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GEOLOGY OF ALLUVIAL FANS IN SEMIARID REGIONS

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A CLASSIC
NOT MUCH NEW

ABSTRACT

An alluvial fan is a body of detrital sediments built up at a mountain base by a mountain stream. Bold relief is essential, moderately arid to semiarid climate favorable for the development of fans. The depositing agents are sheet floods, stream floods, and streams. Compound alluvial fans result from lateral coalescence of single fans.

Development of alluvial fans is affected by changes in the course of a cycle, varying base level, climatic changes, tectonic movements, and slumping of fan deposits. Telescoped or superimposed structure may be developed.

Fan deposits are arkosic or graywacke. Sorting and roundness of particles range widely. The matrix is primary or secondary. In general alluvial-fan deposits are stratified. Channel cut-and-fill is pronounced. Individual strata in fans are up to 20 feet thick. Particles in stream deposits are imbricated.

Talus-slope deposits at the apex of a fan and floodplain deposits at its base can be separated from those of an alluvial fan by particle sizes, angularity and orientation of fragments, sorting, and original dip of strata. Mudflow deposits in an alluvial fan indicate certain climatic conditions during its formation.

Many ancient fan deposits may have escaped recognition because of the common misconception that fan deposits are necessarily unstratified, composed of angular fragments, poorly sorted, and without distinctive sedimentary structures.

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Purpose of Investigation

This paper gives the results of a comprehensive study of alluvial fans. Though detailed field work was carried out only in the southwestern United States, most of the data may be applied to alluvial fans in other areas where similar conditions prevail. Thus, through detailed study of recent alluvial-fan deposits, geologists may be aided in determining whether ancient rocks were formed under similar conditions.

Areas of Field Study

Alluvial fans studied in southern Arizona include those at the southern base of the Santa Catalina Mountains, north and northeast of Tucson, Arizona, and fans of the Tucson Mountains, west and northwest of Tucson, Arizona.

Investigations in the Mammoth area, Arizona, were carried out on alluvial fans on both sides of an intermontane valley of the Black Hills, Arizona, west of Mammoth.

In northern Arizona alluvial fans were studied along the Aubrey Cliffs, northwest of Seligman, Arizona, and along the Bright Angel Trail, north of the Grand Canyon Village, Arizona.

Studies were also carried out on alluvial fans in southern California and southern New Mexico.

Certain alluvial fans were studied in every detail, whereas only certain properties were examined in other fans.

Acknowledgments

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Geology of Alluvial Fans

Definitions

An *alluvial fan* is a body of detrital sediments built up by a mountain stream at the base of a mountain front. It develops because all streams tend to form a graded course. A talus slope differs from an alluvial fan in that it is built up predominantly by gravitational sliding.

The *apex* of an alluvial fan develops at the point where the stream emerges from the mountain. It is the point of highest elevation on the alluvial fan. *Fanhead* applies to the area on the alluvial fan close to the apex; *midfan* designates the area between the fanhead and the outer, lower margins of the fan. *Base* of an alluvial fan is the term applied to the outermost or lowest zone of the fan.

If the fanhead area reaches far into a mountain canyon the term *fan-bay* (Davis, 1938, p. 1374) is applied to it. *Fan-mesa* (Eckis, 1928, p. 243–244) is the term applied to an alluvial fan remnant left standing in the process of degradation of a fan.

General Statement

The occurrence of alluvial fans has been reported from all continents. However, due to conspicuous development and easy accessibility, alluvial fans in California have been studied in more detail than any others (Lawson, 1913, p. 332; Eckis, 1928, p. 232–246; Krumbein, 1937, p. 586–594; Buwalda, 1951, p. 1491).

Investigators generally agree that an alluvial fan resembles geometrically the segment of a cone. From the apex of the fan the surface dips toward the base in which direction the angles of dip gradually become flatter. Thus, a radial profile through the fan is concave upward; a profile at right angles convex. The steepest angle of dip on the alluvial fan is encountered close to its apex.

The angle of dip of the fan surface rarely exceeds 10° (Dana, 1894, p. 194–195; Eckis, 1928, p. 223; Scott, 1932, p. 269; Eardley, 1938, p. 1408). Some authors report no angle greater than 5° or 6° (Lawson, 1915, p. 25; Vaughan, 1922, p. 341). The maximum angles of slope of alluvial fans studied by the writer range from 5° observed on fans of the Aubrey Cliffs, Arizona, to 9° on fans of the Black Hills of Arizona.

Surface angles greater than 5° are characteristic of the upper half or more of small alluvial fans with a radial extent of a few hundred feet like those of the Black Hills of Arizona. Large alluvial fans such as those of the Santa Catalina Mountains, Arizona, with a radial extent of about 4 miles, exhibit surface angles greater than 5° only within the upper one twentieth or less of their extent.

In geologic literature small alluvial fans are commonly called alluvial cones. As no definition specifies the difference between an alluvial fan and a cone, this classification is not followed. Instead the terms steep, gentle, and flat angles of dip are proposed to denote the degree of slope of alluvial fans or parts of them.

Because angles of dip greater than 5° are rare these are called steep. Angles of dip between 2° and 5° are termed gentle, and sloping angles below 2° flat. On the basis of these definitions the slope of the surface of a particular alluvial fan can be described as follows: Alluvial fans of the Santa Catalina Mountains with a radial extent of about 4 miles have steep slopes in the uppermost 0.2 mile of the radial extent of the fans. In the adjoining 0.7 mile surface angles are gentle, while the remaining part, about 3.1 miles, has flat angles of dip.

The radius of an alluvial fan may be as great as 40 miles under exceptional conditions (Gradau, 1913, p. 584). The radii of alluvial fans studied by the writer range from 4 miles at the Catalina Mountains, Arizona, to about 300 feet in the Black Hills, Arizona.

By lateral coalescence of single alluvial fans, a *compound alluvial fan* may result (Miller, 1926, p. 164–166) (Fig. 1; Pl. 1, fig. 1). The compound alluvial fan is equivalent to the alluvial piedmont slope (Lahee, 1941, p. 101) and the "bajada" (Blackwelder, 1931, p. 136).

