THE GEOLOGY OF ALLUVIAL FANS IN ARIZONA

by

Erich Blissenbach

A Thesis

submitted to the faculty of the

Department of Geology

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

in the Graduate College, University of Arizona

1951

Approved: Edwin D. McKee, Sept. 20-1951

Director of Thesis   Date

CONTENTS.

ILLUSTRATIONS.

Plates

Plates

Figures

Figures

Tables

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 semi-arid climate favorable for the development of fans.

The depositing agents are (1) sheetfloods, (2) streamfloods, and (3) streams.

Compound alluvial fans result from lateral coalescence of single fans.

Development of alluvial fans is affected by (1) changes in the course of a cycle, (2) varying base-level, (3) climatic changes, (4) tectonic movements and (5) slumping of fan deposits. Telescoped or superimposed structure may be developed.

Fan deposits are arkosic or graywacke in composition. 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 twenty feet thick. Particles in stream deposits are imbricated.

Many ancient fan deposits may have escaped recognition because of the common misconception that fan deposits are necessarily (1) unstratified, (2) composed of angular fragments, (3) poorly sorted, and (4) without distinctive sedimentary structures.

The rate of change in surface slope of alluvial fans

equals their rate of change in particle sizes.

Different fan levels developed on alluvial fans of the Santa Catalina Mountains, Arizona, are believed to result from climatic changes.

INTRODUCTION.

Purpose of investigation. This paper gives the results of a comprehensive study of alluvial fans. Though detailed field work was carried out only in Arizona most of the results of the investigation may be applied to alluvial fans in other parts of the world where similar conditions prevail. Thus, through detailed study of recent alluvial fan deposits, geologists may be aided in determining whether certain ancient rocks were formed under similar conditions.

A classification of alluvial fans at the end of this paper attempts to recognize different types of fans based on their external shape and their origin and to facilitate further descriptions of alluvial fans.

Method of investigation. Certain alluvial fans were studied in every detail, whereas other fans were selected for examination because they demonstrated one certain property. Detailed descriptions of the methods involved are taken up under the respective chapters. The results obtained by the writer are compared to the findings of previous investigators.

Acknowledgements. The aid and counsel of the members of the faculty of the Department of Geology, University of Arizona, Tucson, particularly Professor Edwin D. McKee, under whose guidance this work was undertaken, is sincerely appreciated.

AREAS OF FIELD STUDY.

Tucson Area.

Santa Catalina Mountains. This mountain range is situated about eight miles to the north and northeast of Tucson, Arizona (pl.III). From the mountain front alluvial fans extend to the north into the San Pedro Valley and to the south into the Tucson basin. Two fans at the southern base of this mountain range were subject to special investigation. In general these alluvial fans are from three to four miles in their radial extent. The difference in elevation between apex and base averages 600 feet.

Numerous steep-walled washes dissect the fan surfaces. Alluvial fans from adjacent canyons interfinger laterally. The boundary between alluvial fans and floodplain is formed by the Rillito Creek running parallel to the mountain range.

One fan at the Santa Catalina front was subject to a detailed study including its history (pl.I; appendix "A") while another was used to demonstrate sedimentary structures (pl.II).

Tucson Mountains. This mountain range is located about five to ten miles to the west and northwest of Tucson, Arizona (pl.III). Alluvial fans extend some two or three miles from the mountain front into the surrounding plain. These fans are moderately dissected and form only a thin cover of alluvial material on the underlying bedrock.

Studies on alluvial fans of the Tucson Mountains were carried out in order to determine the relation between surface angles and particle size distribution.

Mammoth Area.

Black Hills. These mountains are located to the west of Mammoth, Arizona (pl.III). Alluvial fans are conspicuously developed on both sides of an intermontane valley.

Investigations in this area included studies on the overall structure of fans and the degree of sorting in the fan deposits.

Aubrey Valley.

From the cliffs on both sides of the Aubrey Valley, northwest of Seligman, Arizona (pl.III), alluvial fans extend into the valley. Their radial extent is from one to two miles.

The composition of fan deposits, the relation of surface angles of the fans to the particle size distribution and the effect of wind deflation on alluvial fans were studied in this area.

Grand Canyon.

Small alluvial fans are conspicuously developed on both sides of the Bright Angel Trail, Grand Canyon, Arizona (pl.III).

Studies on the overall structure of alluvial fans were carried out on these fans.

A few observations on alluvial fans were made in southern California and southern New Mexico.

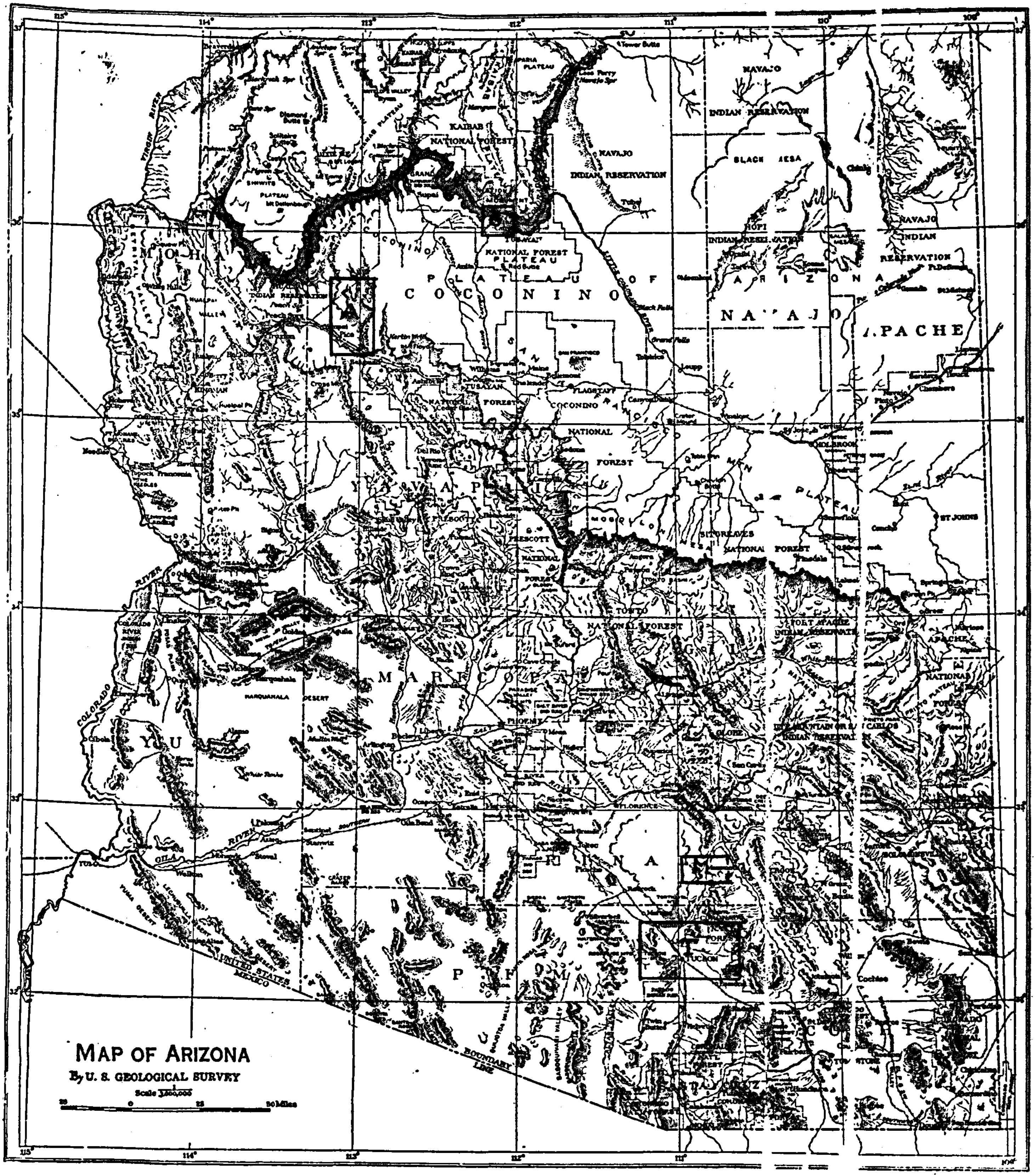


Plate III. Areas of Field Study in Arizona. T - Tucson Area, M - Mammoth Area, A - Aubrey Valley, G - Grand Canyon.

