinson and Peterson, and Schumann and Poland, and also Anderson, appears to be associated with the subsidence. Both the land subsidence and earth fissures are

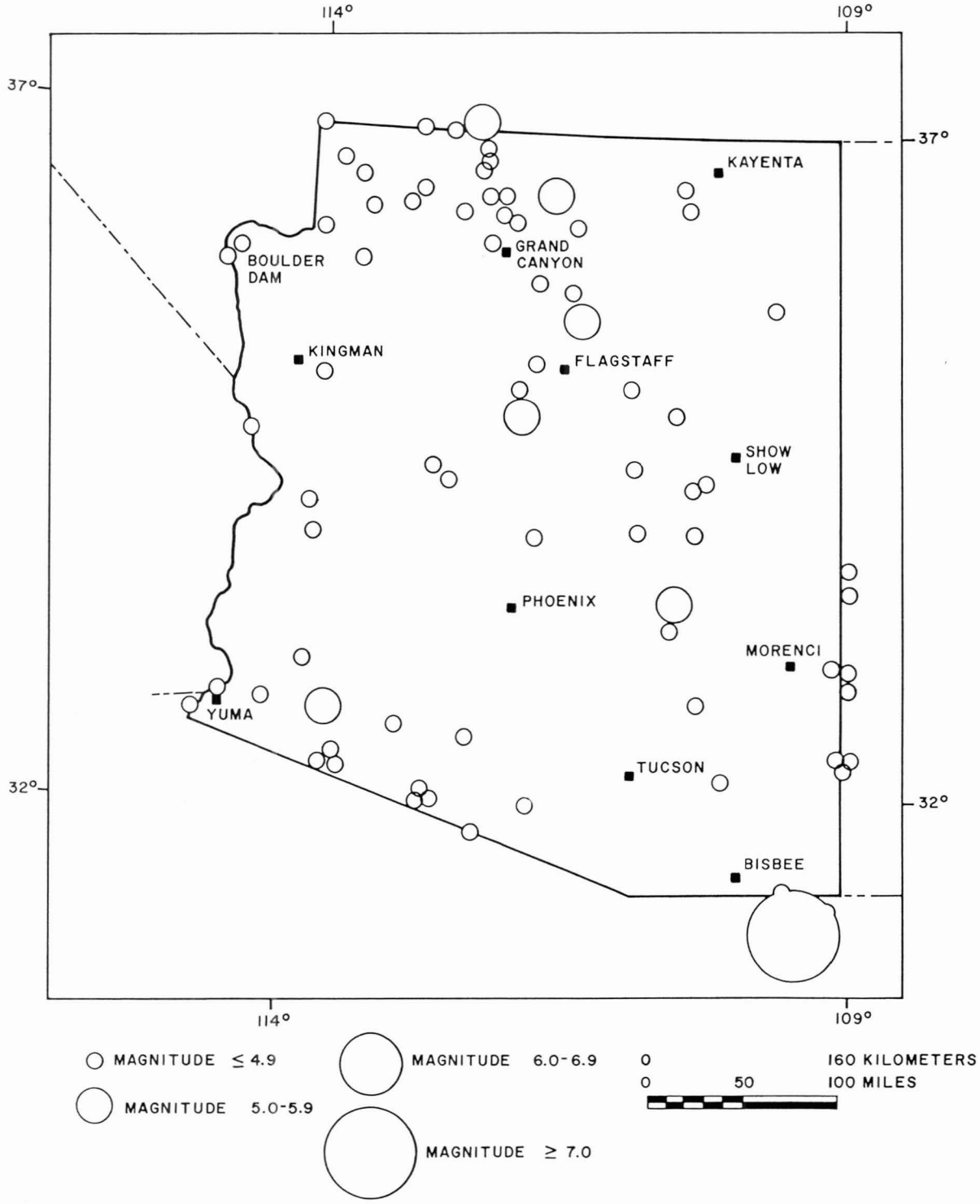


Fig. 11.12 Earthquake epicenters in Arizona, 1950-1966 (Sumner, 1976).

a potential danger to engineering structures, particularly nuclear generating plants, airport runways, and water-transport systems such as the Central Arizona Project canals and distribution systems. Alluvial-fan and other types of basin-fill deposits should be avoided for these purposes, particularly where the deposits contain large amounts of silt and clay.

Pediments

Pediments are suitable for many engineering uses. Pediments that consist of plains of beveled rock may provide good foundation materials for heavy engineering structures. The genesis of pediments outlined earlier indicates that they are most common in areas of minimum tectonic activity. The south-central part of the State has had very few earthquake epicenters (figure 11.12), and this part of the State also has the most extensive pediments. Rock pediments also represent areas that do not have land-subsidence problems and are free of earth fissures. Thus pediments may be excellent places on which to build nuclear generating plants, airports, and water-transport facilities. The downslope parts of rock pediments are particularly well suited for these purposes because of the gentle slopes and the availability of the ground water in the nearby basin fill.