Alluvial fans may be 1000 or more feet in thickness (Eckis, 1928, p. 224). In general, the thickness of alluvial-fan deposits is greatest at the apex of a fan (Scott, 1932, p. 269). Under exceptional conditions, however, a fan may be thicker at the base than at its apex. This is illustrated in an alluvial fan of the Santa Catalina Mountains, Arizona; the thickness of the fan deposits increases from between 0 and 100 feet at the apex to 200 or 300 feet at the base of this fan.

Alluvial fans occur in areas of bold relief, and their development is most conspicuous under moderately arid to semiarid conditions. The influence of bold relief seems obvious as only under such conditions will there be profound erosion and transportation together with a strong tendency for deposition as the mountain streams reach areas of low gradient.

Practically all reductions of rock slope and contributions to alluvial embankment are affected by brief and infrequent periods of downpour (Lawson, 1915, p. 28). This type of precipitation is characteristic of areas with arid and semiarid climate. Under humid conditions also alluvial fans are developed as seen along the Alps and the Himalayas. Fans formed in humid environment commonly are flatter than those of arid environment owing to the abundance of running water which favors the development of gentler gradients. Under conditions of extreme aridity, mountains are buried under their own debris (Lawson, 1906, p. 449), and the deposits formed are in the nature of talus slopes.

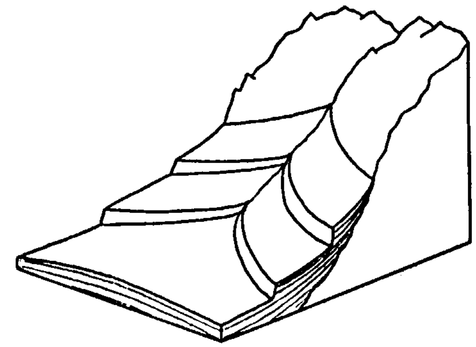

FIGURE 1.—COMPOUND ALLUVIAL FAN FORMED BY LATERAL COALESCENCE OF SINGLE ALLUVIAL FANS

Thus, the climatic conditions most favorable for the development of alluvial fans appear to range from moderately arid to semiarid. The annual precipitation in the region of an alluvial fan studied by Eckis (1928, p. 225) averages about 17 inches. Alluvial fans studied by the writer in Arizona receive a mean annual precipitation ranging from 10 to 19 inches.

Process of Forming Alluvial Fans

In the stage of deposition the surface of an alluvial fan shows a system of radiating channels focused in the main stream at the apex of the fan. This physiographic pattern is referred to as a braiding stream system. Stream channels are distributaries. They commonly are shallow, entrenched but little beneath the gently sloping surface of an alluvial fan (Davis, 1898, p. 291).

Alluvial fans in process of degradation normally are cut by streams that tend to form deep and narrow channels. These streams are tributaries, and the resulting physiographic pattern constitutes a reversal of the braiding stream system focused in the apex of the fan.

Streams emerging from steep mountain canyons commonly are loaded with detrital material, especially if the times of flow are infrequent and separated by long, dry intervals. At the alluvial fan a pronounced tendency for deposition is immediately developed, because of a less steep gradient on the alluvial fan and the pervious nature of the alluvial-fan deposits which effects a continuous decrease in the volume of water.

Thus, fan channels frequently are silted up causing overflows and forming new distributaries. When one sector of a fan has been built up, the streams shift to another, lower section of the fan and build that up (Longwell, Knopf, and Flint, 1948, p. 88). The process is repeated again and again until the mountain stream and the alluvial fan have reached graded conditions.

In arid and semiarid regions short, violent flows normally constitute the transporting and depositing agents responsible for the development of alluvial fans. The depositing agents on alluvial fans may be classified into three types:

(1) Sheetfloods. These occur when an exceedingly large amount of water and detritus emerges from a mountain canyon. The flow, acting like a viscous medium, tends to spread out in the form of a sheet covering the alluvial fan or parts of it. Deep channels on alluvial fans tend to prevent sheetfloods, in the opinion of Davis (1938, p. 1348). Furthermore, he believed that the graded state of compound alluvial fans is effected largely by sheetfloods. A striking peculiarity of sheetfloods is the shortness in distance as well as in time of their flows. Great floods of this type may come only at intervals of decades or centuries (McGee, 1897, p. 108).

(2) Streamfloods. These are confined to definite channels on alluvial fans. They are formed where a large amount of water and detrital material emerges from a mountain canyon. Streamfloods may also form because channels on alluvial fans are too deep to allow a sheetflood to develop. The spasmodic and impetuous character of these floods is such that the term streamflood rather than streams is applied (Davis, 1938, p. 1347). The deposits of violent streamfloods tend to be identical with those of sheetfloods except that, instead of being blanket-shaped, they are linear in plan view.

(3) Streams. These are formed if both the amount of water and the quantity of detritus are less than the requirements for sheetfloods or streamfloods. A steady, rather than abundant supply and recharge of water from the mountains must be maintained. The action of streams is of minor significance in arid or semiarid climates for these climatic conditions do not favor the development of streams. In relatively humid regions, however, as in the Alps or the Himalayas, alluvial-fan deposits laid down by streams are of considerable magnitude.

Every possible gradation between these types of depositing agents must be expected on alluvial fans. Streamflood deposits exhibit gradations ranging from those formed during violent flows to others formed by floods of moderate intensity.

The deposits of sheetfloods and violent streamfloods tend to have a high percentage of mud-sized particles. The term mudflow deposits is commonly applied to these sediments, but this term should not be employed if the deposits can be ascribed to sheetflood or streamflood.

Any one alluvial fan may not show the effect of all three types of depositing agents. Furthermore, certain types of depositing agents may predominate at a particular stage in the development of an alluvial fan. Thus, the action of sheetfloods seems to be most pronounced when a graded stage has been reached—*i.e.*, with completion of the maturity of a fan (Davis, 1938, p. 1340).

The accumulation of flood waters in a mountain area may first give rise to a sheetflood and later, with decreasing recharge of water, change to streamfloods and finally to streams. The duration of sheetfloods is measured in terms of seconds or minutes (McGee, 1897, p. 101), that of streamfloods in minutes or hours, and the flow of streams in hours or even days.