Part I. GEOLOGY OF ALLUVIAL FANS IN GENERAL.

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 as a result of the tendency of all streams to form a graded course. A talus slope differs from an alluvial fan in that it is built up by gravitational sliding and without the action of running water; sedimentary structures are absent.

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.

The term 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 alluvial fan.

Base of an alluvial fan is the term applied to the outermost or lowest zone of the fan.

GEOGRAPHICAL DISTRIBUTION OF RECENT ALLUVIAL FANS.

The occurrence of alluvial fans has been reported from America, Europe, Asia and Australia. They doubtless occur on all continents.

In Europe alluvial fans have been described at the northern base of the Pyrenees and on both sides of the Alps (Penck,1894; Grabau,1913a; Thompson,1947). The Australian continent exhibits alluvial fans in the southern and central parts (Petermann,1867; Grabau,1913a), while on the Asiatic continent alluvial fans related to the Himalayan mountain range are conspicuous (Drew,1873; Oldham,1893; Grabau,1913a).

Alluvial fans are abundant in the southwestern United States of America. Probably more than half the area of the state of Nevada is occupied by alluvial fan deposits and they are the most extensive deposits encountered in large parts of Utah, New Mexico, Arizona, California and Mexico (Lawson, 1913).

Due to conspicuous development and easy accessibility, alluvial fans have been subject to more detailed studies in California than anywhere else (Lawson,1913; Eckis,1928; Krumbein,1937; Buwalda,1951).

MORPHOLOGIC SHAPE.

Investigators generally have agreed that an alluvial fan resembles geometrically the segment of a cone. From the apex of the fan the surface dips towards the base of the fan toward which the dipping angles gradually become flatter. Thus, a radial profile through the fan is concave upward (Lahee,1941,p.381), a profile at right angles convex (fig.1; pl.VI,A,B). The slope of an alluvial fan near its base asymptotically approaches the slope of the bordering morphologic unit which may be a playa lake or a floodplain with almost horizontal surface. In contrast, the steepest angle of dip on the alluvial fan surface is encountered close to its apex.

Most investigators agree that the dipping angle of an alluvial fan rarely exceeds 10 degrees (Dana,1894,pp.194-195; Eckis,1928,p.223; Scott,1932,p.269; Eardley,1938, p.1408). Some authors report no dipping angle greater than 5 or 6 degrees (Lawson,1915,p.25; Vaughan,1922,p.341). In the humid Indus basin alluvial fans exhibit dipping angles of the same order as those reported from arid Southwestern America (Drew,1875,p.441). According to Grabau (1913a, p.584) the maximum slope may reach values from 20 to 30 degrees. The present writer believes that at such steep angles the effect of purely gravitational sliding will be predominant, thus forming deposits of a talus slope rather than those of an alluvial fan.

Field studies by the writer in the parts of Arizona discussed in this paper show that the maximum angle of dip of the alluvial fan surfaces ranges from 5 to 9 degrees. On small alluvial fans like those of the Black Hills in the Mammoth area, Arizona, with a radial extent of several hundred feet, surface angles greater than 5 degrees are characteristic of the upper half or more of the alluvial fan. Large alluvial fans such as those of the Santa Catalina Mountains, with a radial extent of about four miles, exhibit surface angles greater than 5 degrees only within the upper one twentieth of their extent (fig.10).

At numerous places in geologic literature small alluvial fans with steep slopes are 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 slope of alluvial fans or parts of them.

Because angles of dip greater than 5 degrees are rare these are called steep. Angles of dip between 2 and 5 degrees are termed gentle and sloping angles below 2 degrees flat. On the basis of these definitions the slopes of alluvial fan surfaces can be described as follows :

(1) Alluvial fans of the Santa Catalina Mountains, Tucson area, are about 4 miles in their radial extent. The upmost one twentieth of the radial extent of the fan has steep slopes. Of the adjoining area, about one sixth is gently dipping, while the remaining part which is slightly more than three fourths of the fan, has flat angles of dip on its surface (fig.10).

(2) On an alluvial fan of the Aubrey Valley with a radial extent of one mile the upper one fifth of the fan surface exhibits steep slopes and the remaining four fifths has gentle angles of dip.

The surface angles of alluvial fans studied by the writer are further dealt with in part III of this paper (fig.14,15 and 16).

DIMENSIONS.

The radius of an alluvial fan may be as great as 40 miles under exceptional conditions (Grabau,1913a). Eckis (1928,p.224) reports alluvial fans from 15 to 20 miles in extent. The radii of alluvial fans studied by the writer range from 4 miles at the base of the Santa Catalina Mountains to about 500 feet in the Black Hills near Mammoth, Arizona.

By lateral coalescence of single alluvial fans, a compound alluvial fan may result (Miller,1926,pp.164-166; fig.2; pl.IV,A,B; pl.V,A,B). The compound alluvial fan is equivalent to the alluvial piedmont slope (Lahee,1941,p.318) and the "bajada" (Blackwelder,1931,p.136). The lateral extent of such a compound fan is controlled by the size of the mountain range.

Alluvial fans may be one thousand feet or more in thickness (Eckis,1928,p.224). Scott (1932) considers the thickness to be greatest near the apex. That this is not necessarily so is shown by alluvial fans of the Santa Catalina Mountains the thickness of which range from one hundred feet near the apex to about two or three hundred feet at their present base (pl.I,profile a-b).

MODE OF OCCURRENCE AND REQUIREMENTS FOR THE FORMING OF ALLUVIAL FANS.

Alluvial fans are limited in their occurrence to areas of bold relief, and their development is most conspicuous under the conditions of arid and semi-arid climate. This conclusion has been reached by the majority of investigators (Lawson,1913; Longwell,Knopf,Flint,1932; Emmons,Thiel, Stauffer,Allison,1949).

The influence of high relief seems to be 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. Because boldest relief is produced by large-scale displacement along steeply dipping fault planes, optimum development of alluvial fans is found under these conditions. The majority of fans studied during the present investigation are related to large-scale, high-angled faults.

Lawson (1915,p.28) mentions that practically all reductions of rock slope and contributions to alluvial embankment are affected by brief and infrequent periods of downpour. This type of precipitation is characteristic of areas with arid and semi-arid climate (Miller,1926,p.166). Under humid conditions alluvial fans are also developed as it is seen along the Alps and the Himalayas. Fans formed in humid environment commonly are smaller, flatter and less conspicuous than alluvial fans of arid regions such as the southwestern United States. 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 exhibiting predominantly the effects of gravitational sliding. Thus, the climatic conditions most favorable for the development of alluvial fans appear to range from moderately arid to semi-arid. Eckis (1928,p.225) mentions the annual precipitation on an alluvial fan studied by him as averaging about 17 inches. Alluvial fans studied by the writer receive a mean annual precipitation of about 15 inches, ranging from an average of about 11 inches in the Tucson area to about 19 inches in the Mammoth area (Smith,H.V., 1945,pp.15,89).

Dividing the requirements for the forming of alluvial fans into essential conditions and favorable conditions, it may be stated that :

(a) bold relief appears to be essential,

(b) moderately arid to semi-arid climate is favorable.

THE PROCESS OF FORMING OF ALLUVIAL FANS AND THE DEPOSITING AGENTS.

The physiographic pattern. 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. The stream channels commonly are shallow, entrenched but little beneath the gently sloping surface of the 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 (Twenhofel,1939,p.66). Smaller streams up-fan tend to join bigger ones down-fan and the resulting physiographic pattern constitutes a reversal of the braiding stream system focused in the apex of the fan.

The process of forming of alluvial fans. 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. During dry intervals abundant detrital material is prepared for transport by the action of mechanical weathering.