The environmental problems of pediments are chiefly hydrological. Only limited ground water is available from the cracks and fractures of pedimented rocks, and those parts of pediments that are far removed from water supplies may be undesirable for urban and agricultural development. The town of Sells has had water shortages because it was built on a pediment. Most of the water now used in the town is being pumped 11 kilometers uphill from two wells that have been drilled in the basin fill west of the pediment. The small amounts of water that can be obtained from pediments are suitable for widely spaced domestic use and for livestock wells. Favorable situations for accumulation of small amounts of ground water occur where a permeable pediment mantle allows streamflow to infiltrate underground and then become trapped above impermeable bedrock or cemented alluvium. Pediments also may be subject to flash flooding during the rainy season of summer and early fall. Beveled bedrock surfaces, and the thin veneers of mantle above them, can absorb only limited amounts of water during prolonged intense rains. Additional rainfall flows rapidly to the streams to cause flash flooding. Thus planners should be aware of the extent of pedimented landscape upslope from a proposed development, because the presence of bare bedrock may increase flood hazards.

SUMMARY AND CONCLUSIONS

Pediments and coalescing alluvial fans are common types of landscapes forming the plains between the mountain ranges of southern Arizona. In trying to recognize fans or pediments it is useful to remember that alluvial fans are formed in a depositional environment, and that pediments are formed in an erosional environment.

An alluvial fan is a deposit with a surface that approximates a segment of a cone that radiates downslope from where a stream spreads out on a plain. Topographic contours of fans bow downslope, the cross-fan topography is convex, and the outline of a fan commonly is fan shaped. The thicknesses of fans generally are more than 1/100 the length of the fan, and large fans may be several hundred meters thick. A relatively straight mountain front upslope from coalescing fans may correspond to the position of the fault responsible for the uplift of the mountains.

Deposition occurs where the depth and velocity of stream-flow decrease as the flow spreads out on a fan and is caused in part by the infiltration of water into the pre-existing surficial deposits. Alluvial fans consist of water-laid sediments, debris-flow deposits, or both. Water-laid deposits occur as sheetflood and channel sediments. Sheets of sandy or gravelly sediments commonly are deposited by a network of braided streams, and the entrenched channels generally are filled with gravel. Debris-flow deposits consist of bouldery gravel in a poorly sorted matrix of mud and may be deposited as levees along the sides of channels or as massive sheets on the fan surface.

The vast number of beds that accumulate in an alluvial fan differ greatly in extent, thickness, and physical characteristics and reflect the infinite variety of streamflow events derived from the mountainous source area of the fan. The typical fan consists of lenticular sheets of water-laid sediments and debris flows, with backfilled stream channels being most

common near the mountains. Adjacent beds vary greatly in thickness and in mode of deposition. Individual beds extend for long distances along radial sections and channel deposits are rare. Cross-fan sections reveal overlapping beds of limited extent that are interrupted by backfilled stream channels.

A pediment is an erosion surface cut in bedrock or in softer materials such as alluvium. Many Arizona pediments consist of a single erosion surface that is beveled across bedrock near the mountains and across cemented alluvium downslope from the original position of the mountain front. Isolated hills of bedrock project above the mantle of alluvium that veneers the bedrock portions of most pediments. Where pedimentation has been extensive, only a few ridges and hills remain from the former mountain range. The sinuous mountain fronts of pedimented landscapes are far upslope from the tectonically inactive faults along which the earlier mountain uplift occurred. Wide valley floors in the mountains give the valleys U-shaped cross sections, and these valleys are embayments of the pediment extending into the mountains. During the course of geologic time, pediment embayments from the opposite sides of a mountain range may join to form pediment passes.

Most pediments are formed by several erosional processes. Weathering of rock into detritus that can be carried by streamflow and sheetflow is important. Some rocks (such as granite) weather more rapidly where buried than where exposed to the drier micro-environment of the atmosphere. Runoff from the hills soaks into the ground at the base of the hillslope and thus provides the moisture needed to accelerate weathering of the mountain front and thus maintain the sharpness of the junction between the mountains and the pediment. Streams flowing across a pediment cut laterally into the remaining outcrops of bedrock. Sheetflow tends to smooth out the surficial mantle of weathering products and alluvium that covers much of the lower slopes of a pediment.

Both alluvial fans and pediments have been important in the development of the Arizona landscape. Alluvial fans were most common during the times when uplift of mountains along active faults allowed thick fan deposits to accumulate next to the mountains. Stream channels became entrenched into the fans as the uplift decreased, and deposition of the debris washed out of the mountains no longer occurred next to the mountain front. Erosion, instead of deposition, became the dominant process. Weathering and erosion of the bedrock resulted in the backwearing of the mountain front as well as lowering of the erosional plain. Erosion also removed the upper part of the fan deposits thus destroying the characteristic surfaces formed during deposition of the individual alluvial fans (as shown in figure 11.11). A single continuous erosion surface was beveled across bedrock near the mountains and across alluvium downslope from the position of the inactive fault that was at the original mountain front.

Knowledge of alluvial fans and pediments is important to the wise use of Arizona's resources. Thick alluvial fans are indicative of continuing uplift of the mountains, but rock pediments are suggestive of stable conditions and may be suitable sites for structures such as nuclear generating plants, which should not be built in areas of potential surface rupture. The present distribution of fans and pediments indicates that the south-central part of the State is the least active tectonically. Alluvial-fan deposits form much of the ground-water reservoir in the basin fills, and much of the recharge of the ground water is through the coarse-grained fan deposits that fringe the basins. However, intensive pumping of ground water in some agricultural areas has caused land subsidence and earth fissuring. Rock pediments are free of subsidence and fissuring problems and generally provide a good foundation for engineering structures. Only limited ground water is available from rock pediments, because of the few cracks where water can be stored. Pediments also are areas of potential flash flooding during times of intense rain when only part of the rainfall can soak into the pediment.

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