Pack (1923, p. 349–356) described a flood along the west front of the Wasatch Mountains, Utah, in which he recognized three stages of flooding: (1) torrential streamflood, (2) mudflow, (3) dwindling streamflood. These stages compare well with the classification of depositing agents adopted by the writer.

Alluvial fans studied by the writer in southwestern United States suggest that all three depositing agents—(1) sheetfloods, (2) streamfloods, and (3) streams—participated to a varying degree in their formation. In the Black Hills of Arizona, with a mean annual precipitation of 19 inches, mudflow deposits—*i.e.*, those formed by sheetfloods and violent streamfloods—constitute about 5 to 10 per cent of the fan deposits; moderate streamfloods or streams are responsible for the other 90 to 95 per cent. In the Tucson area with a mean annual precipitation of about 11 inches, mudflow deposits form from about 20 to 40 per cent of the alluvial fans, while streams and moderate streamfloods are responsible for the deposition of the other sediments in these fans.

Late-Stage Development

Changes in Normal Course of a Cycle

Until graded conditions are reached, erosion predominates along a mountain canyon, deposition on an alluvial fan. Upon development of a graded course in a mountain stream and an alluvial fan, erosion will reach over the apex of the fan and affect the fanhead area. Thus, the fanhead area undergoes dissection while a depositional tendency prevails farther downfan. The importance of such changes in the cycle of fan aggradation and degradation was first realized by Eckis (1928, p. 237).

Recession of a mountain front results in formation of a rock pediment normally covered by the fanhead part of an alluvial fan. Dissection of the fanhead area due to changes in the normal course of a cycle or to other causes may strip the rock pediment of its alluvial cover and expose it. A rock pediment may be an important indicator of the extent of an alluvial fan at its maturity.

The results attained by a single alluvial fan may also be developed on a compound type of fan. The normal change in a cycle, however, need not take place on adjacent units within a compound fan at the same time. Accomplishment of the maturity of a fan and the beginning of late-stage development is mainly a function of the size of the mountain stream and its gradient, factors which may vary considerably among different units of the same compound fan.

The compound fan at the southern base of the Santa Catalina Mountains, Arizona, is more heavily dissected along its eastern extent than in the west. In the absence of evidence for tectonic activities, the writer believes that the heavier erosion in the eastern part of the compound fan results from larger streams in the eastern part of the range whereby the maturity of fans and the beginning of late-stage development is accelerated. Slow development of alluvial fans and similarly slow changes in the cycle must be expected along the western extent of the compound fan where mountain streams are comparatively small.

Effects of Varying Base Level

Changes in the base level of a fan are commonly effected by a stream flowing along the fan base. Degradation of a fan base may also be caused by wind deflation as seen on some alluvial fans of the Aubrey Cliffs, Arizona (Blissenbach, 1952, p. 123).

Aggrading base level may be reflected in accelerated deposition on an alluvial fan. Under such conditions, the apex of a fan may migrate into the mountain canyon, and fan-bays may be developed.

Degrading base level results in erosion on an alluvial fan. Available evidence indicates that several of the fans studied by the writer have been affected by strong dissection due in part to the cutting in of a stream at the base of these fans.

The effects of the lateral swing of a river at the base of a fan is a combination of the effects of aggrading and degrading base level. The Colorado River has swung westward against the base of an alluvial fan, about 20 miles north of Needles. As a consequence of this undercutting, this alluvial fan is strongly dissected (Davis, 1938, p. 1349). In contrast, a lateral swing of a river away from the fan base favors depositional tendencies on a fan, and the graded conditions may be restored.

A small alluvial fan of recent age, at the base of the compound fan of the Santa Catalina Mountains, Arizona, is built up of alter-

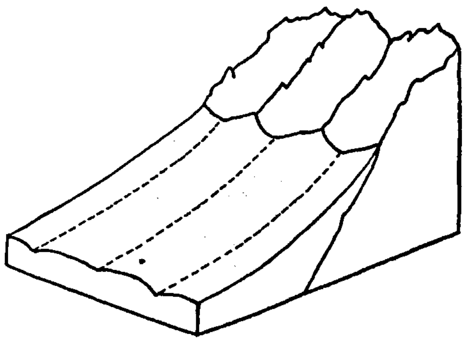

FIGURE 2.—ALLUVIAL FAN WITH TELESCOPE STRUCTURE

nating layers of stream or streamflood and sheetflood deposits. Development of this fan is controlled in part by the lateral swinging of the Rillito Creek at the fan base. Each stream or streamflood deposit and the overlying sheetflood deposit constitute a depositional cycle; deep channels cut in the sheetflood deposits represent an erosional cycle. At times when the Rillito Creek swung toward the base of this fan, erosion was active on the fan, and deep channels were formed. When the river migrated away from the base, these channels were filled by stream and streamflood deposits. Upon accomplishment of graded conditions, sheetfloods may have once more contributed to the building up of this fan.

As a result of the lateral swinging of a river at the base of a fan a peculiar overall structure may be developed in the fan. It is characterized by younger fans with flatter gradients spreading out from between fan mesas of older fans with steeper gradients; the name *telescope structure* is proposed for it (Fig. 2). Alluvial fans with telescope structure in the Indus basin are illustrated by Drew (1873, p. 454). Conspicuous development of telescope structure is shown in fans of the Santa Catalina Mountains, Arizona, the Black Hills, near Mammoth, Arizona (Pl. 1, fig. 2), and near Indian Garden Springs, Grand Canyon, Arizona.

Effects of Climatic Changes

Of all possible changes in climatic conditions, a variation in the amount of precipitation has the most profound effect on the development of alluvial fans. Increased precipitation results in dissection of fans and the development of a gentler gradient (Eckis, 1928, p. 237; Davis, 1938, p. 1349). In contrast, a decrease in precipitation may be responsible for a period of aggradation and the development of steeper gradients.

Telescope structure may be developed as a result of climatic changes. Individual levels of the telescope structure correspond to arid periods with their tendency for aggradation; the erosion cycles separating aggradation periods mark the humid stages with their tendency for erosion.

The development of telescope structure in alluvial fans at the southern base of the Santa Catalina Mountains, Arizona, is believed to have resulted from climatic changes. These fans formed in Pleistocene and Recent time during which climatic changes were numerous.