On reaching the apex of an alluvial fan the flow of water carrying the detrital material occupies one or more channels of the braiding stream system. When the flow meets the alluvial fan surface and its channels, a pronounced tendency for deposition is immediately developed. This trend is mainly due to:

(a) a less steep gradient encountered on the alluvial fan whereby the velocity of the flow is retarded and deposition favored, and

(b) the pervious nature of the alluvial fan deposits which allows the volume of water to decrease continuously and thus develop a depositional tendency.

The foregoing explanation shows why channels on alluvial fans frequently are silted up causing overflows and the forming of new distributaries. When one sector of a fan has been built up, the stream shifts to another, lower section and builds that up (Longwell,Knopf,Flint,1948,p.88). The process of sedimentation as described is repeated again and again till the mountain stream and the alluvial fan have reached graded conditions.

Upon accomplishment of such a state of equilibrium, the full maturity of an alluvial fan is achieved. Older stages in the development of alluvial fans are dealt with later.

The similarity of alluvial fan deposits to those of deltas formed in standing bodies of water has lead investigators to refer to alluvial fans as dry deltas (Grabau,1913b, p.401).

The depositing agents. Through-flowing streams are characteristically developed in humid regions, intermittent and infrequent flows form in arid and semi-arid regions. Because alluvial fans are most conspicuously developed in arid and semi-arid regions short, violent flows normally constitute the transporting and depositing agents responsible for the development of fans.

Flows of intermittent streams on alluvial fans may be classified into the three following types :

(a) Sheetfloods. These occur when an exceedingly large amount of water emerges from the channel of the mountain stream and when this flow is loaded to capacity with detritus. The amount of water available, together with the load of sediment, must greatly exceed the capacity of the channels on the alluvial fan. Thus, a considerable amount of water may sink rapidly into the pervious ground but still an excess in the volume of the flow over the volume of the channels is present. If such an excessive recharge is maintained, the flow, acting like a viscuous medium, tends to spread out in the form of a sheet covering the alluvial fan or parts of it.

Sooner or later the recharge ceases to be excessive and deposition of the detrital material carried by the sheetflood results. Commonly a big percentage of the detrital material transported and deposited is composed of mud-sized particles and for this reason the term mudflow for such sheetfloods is in common usage.

The first comprehensive work on the phenomenon of sheetfloods is by McGee (1897,pp.87-112). He believes that the amount of precipitation, the quantity of detrital material available for transport, the slope of the surface and a suitable interrelation of the foregoing factors are the essentials for the development of a sheetflood.

Blackwelder (1928) stresses the importance of mudflows, and presents ample evidence of their action in the deposition of alluvial fans. Davis (1938) states that deep channels on an alluvial fan would tend to prevent sheetfloods. Furthermore, he believes that the graded state of compound alluvial fans is effected largely by such sheetfloods (pl.V,B).

One of the most striking peculiarities of sheetfloods is the shortness in distance as well as in time of their flows (Davis,1938,p.1344). Great floods of this type may come only at intervals of decades or centuries (McGee,1897,p.108).

Sheetflood deposits are distinguished from sediments of certain other depositing agents by their wide areal extent.

Deposits within the alluvial fans of the Santa Catalina Mountains and the Black Hills suggest that they may have been deposited by sheetfloods (pl.V,B). Other fans studied by the writer did not offer exposures in which evidence of a possible participation of sheetflood deposits within the fans could be examined.

(b) Streamfloods. These are confined to definite channels on alluvial fans. They are formed where the amount of water emerging from the mountains and the detrital material available are less than in the case of a sheetflood.

Streamfloods also may form because channels on the alluvial fan are too deep and broad to allow a sheetflood to develop.

The spasmodic and impetuous character of these floods is such that the term streamflood rather than stream is applied (Davis,1938,p.1347). The material carried by such streamfloods is deposited largely because of the continuous loss of water through sinking into the pervious bottom of stream channels.

The deposits of spasmodic streamfloods tend to be identical with those laid down by sheetfloods except that, instead of being blanket-shaped, they are linear in plan view. Because of their similarity in composition streamflood deposits commonly also are referred to as mudflow sediments.

Recently Buwalda (1951) stressed the importance of mudflow deposits in channels on alluvial fans.

Alluvial fan deposits in different parts of Arizona studied by the writer suggest that they were formed in part by the action of streamfloods.

(c) Streams. These form if both the amount of water and the quantity of detritus available for transport are moderate. Detrital material carried by the flow will be deposited as the volume of the flow decreases due to sinking of water into the peryious bottom of the wash. In order to develop this type of flow a steady, rather than an abundant supply and recharge of water from the mountains must be maintained.

Minor significance may be attached to the action of streams on alluvial fans under semi-arid to arid conditions for these do not favor their development. In relatively humid regions, however, as in the Alps or the Himalayas, alluvial fan deposits laid down by streams are of considerable magnitude.

Stream deposits are of linear shape. Several of the fans studied by the writer suggest that streams participated on a small scale in their development.

Every possible gradation from one to another of the above three types of depositing agents must be expected on fans. Similarly, the deposits of these fans may exhibit gradations that cannot be ascribed to one definite depositing agent. Streamflood sediments especially exhibit gradations ranging from those formed during a violent flow to others formed by floods of moderate intensity.

Any one alluvial fan may not show the effect of all three types of depositing agents. For example, some alluvial fans may not contain mudflow deposits (Blackwelder,1928, p.473). 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 and minutes (McGee,1897,p.101), that of streamfloods in minutes or hours, and the flow of streams in hours or even days.

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

A summary of the depositing agents and some of their characteristics is presented in table I.

TABLE I.

The transporting and depositing agents on alluvial fans.

Agent	Shape of flow	Duration of flow	Volume of water and detritus
Sheetfloods	areal	seconds or minutes	large
Mudflows			
Streamfloods	linear	minutes or hours	moderate
Streams	linear	hours or days	small

<u>Lateral arrangement of alluvial fans.</u> By the lateral interfingering of alluvial fans from adjacent canyons a compound fan is formed (fig.2; pl.IV,A,B; pl.V,A,B). Commonly the single fans building up the compound type are of equal size and the contact between the mountain front and the compound fan is a rather regular, zig-zag line. Most of the compound fans studied by the writer exhibit such a pattern.

In some places, however, as in parts of the Aubrey

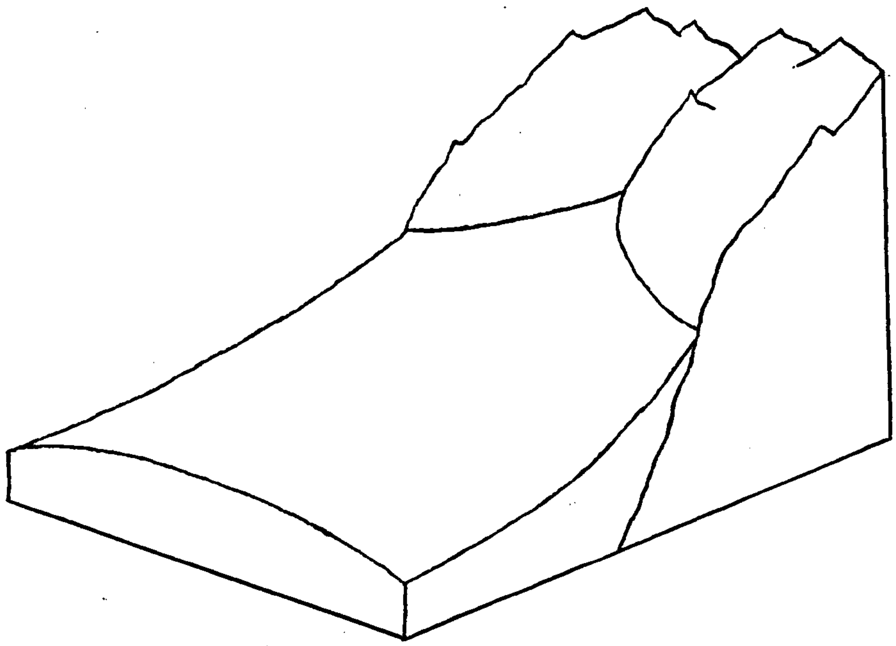


Fig.1. Single Alluvial Fan

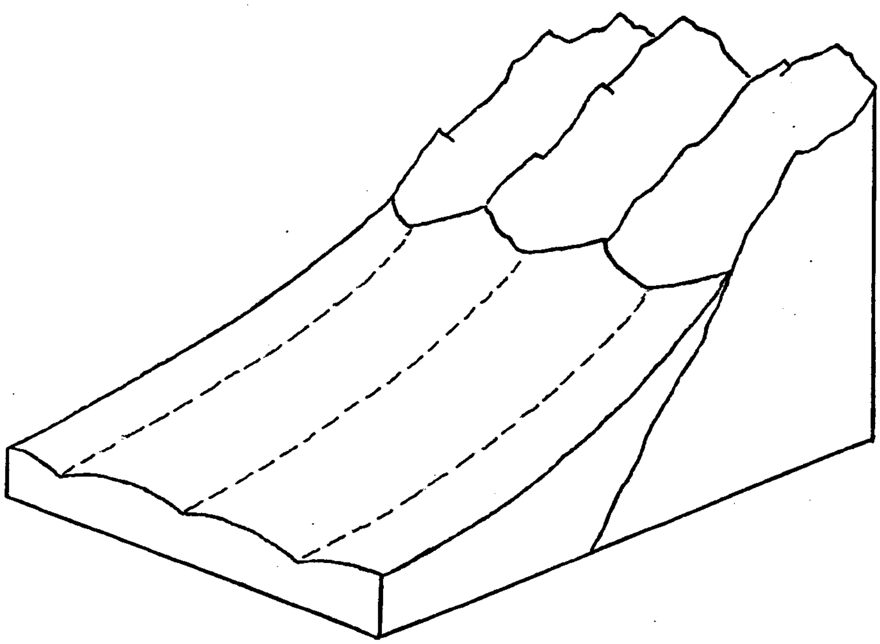


Fig.2. Compound Alluvial Fan

Valley, larger alluvial fans alternate laterally with smaller fans. The larger fans build faster into the valley and thus interfinger laterally. The smaller fans, on the other side, develop at places left vacant by the larger variety of fan. Thus, a pattern is developed which resembles a chessboard.

The development of such a chessboard pattern is due to a lateral alternation of larger and smaller canyons. The resemblance of such a compound fan to a chessboard pattern is intensified if the intake areas of the larger and the smaller canyons cover different rock formations whereby the resulting larger alluvial fans are different in color from the smaller ones. Chessboard pattern of this type is well demonstrated in the compound fans along the Aubrey Cliffs (fig.3).

LATE STAGE DEVELOPMENT.

For the following discussion it is assumed that an alluvial fan has been built up by the processes previously described and that a graded condition between the mountain canyon and the alluvial fan has been reached.

Changes in the normal course of a cycle. Until graded conditions are reached, erosion will predominate 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 further down-fan.

The change from deposition to erosion in the fanhead area is gradual so the development of conspicuous fan remnants can hardly be expected. Well-rounded hills in the fanhead area may give a faint indication as to the original fan level. Changes of this kind are ever-present once the maturity of a fan is reached. Other changes, due to tectonic disturbance or changing climatic conditions or varying base-level are merely superimposed on the normal change in the course of the cycle. The importance of such a change within the cycle was first realized by Eckis (1928,p.237).

After the development of bold relief, as the initial stage for the forming of an alluvial fan, the mountain front recedes. This recession caused by physical back-weathering (Lawson,1915; Davis,1938) or by lateral erosion of streams (Johnson,1932) leaves a more or less smooth rock surface normally covered by the upper parts of an alluvial fan. This rock surface is commonly called a rock pediment (pl.VIII,B).

With the removal of material in the fanhead area due to a normal change in the cycle, the rock pediment may be stripped of its alluvial cover and become exposed. Normally the rock pediment is of more consolidated nature than the alluvial fan deposits and thus, the rock pediment may attain a morphologic shape which indicates the extent of an alluvial fan at its maturity.

The results attained by a single alluvial fan can also be developed on a compound type of fan. The normal change in the 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 a function of the size of the mountain stream and its gradient, factors which may vary considerably between different units of the same compound fan.

The compound fan at the southern base of the Santa Catalina Mountains is more heavily dissected along its eastern lateral extent than in the west. Davis (1931,p.299) ascribed the different degree of erosion to differences in later tectonic disturbance. The possibility of tectonic movements is admitted, however, there seems to be no necessity for such an assumption. Streams along the eastern parts of the range are larger and therefore the accomplishment of the maturity of alluvial fans and their late stage development is accelerated in these areas. Slow development of alluvial fans and similarly slow change in the cycle must be expected along the western parts of the compound fan where mountain streams are comparatively small.

<u>The effects of aggrading base-level.</u> Building up of the base-level is commonly affected by a stream flowing along the base of an alluvial fan. Aggradation of the base-level, if

slow, does not show pronounced effects on the alluvial fan. The erosional tendency moving down-fan may be compensated by the aggrading tendency moving up-fan from the base.

Fast aggradation at the base of the fan, however, may transmit a depositional tendency up-fan and over the whole extent of the fan. The apex of the fan then migrates into the mountain canyon. The fanhead area reaching into the mountain canyon is sometimes called a fan-bay (Davis,1938).

A resemblance of fan-bays to drowned valleys or fiords is remarkable. The common cause for the formation of both fan-bays and fiords is a rise in base-level under terrestrial and marine conditions, respectively.

The effects of degrading base-level. Erosion of a stream at the base of an alluvial fan results in pronounced erosion of the lower parts of the fan close to the eroding stream at the base. Erosion works up-fan and finally covers the whole extent of the fan to the apex.

Available evidence indicates that several of the alluvial fans studied by the writer are affected by strong dissection due in part to the cutting in of a stream at the base of the fans.

In a recent study (1951) the writer describes alluvial fans in the Aubrey Valley which do not gradually merge into the floodplain but terminate with a rather pronounced drop to form a distinct boundary between fans and floodplain. The absence of stream channels along this boundary line and the presence of recent sand dunes nearby suggest that the base of these alluvial fans has been subject to wind deflation. Subsequent to forming this relief, precipitation on the fans and their intake area probably has not been high enough to allow streams on the fans to cut down to the lower base-level. Dissection of these fans will result, however, as soon as an adequate supply of water is received by the fan streams.

The effects of the lateral swing of a river at the base of the fan. An account of the erosional effect on an alluvial fan of the undercutting of its base by a river is given by Eckis (1928,p.237). Davis (1938,pp.1349-50) states that 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, the alluvial fan is strongly dissected.

Thus, the undercutting of the base of a fan results in erosion on the fan. In contrast, a lateral swing of the river away from the fan base may favor depositional tendencies and the graded condition of the alluvial fan may be restituted.

A small alluvial fan of recent age at the base of the compound fan of the Santa Catalina Mountains (pl.II) is built up of alternating layers of stream and mudflow deposits. Erosion and deposition on this fan is controlled by lateral swinging of the Rillito Creek at the fan base.

Each stream deposit and overlying mudflow deposit is believed to constitute one cycle of deposition. At times when the Rillito Creek swung towards the base of the fan, erosion resulted on the fan and deep channels were formed. With the beginning of river migration away from the base, these channels were filled by stream and streamflood deposits. Subsequently, upon accomplishment of graded conditions again, sheetfloods may have once more contributed to the building up of the fan.

A peculiar overall structure may be developed in fans as a result of lateral swinging of a river at their bases. This structure, which is characterized by younger fans with flatter gradients spreading out from between remainders of older fans with steeper gradients, will be called <u>telescope structure</u> (fig.4).

In the Indus basin, alluvial fans with telescope structure are described by Drew (1873,p.454). In the Santa Catalina Mountains a small alluvial fan at the base of the compound fan examined in this study is slightly telescoped. Conspicuous development of telescope structure is shown in alluvial fans of the Black Hills, Arizona (pl.VI,A,B), and in fans near Indian Gardens, Grand Canyon, Arizona.