Climatic changes may exert an indirect influence on the development of alluvial fans by allowing a through-flowing stream to form at the base of fans. This stream may, in turn, control development of an alluvial fan by changing its base level. Thus, the San Pedro River, north of the Santa Catalina Mountains, Arizona, was a through-flowing stream during a late Pleistocene stage. Alluvial fans extending north from the Santa Catalina Mountains into the San Pedro Valley were dissected by the erosive action of the main river (Davis, 1938).

Effects of Tectonic Movements

Alluvial fans occur commonly at the base of up-faulted mountain blocks. Rejuvenation of tectonic activities along the same fault lines is a frequent phenomenon. Tectonic disturbance is believed the most important reason for changes on alluvial fans, in the opinion of Davis (1938, p. 1348).

If the relief between mountains and fans is increased by tectonic movements, a new stage of deposition may set in; alluvial fans with steeper gradients begin to form. For these newly deposited fans with steeper gradients the name *superimposed fans* is proposed. Superimposed and original fans do not exhibit distinct boundary lines, and morphologically they cannot be separated. In sections, however, a separation of the two different generations of alluvial fans may be possible (Fig. 3).

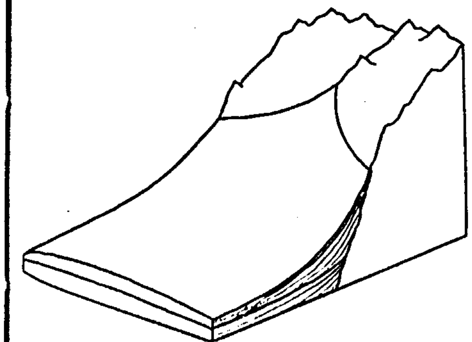

FIGURE 3.—SUPERIMPOSED ALLUVIAL FAN

If the relief between mountains and alluvial fans is decreased by tectonic activities, erosion will be active on the fans, and flatter gradients will be developed. Telescope structure may result. Recognition of rock pediments along the mountain front and their correlation with fan levels may indicate whether telescope structure in fans is due to tectonic movements or to other influences.

In cases where individual parts of an alluvial fan are subjected to tectonic movements, no generalization can be made, and the effects on fans depend on the location, the extent, and the nature of tectonic activities.

Effects of Slumping of Unconsolidated Fan Material

Slumping of unconsolidated fan deposits is a common cause for changes on alluvial fans (Gilbert, 1928, p. 12). An alluvial fan in Nevada on which the effects of slumping were observed is described by Longwell (1930, p. 8).

Slumping of alluvial-fan deposits is favored by the comparatively steep, original dip of strata, the presence of ground water acting as lubricant, the presence of layers with mud-sized constituents acting as sliding planes, and ample voids in coarse-grained layers allowing for considerable settling of strata.

Slumping of unconsolidated fan deposits is responsible for the development of *pseudo-telescope structure*. The difference from true telescope structure may be obvious only in favorable exposures (Fig. 4).

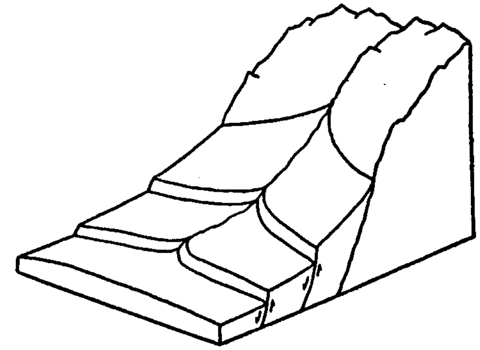

FIGURE 4.—PSEUDO-TELESCOPE STRUCTURE (Modified After Gilbert)

These are the main causes for changes taking place on alluvial fans. Several of these influences may be at work at the same time; their effects may enforce each other, or their tendencies may be opposite and tend to compensate each other. Therefore, the investigator may not always be able to ascribe a particular change in the development of an alluvial fan to any definite cause.

Secondary Alluvial Fans

These form at the base of primary fans. The deposits of secondary alluvial fans are mainly reworked primary fan deposits.

At the base of the large, primary fans at the southern flank of the Santa Catalina Mountains, Arizona, small, secondary fans are in the process of forming (Pl. 1, fig. 3).

GEOLOGY OF ALLUVIAL-FAN DEPOSITS

Facies

The facies of unconsolidated fan deposits are fan gravel, fan sand, and fan mud. The lithified equivalents are fanglomerate (Lawson, 1913, p. 17), fan sandstone, and fan mudstone.

Only one or two of these sedimentary facies normally are developed in an alluvial fan. Many alluvial fans in Arizona, southern California, and southwestern New Mexico show a unifacial, fanglomeratic development. In contrast, in small alluvial fans of the Black Hills of Arizona, only the sand facies is developed.

If alluvial fans are built up in dry regions, eolian deposits may be incorporated in the fluviatile deposits. In the Aubrey Valley, Arizona, sand dunes rest on the lower parts of some alluvial fans. Further building up of these fans may eventually incorporate the sand dunes within the alluvial-fan deposits (Blissenbach, 1952, p. 123).

Particle Sizes and Particle-Size Distribution

The particles in alluvial-fan deposits range from boulder to clay size. In general, coarse gravels predominate near the apex of an alluvial fan; material of intermediate particle size may occupy a central zone, and silts and clays in the area close to the base of a fan (Lawson, 1913, p. 330–331; Vaughan, 1922, p. 340; Troxell and others, 1942, p. 322).

Particle-size distribution curves along radial profiles of alluvial fans have been established by the writer for the fans examined. The distribution curve of particle sizes of an alluvial fan of the Santa Catalina Mountains, Arizona, was compiled from a great number of measurements of the maximum particle size (Fig. 5). This distribution curve is typical for alluvial fans; it shows the rapid change in particle sizes close to the apex of a fan. Available evidence indicates that the mean particle size behaves similarly.