The degree of development of telescope structure is a function of the ratio of the amplitude of the lateral swing of the river to the radial extent of the alluvial fan. Thus,

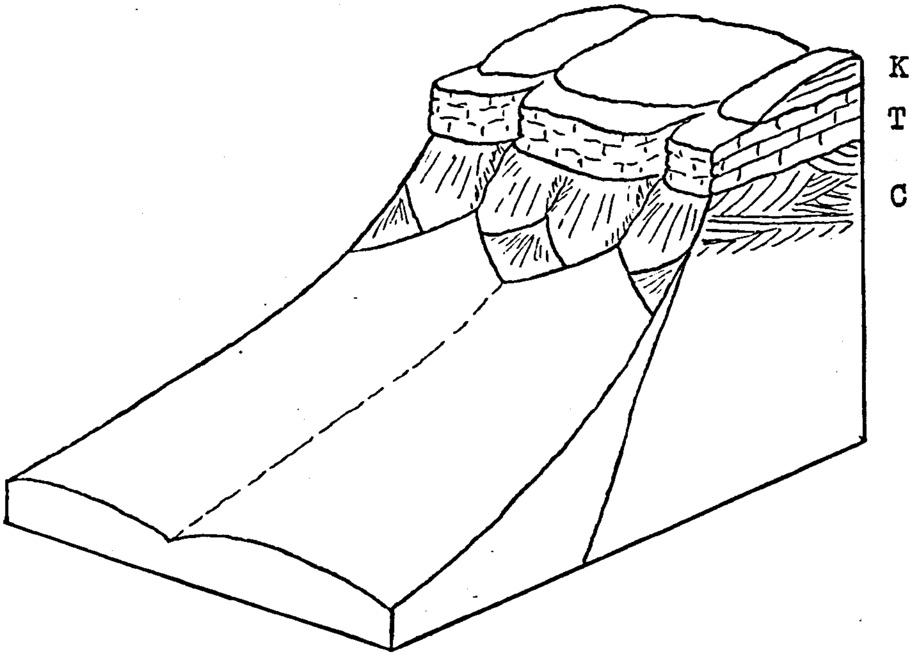


Fig.3. Compound Alluvial Fan with Chessboard Pattern, Aubrey Cliffs, Arizona. K, T - Kaibab and Toroweap limestone, white to light grey; C - Coconino sandstone, orange to light brown.

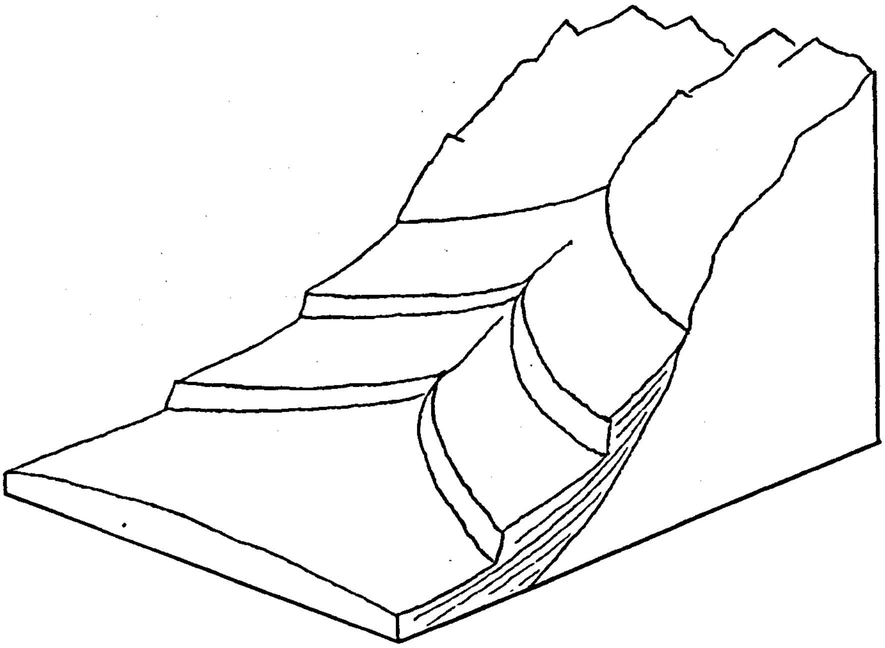


Fig.4. Alluvial Fan with Telescope Structure.

development is best if the fan is small and the amplitude of the swing of the river wide.

Telescope structure is effected not only by the lateral swing of rivers at the base of a fan but may also result from changes in climatic conditions or tectonic activity.

<u>The effects of climatic changes.</u> Of all possible changes in climatic conditions, a variation in the amount of precipitation will have the most profound effect on the development of alluvial fans. Both Eckis (1928,p.237) and Davis (1938,p.1350) claim that a climatic change involving an increased amount of precipitation will result in dissection of alluvial fans. This results in a tendency toward the development of a flatter gradient.

On the other hand, a decrease in precipitation, may be responsible for a period of aggradation and steeper gradients will be developed.

If the change in climate is rapid in a geologic sense conspicuous remnants of older alluvial fans may be preserved. As suggested by Eckis (1928) these fan remnants are called <u>fan-mesas</u>(pl.VII,A).

Telescope structure may be developed as a result of climatic changes. Individual fan levels within 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.

In the Santa Catalina fans there are three different fan levels (appendix "A"). The younger alluvial fans are telescoped into the older fans at higher levels. A rock pediment at the mountain front is in line with the oldest and highest fan level (pl.I,profile a-b) so tectonic movements between the mountain block of the Santa Catalinas and the basin block on which the alluvial fans rest do not seem a likely explanation for the development of later fan stages. The influence of tectonic activity on changes in the Santa Catalina fans was assumed by Davis (1938). It is believed that the telescope structures in the Santa Catalina fans are due to climatic changes. The development of these fans occurred 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 the fan. This stream may, in turn, control development of an alluvial fan by changing the base-level.

Davis (1938,pp.1349-50) believes that the San Pedro River, to the north of the Santa Catalina Mountains, was a through-flowing stream during a late Pleistocene stage. Thus, alluvial fans extending from the Santa Catalinas into the San Pedro Valley were dissected due to the erosive action of the main river.

<u>The effects of orogenic movements.</u> Alluvial fans occur commonly at the base of up-faulted mountain blocks. Re-

juvenation of tectonic activities along the same fault lines is a frequent phenomenon. Davis (1938) lists tectonic disturbance as the most important reason for changes taking place on alluvial fans.

If a mountain area is up-lifted relative to a foreland, a steeper gradient will be developed and a new stage of deposition will set in. This newly deposited fan will be called a superimposed alluvial fan (fig.5). Superimposed and original fans do not exhibit distinct boundary lines and morphologically they cannot be separated. In exposures a separation of the two different generations of alluvial fans may be possible (fig.5).

If a mountain block is lowered relative to a basin block, profound erosion results on the original fans. New fans will be deposited at a lower level and with flatter slopes. Telescope structure may be developed in these fans.

A decision as to whether a telescope structure is due to tectonic disturbance or climatic change rests on the recognition of rock pediments along the mountain front and their correlation to levels on the alluvial fans.

Eckis (1928,p.327) states that individual parts of an alluvial fan may be subject to vertical displacement. In such a case no generalization can be made and the effects on the alluvial fan will depend entirely on the location, the extent, and the nature of tectonic movement.

<u>The effects of epeirogenic movements.</u> Movements of this nature probably affect mountain and basin blocks at the same time and in the same direction.

An epeirogenic rise of the area concerned may be reflected in accelerated erosion on an alluvial fan, while slow subsidence will favor depositional tendencies. Such gradual changes do not tend to leave traces on the alluvial fans which would enable the investigators to reconstruct the development of these fans.

<u>The effects of slumping of unconsolidated fan material.</u> Gilbert (1928,pp.34-39) states that slumping of unconsolidated fan deposits is a common cause for changes on alluvial fans. Longwell (1930) describes an alluvial fan in Nevada in which he observed the effects of slumping.

Slumping of alluvial fan deposits may be favored by :

(a) comparatively steep, original dip of strata,
(b) presence of groundwater acting as lubricant,
(c) presence of layers with mud-sized constituents acting as sliding planes, and
(d) ample void space in coarse-grained layers allowing for considerable settling of strata.

Slumping in unconsolidated fan deposits may be responsible for the development of a <u>pseudo-telescope structure</u> (fig.6) and the difference from the true telescope structure may only be obvious in favorable exposures.

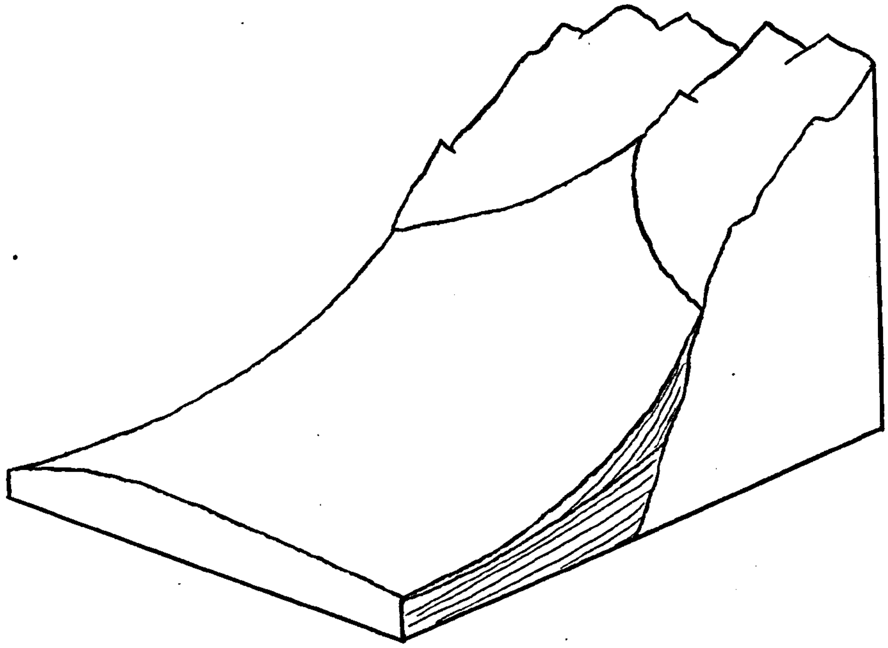


Fig.5. Superimposed Alluvial Fan.

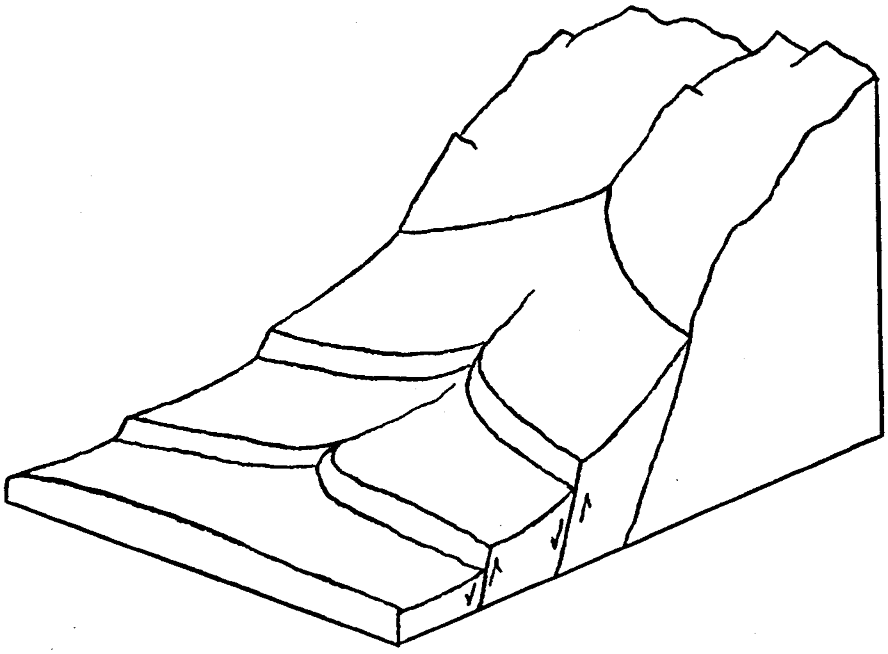


Fig.6. Pseudo-Telescope Structure (modified after Gilbert)

The foregoing reasons constitute the main causes for changes effected on alluvial fans. Changes in the normal course of the cycle are ever-present once the maturity of an alluvial fan has been reached. Other influences are merely superimposed. Several of the 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. The resulting overall structure of an alluvial fan may be complicated and the investigator may not be able to ascribe the present or former fan stages to any definite cause.

Secondary alluvial fans. Fans with deposits derived from an older alluvial fan shall be termed secondary. The original fan may be called the primary one.

For example, at the base of the large, primary Santa Catalina fans small, secondary fans spread out (pl.I; pl.VII, B).

Part II. GEOLOGY OF ALLUVIAL FAN DEPOSITS.

FACIES.

Deposits of recent alluvial fans comprise sediments of gravel, sand and mud size. The lithified equivalents of these deposits are fanglomerate (Lawson,1913,p.330), fan sandstone and fan mudstone. Fan gravels are best developed at and close to the apex of a fan. These sediments may laterally grade into sands and these, in turn, into mud.

Only one or two of the three sedimentary facies described above are normally developed in an alluvial fan deposit. Quite commonly only the fan gravel facies is developed. This is well demonstrated in the alluvial fan deposits of the Santa Catalina Mountains where a fanglomeratic facies predominates in a thickness of several hundred feet and a radial extent of four miles. Many alluvial fans in southern California and southwestern New Mexico observed by the writer also show such a uni-facial, fanglomeratic development. In contrast, among the small alluvial fans of the Black Hills, Arizona, only the sand facies is developed.

If alluvial fans are built up in dry regions, aeolian deposits may be incorporated in the fluviatile deposits (Twenhofel,1939,p.67). Thus, sand dunes rest on the lower parts of some alluvial fans in the Aubrey Valley of Arizona. Any future building up of these fans may incorporate these sand dunes within the alluvial fan deposits.

TABLE II.

Facies on alluvial fans.

STATE OF CONSOLIDATION	FACIES		
Unconsolidated	Fan gravels	Fan sands	Fan muds
Consolidated	Fanglomerate	Fan sandstone	Fan mudstone

PARTICLE SIZES AND PARTICLE SIZE DISTRIBUTION.

The particles in alluvial fan deposits range from boulder to clay size. A block several hundred tons in weight in an alluvial fan deposit in California is illustrated by Tolman (1937,fig.138,p.368). Boulders between 400 and 500 centimeters in diameter were found by the writer in the fanglomerates of the Santa Catalina Mountains, Arizona.

Regarding the size distribution of particles in alluvial fan deposits, three characteristics appear to be common. These are :

(a) a wide range in particle sizes in any particular sample (this property denoting the so-called sorting which is treated in more detail later),

(b) unsystematic but abrupt changes in vertical direction in the average particle size (this property forming the common conception of an alluvial fan being built up of alternating coarse-grained and fine-grained layers treated later under porosity and permeability),

(c) systematic and comparatively abrupt changes in the average and maximum particle sizes along a radial profile of alluvial fans.

The property of changes along a radial profile is the principal one with which the writer is concerned in this chapter. Investigators agree that coarse gravels, frequently of boulder size, predominate near the apex of an alluvial fan, material of intermediate particle size may occupy a central zone and silts and clays the area close to the base of the fan (Lawson,1913,p.331; Vaughan,1922,p.340; Troxell and others,1942,p.337).

Numerical values for particle sizes on several alluvial fans are offered by Eckis (1928,p.223). His figures were obtained, however, from three localities only on each alluvial fan and do not allow the forming of a comprehensive picture as to the rate of change of particle sizes.