Composition

The composition of alluvial-fan deposits is determined by:

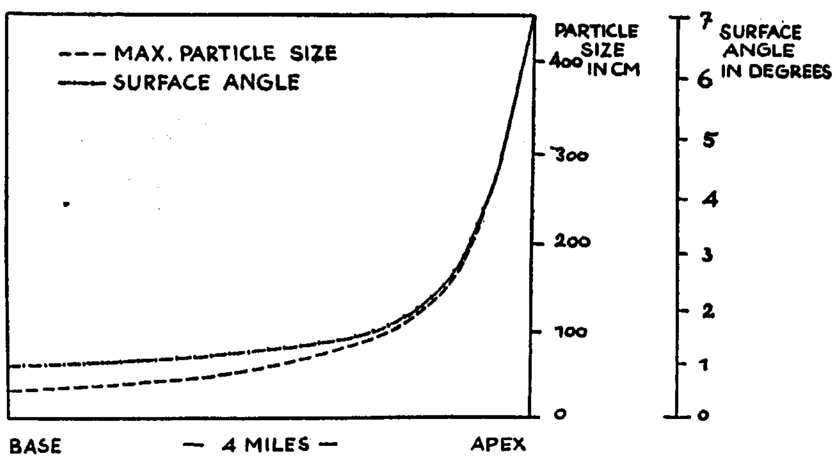

FIGURE 5.—DISTRIBUTION OF MAXIMUM PARTICLE SIZES AND SURFACE ANGLES ALONG A RADIAL PROFILE ON AN ALLUVIAL FAN OF THE SANTA CATALINA MOUNTAINS, ARIZONA

(1) the composition of the parent rock from which the fan deposits are derived;

(2) the type and degree of weathering to which the parent rock is subjected;

(3) syngenetic alterations during transport from the source to the site of deposition;

(4) epigenetic alterations effected after deposition.

In arid and semiarid regions, the action of mechanical weathering predominates over the action of chemical weathering. Therefore the composition of the detritus prepared for transport differs only slightly from the composition of the parent rock. In humid regions, however, considerable allowance must be made for alterations effected by the action of chemical weathering.

Syngenetic alterations have little influence on changes in the composition of fan deposits because both the distance of transport and the time during which the detritus is in contact with water are short. Epigenetic alterations are more effective, however. They include the addition of mineral constituents treated later under Cementation.

Based on the classification of compositional groups proposed by Short, McKee, and Jahns (1953), most alluvial-fan deposits belong to one of two compositional groups, the arkose and the graywacke. Mountains exposing plutonic or coarsely crystalline metamorphic rocks commonly exhibit alluvial fans of arkosic composition. In some places the fan deposits of the gneissic Santa Catalina Mountains, Arizona, show a percentage of feldspars twice as high as the minimum requirement of 20 per cent. Mountains composed of fine-grained metamorphic (mostly volcanic and sedimentary) rocks have alluvial fans with graywacke composition. Fans of the volcanic Tucson Mountains, Arizona, and those of the Aubrey Cliffs, Arizona, exposing sedimentary rocks are of this compositional type.

The composition of fan gravels does not appear to change considerably along a radial profile of a fan. Thus, at the apex of an alluvial fan of the Aubrey Cliffs, Arizona, the composition of fan gravels is 45 per cent sandstones and 55 per cent limestones; at the base of this fan the fan gravels are composed of 48 per cent sandstones and 52 per cent limestones. The slight difference in composition may be accidental, and no definite tendency in compositional change can be recognized.

In some areas fans of contrasting compositional types occur side by side because their apices head in different source rocks. This is illustrated in alluvial fans of the Aubrey Cliffs, Arizona, where large fans are fed from the Kaibab and Toroweap formations and adjacent small fans from the Coconino sandstone.

Sorting

Sorting of alluvial-fan deposits varies widely. In general sorting of alluvial-fan deposits may be regarded as a function of:

(1) the range in particle sizes of the detritus prepared for transport in a mountain area;

(2) the type of transporting and depositing agent;

(3) the distance of transport.

Detritus prepared for transport in a mountain area normally has a wide range in particle sizes. An exception to this trend is found in the Black Hills of Arizona, where the source rock of some alluvial fans is a plutonic rock of granitic texture which weathers to equigranular detritus. The breakdown of this parent rock to uniform particle sizes is responsible for the comparatively high degree of sorting in the resulting fan deposits.

There is considerable variation in the degree of sorting of alluvial-fan deposits depending on whether sheetfloods, streamfloods, or streams are responsible for forming a particular deposit.

Sheetfloods tend to accomplish the least amount of sorting (McGee, 1897, p. 106); Davis, 1938, p. 1344). The coefficient of sorting (Trask, 1932, p. 70) of a sheetflood deposit in a small alluvial fan of the Santa Catalina Mountains, Arizona, is about 3.0. Stream deposits, in contrast, show fair to good sorting. The coefficient of sorting of a stream deposit in a small alluvial fan of the Santa Catalina Mountains, Arizona, is 1.7. Streamflood deposits occupy a position in degree of sorting intermediate between that of sheetflood and of stream deposits.

Most alluvial-fan deposits have been transported only short distances and therefore are not well sorted. However, fairly good sorting of fan deposits may be expected near the base of large fans. Comparatively good sorting is also exhibited in secondary fans due to reworking and selective transport of detritus from primary fans. Thus, deposits of a small, secondary fan at the base of the large, primary Santa Catalina Mountain fans (Pl. 1, fig. 3) show a fair to good degree of sorting.

Roundness

A study of the roundness of fragments in alluvial-fan deposits was carried out on a fan at the southern base of the Santa Catalina Mountains, Arizona. Samples of 25 fragments of about equal size were obtained from 13 points along the radial profile of this fan; determination of the roundness was based on Krumbein's charts (1941, p. 68).

The minimum roundness of fragments in the Santa Catalina Mountain fan studied is 0.2, at the point closest to the apex of this fan; the maximum roundness is 0.7, at the point closest to the fan base (Fig. 6). The roundness distribution curve (Fig. 6) suggests that the function between the roundness of fan particles and the distance from the apex is approximately linear for this fan.