Particle size distribution curves along radial profiles of alluvial fans have been established by the writer for the fans that he has examined. The distribution curve of particle sizes of the Santa Catalina fans (fig.7) was compiled from a great number of measurements of the maximum particle size. This distribution curve indicates a rather systematic change

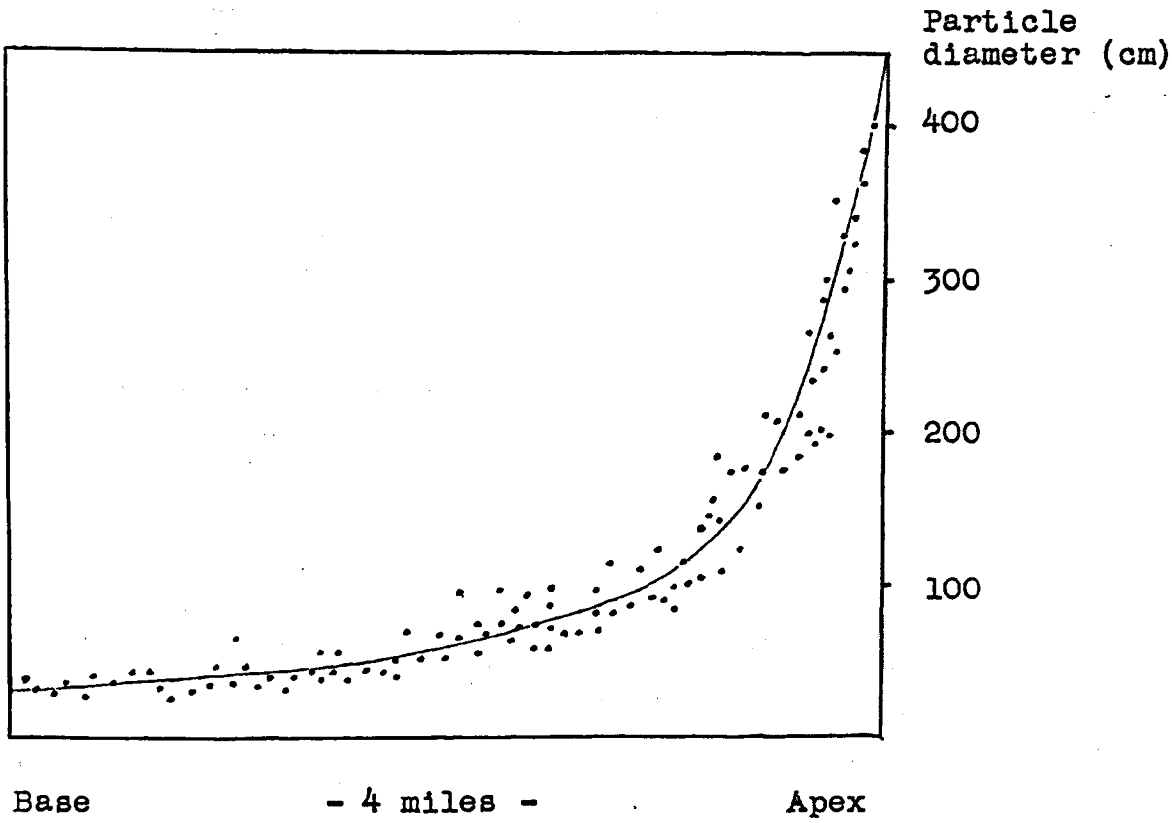


Fig.7. Distribution curve of maximum particle sizes along a radial profile on an alluvial fan of the Santa Catalina Mountains, Arizona (pl.I).

over the whole lateral extent of the fan which is about four miles.

The change in average particle size in deposits of a small alluvial fan of recent age (pl.II) is illustrated in figures 8 and 9. Though these diagrams are composed of findings representing a distance of several hundred feet only, a pronounced tendency for such a change can be seen.

Three more particle size distribution curves are

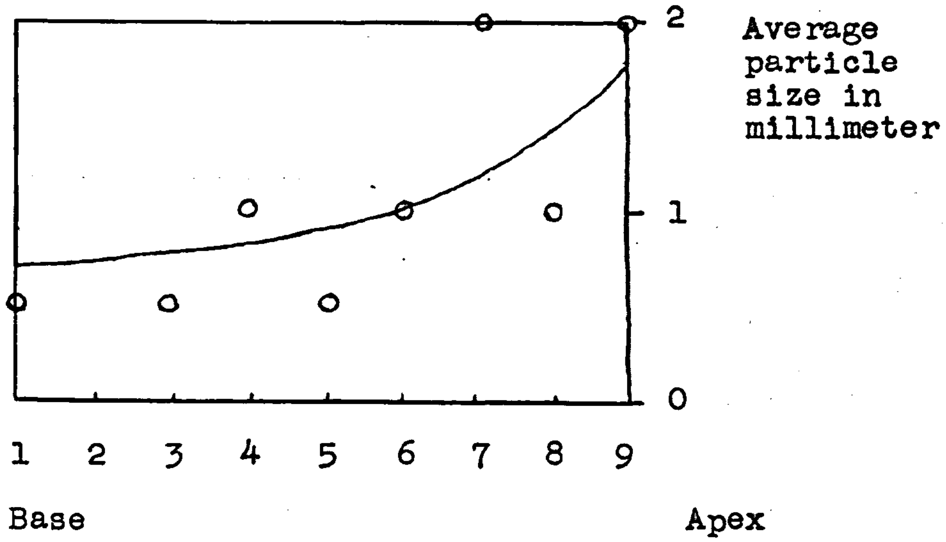


Fig.8. Distribution of average particle size along the lower 400 feet of the radial profile of a small alluvial fan (pl.II); arabic numbers on horizontal axis correspond to localities where samples were obtained as designated in plate II.

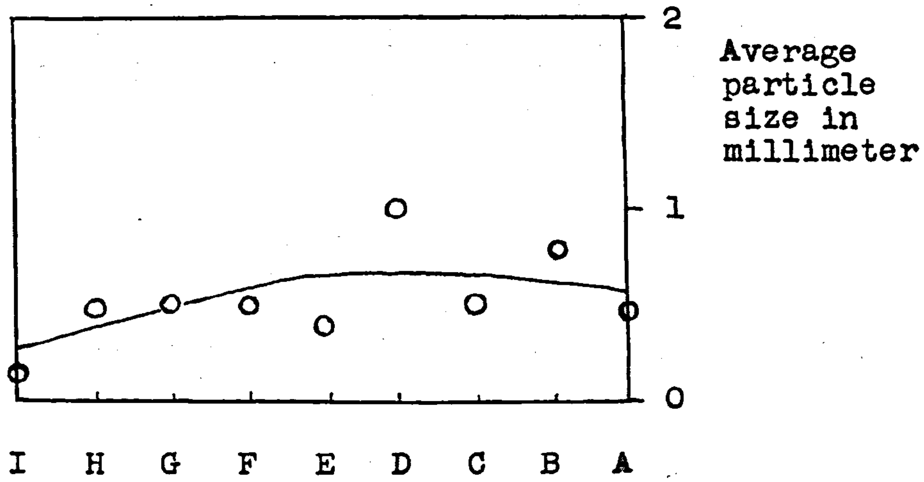


Fig.9. Distribution of average particle size in samples from the localities A to I, as designated in plate II.

shown in figures 14, 15 and 16, in part III of this report.