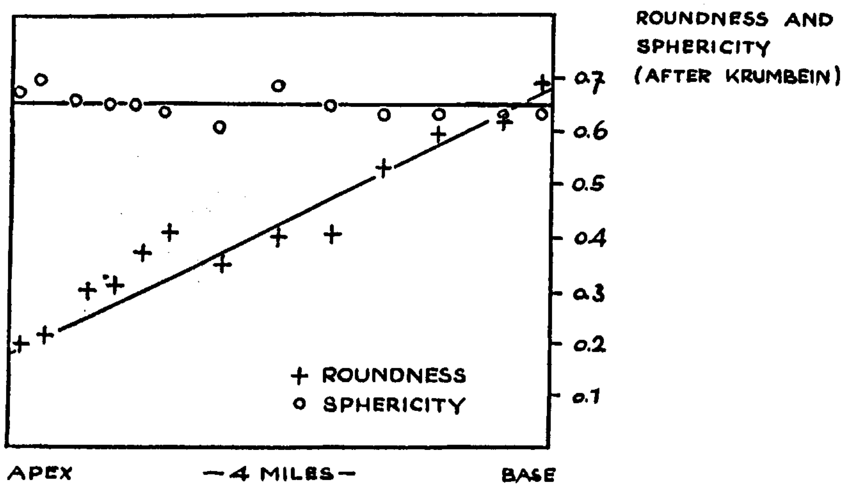

FIGURE 6.—DISTRIBUTION OF ROUNDNESS AND SPHERICITY OF ALLUVIAL FAN PARTICLES ALONG THE SAME RADIAL PROFILE AS FIGURE 5
Base of Santa Catalina Mountains, Arizona

As gneiss particles predominate in alluvial fans of the Santa Catalina Mountains, and as gneiss occupies an intermediate position between the extremely resistant and the highly soluble and friable rocks, a roundness distribution of fan particles in the Santa Catalina Mountain fans may serve as illustration for the normal change in roundness with distance from the apex. Based on the classification of roundness proposed by Short, McKee, and Jahns (1953), fragments of this fan may be described as angular, subangular, and subrounded. As the radial extent of alluvial fans may greatly exceed the 4-mile extent of the Santa Catalina Mountain fans, rounded fragments must be expected on larger fans. The common conception of alluvial-fan deposits being necessarily characterized by angularity of their fragments (Chawner, 1935, p. 259) must therefore be abandoned.

Pliocene gravel deposits at Blue Mountain, northwest of Seligman, Arizona, are described in a recent study by the writer (1952, p. 120). The Blue Mountain gravels were deposited in part on alluvial fans. The high degree of rounding observed in these gravels was attained by long transport in a floodplain environment (Koons, 1948, p. 59). Later faulting brought these gravels into a position from which they could be redeposited as fan gravels. Thus, the high degree of rounding in these fan gravels was not accomplished on an alluvial fan but in a floodplain environment.

Sphericity

Sphericity meansurements in alluvial-fan deposits of the Santa Catalina Mountains, Arizona, were made of the samples obtained for the determination of roundness. For the determination of the sphericity of fan particles, Krumbein's charts (1941, p. 66) were employed. The mean sphericity of particles in this fan is 0.65. The maximum and the minimum values of the sphericity of fan particles along the 4-mile extent of this fan deviate but 7 per cent from the value for the mean sphericity (Fig. 6).

No major change in the sphericity of fan particles is expected on any particular fan as long as there is no change in composition or facies of the fan deposits.

Matrix

Particles forming the matrix of alluvial-fan gravels range from sand to mud size. Finer particles predominate in the matrix of sheetflood deposits, coarser particles in that of stream deposits. A typical sample from the matrix of a sheetflood deposit of a small alluvial fan of the Santa Catalina Mountains, Arizona, shows a mean particle size of 0.15 mm. The mean particle size of the matrix of a stream deposit in the same alluvial fan is 0.7 mm.

The composition of the matrix in a fan deposit determines its compositional classification. Commonly the matrix is arkosic or graywacke.

A secondary matrix is a common feature in fan gravels. This results from removal of an original interstitial fill between fan gravels and later filling of interstices. This process may be seen in action on alluvial fans of the Santa Catalina Mountains, Arizona.

Cement

Calcium carbonate is the commonest cement in alluvial-fan deposits in most areas. It is precipitated from ascending or descending ground water and coats fan particles as solid layers or concretions, or is disseminated as minute calcite crystals in the matrix. If all available pore space is filled with calcium carbonate the cement may constitute up to 30 per cent of the volume of the composite fan deposit. Limonite cement is encountered in a few places in alluvial-fan deposits.

Color

The colors of alluvial-fan deposits are due largely to the types of rock of which they are composed, but they vary somewhat with the climate.

Mudflow deposits of alluvial fans of the Santa Catalina Mountains, Arizona, are light yellow; the interbedded stream deposits are a darker yellow. Where calcium carbonate cement is abundant, alluvial-fan deposits range from gray to white.

Porosity

The porosity in pebble lenses with loose packing, observed in a small, recent fan of the Santa Catalina Mountains, Arizona, was estimated to be 30 per cent. Owing to cementation the porosity in the deposits of older fans along these mountains does not exceed 15 per cent. The porosity of alluvial-fan deposits may attain any value between the above extremes and zero, as controlled by sorting, degree of packing, roundness of particles, compaction, and cementation.

In general poorly sorted mudflow deposits have low porosity; well-sorted stream deposits have high porosity.

Permeability

The permeability of alluvial-fan deposits depends on their porosity and, in addition, is a function of the size of interstitial space. In addition to their low porosity, mudflow deposits have small interstitial openings. Molecular forces therefore tend to retain water, and ground water cannot circulate freely. Thus, mudflow deposits are ideal aquicludes. In contrast, stream deposits in alluvial fans have comparatively large pore spaces which account for the case with which ground water can move through them. Stream deposits therefore are good aquifers.

Alluvial fans built up by streams and mudflows are, in terms of ground-water geology, "alternating aquifers and aquicludes". This property together with the original dip of the fan strata tends to make an alluvial fan an ideal site for the recovery of artesian water (Tolman, 1937, p. 364–365; Eardley, 1938, p. 1408).

Sedimentary Structures

Alluvial-fan deposits are laid down in beds approximately parallel to the surface of a fan. Thus, the surface angles of alluvial fans are repeated within the fan strata. The classification adopted for the angles of dip of a fan surface may also be applied to the dip of the strata in an alluvial fan; the dip may be described as steep, gentle, or flat.

The overall stratification of most alluvial fans is fair. In fans built up through their entire extent by mudflows, stratification may be poor. In general mudflow deposits form one solid layer. Mudflow deposits show distinct contacts with stream deposits (Fig. 7). Deposits laid down by streams or moderate streamfloods show good stratification; they are subdivided into thinner layers (Pl. 2, fig. 2). Where the mean particle size of these deposits allows such development, lamination is common.

Cross-stratification is well developed in deposits formed by streams on alluvial fans. feet. Most deposits laid down by streams on alluvial fans are in layers from 1 inch to 1 foot in thickness. Successive stream deposits may attain a vertical extent of several tens of feet.

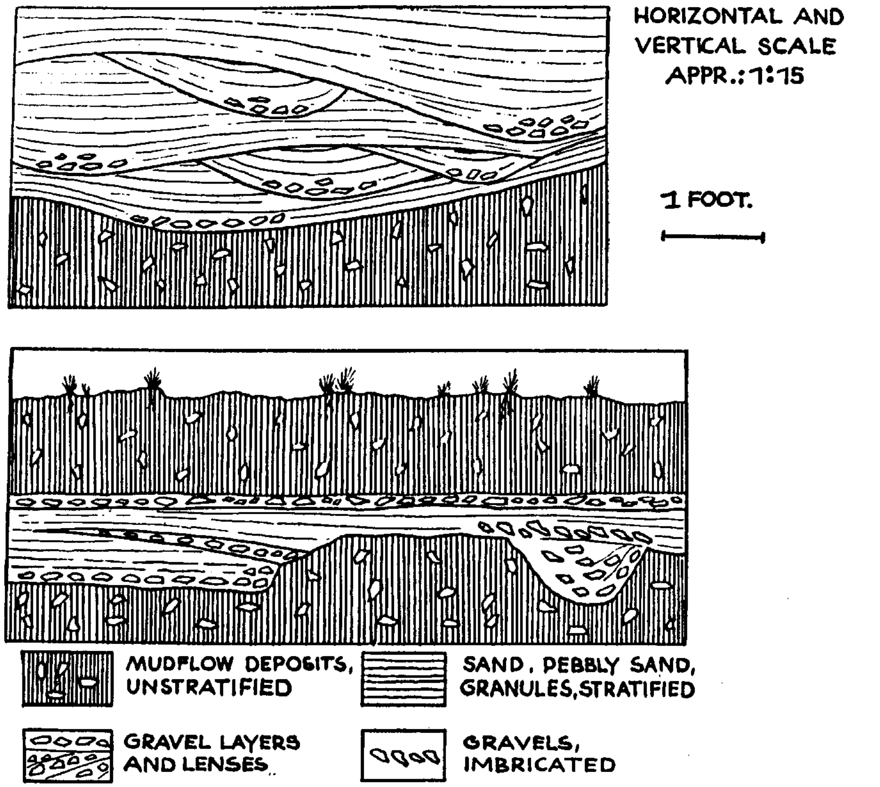

FIGURE 7.—CHARACTERISTIC SEDIMENTARY STRUCTURES IN AN ALLUVIAL FAN OF THE SANTA CATALINA MOUNTAINS, ARIZONA

Main direction of transport from right to left.

Current ripple marks may be present (Twenhofel, 1950, p. 71). The most common and conspicuous type of cross-stratification is due to the filling of channels that have been cut into the underlying deposits (Fig. 7; Pl. 2, fig. 2).

The thickness of individual strata in fans ranges from a fraction of an inch to 15 or 20 feet

Individual mudflow deposits range in thickness from 1 foot on small fans to 15 or 20 feet on large fans. Alternating mudflow deposits and series of stream deposits commonly are of comparable thickness.

Particles in mudflow deposits frequently stand on edge, and in all other normal positions

PLATE 1.—ALLUVIAL FANS

FIGURE 1.—COMPOUND ALLUVIAL FAN ON THE SOUTH FLANK OF THE SANTA CATALINA MOUNTAINS, ARIZONA

FIGURE 2.—SMALL ALLUVIAL FAN WITH TELESCOPE STRUCTURE, BLACK HILLS, ARIZONA

FIGURE 3.—SECONDARY ALLUVIAL FANS (S) AT THE BASE OF PRIMARY FANS (P), SANTA CATALINA MOUNTAINS, ARIZONA

FIGURE 1

FIGURE 2

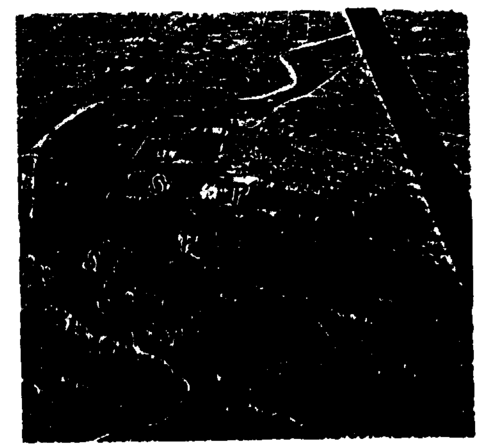

FIGURE 3

ALLUVIAL FANS

Figure 1

Figure 2

Figure 3

ALLUVIAL-FAN DEPOSITS

repose (Fig. 7; Pl. 2, fig. 1) they do not exhibit any preferred orientation. Imbrication is pronounced in deposits laid down by streams or moderate streamfloods wherever the shape of the particles allows such development. The gneissic bedrock of the Santa Catalina Mountains, Arizona, tends to break down to platy or disc-shaped fragments; therefore imbrication is distinct in certain fan deposits at the base of these mountains (Fig. 7). The disc-shaped fragments are inclined toward the site of derivation as might be expected within a fluviatile environment. The angle of inclination reaches a maximum of 30° among particles of pebble and cobble size; boulders, 100 to 200 cm in diameter, have no inclination greater than 15° (Pl. 2, fig. 3).

Stream and streamflood deposits are rudely lenticular. They are deposited in channels and follow in their extent the winding courses of the former channels. Sheetflood deposits, in contrast, are laid down in definite sheets. They terminate, however, with sharp, abrupt edges (Chawner, 1935, p. 256).

Organic Contents

Fossils are rare in the deposits of an alluvial fan, but there may be local occurrences of abundant fossils due to sudden floods which caused wholesale killing and rapid burial (Twenhofel, 1950, p. 71). Fossil animals were not found within the alluvial fans studied by the writer. Fossil plants or plant fragments, however, appear to be abundant in certain fan deposits.

Ancient Alluvial-Fan Deposits

Occurrence

Numerous occurrences of ancient alluvial-fan deposits are listed by Twenhofel (1950, p. 72). According to him, the earliest recorded alluvial-fan deposits are represented by some of the coarse sediments of the Huronian and some of the Keweenawan conglomerates and sandstones of the Lake Superior region. Alluvial-fan deposits have been recognized in many younger sedimentary formations in all parts of the world.

Relative Abundance

The failure to recognize alluvial-fan deposits in the geologic column to the extent they are known among Recent sediments may be explained by the following factors:

(1) The bold relief necessary for the development of alluvial fans was not present in many parts of the geologic past (Barrell, 1925, p. 292).

(2) A combination of bold relief and aridity favorable for the building of alluvial fans was not common in the geologic past (Lawson, 1913, p. 334).

(3) The dominance of land, as in the Quaternary, is exceptional in geologic history (Lawson, 1913, p. 334).

(4) The process of peneplanation eroding the mountains to their roots also affects the alluvial fans adjacent to the mountains and tends to remove them. Only where some unusual feature such as extensive downfaulting, like that involving the Newark series, has protected the alluvial-fan deposits from further erosion may they be preserved.

Alluvial-fan deposits have not always been described as such but have been classified as angular conglomerates or sedimentary breccias (Lawson, 1913, p. 333). In the opinion of the present writer, the misconception common in geologic literature that fan deposits are necessarily unstratified, composed of highly angular particles, poorly sorted, and without distinctive

Plate 2.—ALLUVIAL-FAN DEPOSITS

Figure 1.—Fanglomerate Deposited by Mudflow

Poor sorting, random orientationof particles. Largest particles in picture are 10 centimeters in diameter. Santa Catalina Mountain fans, Arizona

Figure 2.—Fanglomerate Deposited by Stream or Moderate Stream-Flood

The effect of channel cut-and-fill is pronounced. Ruler is 15 centimeters. Main direction of deposition from left to right. Santa Catalina Mountain fans, Arizona.

Figure 3.—Imbrication in Large Particles

Up to 15° centimeters. Direction of transport from right to left. Close to the apex of an alluvial fan of the Santa Catalina Mountains, Arizona sedimentary structures may in part be responsible for such classification.

Criteria for Recognition of Ancient Alluvial-Fan Deposits

The following criteria can be applied where erosion or tectonic movements have obscured the original surface of a deposit. The recognition of an ancient alluvial-fan deposit must rest on a number of criteria.

The facies of alluvial-fan deposits is coarse detrital as a rule but may be fine detrital under exceptional conditions. Individual particles in these deposits may range from boulder to clay size. A rapid change in the maximum or the mean particle size suggests an origin on an alluvial fan. The presence of sheetflood deposits makes such an assumption more probable. Arkoses and graywackes are the compositional groups in which alluvial-fan deposits commonly range.

The coefficient of sorting (Trask, 1932, p. 70) of fan deposits may range from about 1.5 to 3.0. Fragments in alluvial-fan deposits are angular, subangular, subrounded, and rounded. The change in roundness is rapid close to the area of derivation.

The matrix of fan gravels is sand or mud in size; arkose or graywacke in composition; of primary or secondary origin. The original dip of fan strata may be steep, gentle, or flat. Alluvial-fan deposits have good to poor stratification depending on the relative abundance of unstratified mudflow deposits and stratified stream deposits. Channel cut-and-fill is common in the deposits formed by streams and moderate streamfloods. In these sediments imbrication is pronounced; particles are inclined toward the site of derivation; the inclination commonly does not exceed 30°.

The thickness of individual fan strata ranges from a fraction of an inch to 15 or 20 feet. Stream and streamflood deposits follow the winding courses of former channels; sheetflood deposits form definite sheets.

In some places the fanhead area may be in contact with a talus slope, and in these places fan deposits may be expected to interfinger with talus-slope deposits. The following characteristics of talus-slope deposits may help to separate these sediments from the strata of an alluvial fan. Talus-slope deposits are almost devoid of sedimentary structures as deposition takes place by gravitational sliding. Particles are larger than those found in the adjacent fan deposits. Roundness of talus-slope particles is expected to be of a low degree. Platy fragments may be arranged parallel to the former surface of a talus slope whose original dip may range from 10° to 30°.

At the base of a fan the deposits of an alluvial fan may interfinger with the sediments of a floodplain or a playa lake. The deposits of a playa lake are easily distinguished from the fan deposits as they comprise sediments of clay size and chemical deposits both of which are uncommon or absent in alluvial-fan strata. Floodplain deposits have better stratification than those of alluvial fans; mudflow deposits are uncommon in a floodplain environment. Sorting of the deposits and rounding of sedimentary particles are likely to attain better values in a floodplain than on an alluvial fan. Floodplain deposits are laid down at angles commonly lower than 1°.

This discussion offers some suggestions for the recognition of the climatic conditions under which an ancient fan deposit was formed. With increased precipitation, mudflow deposits become progressively less numerous. From findings on recent alluvial fans it appears that no mudflow deposits are expected in alluvial-fan strata if the mean annual precipitation exceeds 20 or 25 inches. If mudflow deposits make up 50 per cent of an alluvial fan, 5 to 15 inches of annual rainfall appears to be a conservative estimate for the climate under which these fans were formed. The types of rainfall and their distribution through the year as well as the relative abundance of vegetation are factors which control the development of certain types of deposits, in addition to the total amount of precipitation.

Abundance of mudflow deposits in an alluvial fan does not necessarily imply the forming of this fan in a tropical or hot, arid region; it may have been formed in zones with moderate temperatures or even in periglacial environment. Conspicuous development of mudflow deposits may be expected especially along the margins of glaciated areas where they is no movement of water during the colder season and a sudden release of abundant water with the beginning of a warmer season. Fragments in these deposits probably bear ample evidence in their surface texture as to their source within the glaciated area.

Humid conditions during the formation of an ancient alluvial fan may be assumed if the composition of the deposits of the fan is considerably different from that of the parent rock indicating a predominance of chemical over mechanical weathering.

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