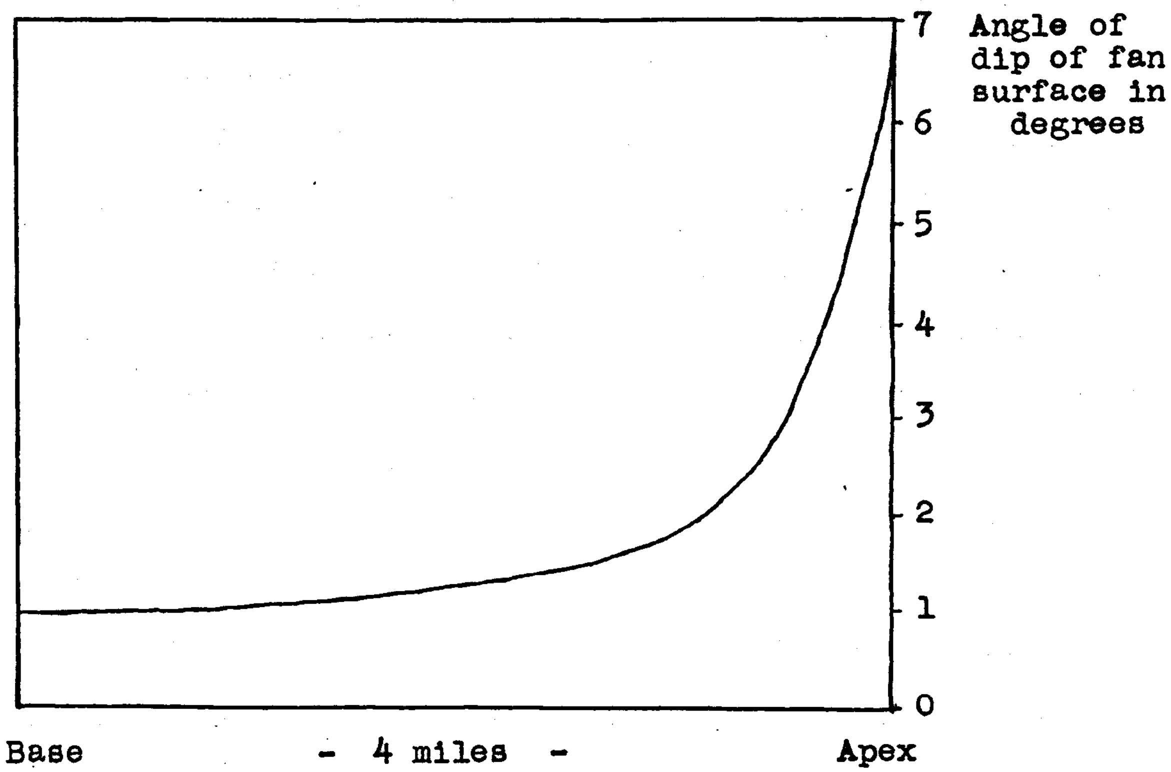


Fig.10. Distribution curve of angles of dip of the surface of an alluvial fan, Santa Catalina Mountains, Arizona (pl.I), along the same radial profile as in fig.7.

COMPOSITION.

The composition of alluvial fan deposits is determined by :

(a) the composition of the parent rock from which the fan deposits are derived,

(b) the type and degree of weathering to which the parent rock is subjected,

(c) syngenetic alterations during transport from the source to the site of deposition, depending on the type of transporting agent and the distance of transport,

(d) epigenetic alterations effected after deposition.

In arid and semi-arid regions the action of mechanical weathering predominates over the action of chemical weathering. Therefore the composition of the detritus available 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 but little importance on changes of composition because both the distance of transport and the time during which the detritus is in contact with water on alluvial fans are short. Epigenetic alterations are more effective, however. They include removal of certain mineral constituents and addition of others by subsurface waters. The subject of addition of mineral substance by groundwater is treated in more detail in the chapter on cementation of alluvial fan deposits.

Commonly alluvial fan deposits belong to one of two compositional groups, the arkose and the graywacke. The classification of compositional groups adopted here is that proposed by Short and McKee (1951).

Up-lifted fault blocks may expose a core of plutonic rock, therefore alluvial fans derived from such blocks commonly are of arkosic composition. Thus, the Santa Catalina Mountains of gneissic composition exhibit alluvial fans of arkosic composition throughout their entire extent. In some places the percentage of feldspars in these deposits is twice as high as the minimum requirement of 20 per cent.

Mountains composed of fine-grained metamorphic, volcanic and sedimentary rocks will give rise to alluvial fans with graywacke composition. Thus, the volcanic Tucson Mountains and the sedimentary Aubrey Cliffs exhibit alluvial fans of this compositional type.

In fans examined during the present study composition of larger particles did not seem to change considerably along a radial profile. The following observations were made on an alluvial fan of the Aubrey Cliffs, Arizona. At the apex, the larger particles within the fanglomerates are composed of 45 per cent sandstones and 55 per cent limestones. Close to the base, about one mile from the apex, the composition is 48 per cent sandstones and 52 per cent limestones. The slight difference in composition between apex and base of this fan may be accidental and no definite tendency in composition change can be recognized.

In some areas fans of contrasting compositional types occur side by side because their apeces head in source rocks of different types. An illustration of this phenomenon is found in the Aubrey Cliffs, Arizona, where large fans are fed from the Kaibab and Toroweap formations and adjacent, small fans from the Coconino sandstone (fig.3).

SORTING.

Sorting, which denotes the range in particle sizes in a sediment, appears to vary widely in the deposits of an alluvial fan.

Sorting of alluvial deposits may be regarded as a function of

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

(b) the type of transporting and depositing agent,

(c) the distance of transport.

In general detritus prepared for transport in a mountain area tends to have a wide range in particle size. This tendency favors poor sorting in alluvial fan deposits . Sorting is good, however, in some of the alluvial fans of the Black Hills of southern Arizona. This unusual situation is due to the fact that the parent rock is a granite that weathers to equi-granular detritus. The high degree of sorting of these fan deposits is not due to long distance of transport as the radial extent of these fans is of the order of only several hundred feet.

There is considerable variation in the degree of sorting of alluvial fan deposits depending on which of the three depositing agents, (a) sheetfloods, (b) streamfloods and (c) streams, is responsible for forming a particular deposit. Sheetfloods tend to accomplish the least amount of sorting of fan deposits (McGee,1897; Davis,1938). A sheetflood deposit normally is a heterogeneous mass of rock material of all particle sizes (Blackwelder,1928). The coefficient of sorting (Trask,1932) of a sheetflood deposit in a small alluvial fan of the Santa Catalina Mountains, Arizona (pl.II), is 2.6.

Stream deposits, in contrast, show fair to good sorting. The degree of sorting may exceptionally reach values equal to those attained in the floodplain environment or to those of beach gravels and sands. The coefficient of sorting (Trask,1932) of a stream deposit in a small alluvial fan of the Santa Catalina Mountains, Arizona (pl.II), is 1.7.

Streamflood deposits occupy a position intermediate in their sorting between sheetflood and stream deposits. They tend to be poorly sorted if the intensity of the flow is high; they show fair sorting if the flow is more moderate.

Most alluvial fan deposits have been transported only short distances and therefore are not well sorted. In large fans, however, deposits close to the base of the fan may show fair sorting due to a comparatively long distance of transport. Fair to good sorting is also exhibited in secondary fans by reworking and by selective transport of material from primary fans.

A small alluvial fan at the base of the large Santa Catalina fans and built up of material from them was found to have fairly well sorted deposits. Reworking of primary fan deposits and a comparatively long distance of transport are responsible for the high degree of sorting in these fan deposits.

Most alluvial fan deposits are poorly sorted (Trowbridge, 1911,pp.706-747; Twenhofel,1926,p.565; Eckis,1928,p.232; Chawner,1935,p.259; Troxell and others,1942,p.337). Exceptionally, however, as demonstrated in the two alluvial fans described before, sorting may attain a fair to good degree due to the tendency in a parent rock to break down into particles of similar size or due to a comparatively long distance of transport. Such a tendency for good sorting is accentuated if a stream constitutes the transporting and depositing agent.

TABLE III.

Sorting in alluvial fan deposits.

SORTING	POOR	GOOD
Particle sizes of weathered parent rock	heterogeneous	homogeneous
Trans. and depos. agent	sheetflood	stream
Distance of trans.	short	long

ROUNDNESS.

Roundness of sedimentary particles generally is a function of the distance of transport. For this reason the roundness of fragments from alluvial fan deposits may be expected to increase from the apex towards the base of any particular fan.

Field studies to determine the roundness of fragments in alluvial fan deposits were carried out on the Santa Catalina fans, Arizona, along the four mile extent of a fan. Samples of 25 fragments of about equal size were obtained from 13 points along the radial profile and determination of the roundness was based on Krumbein's charts (1941).

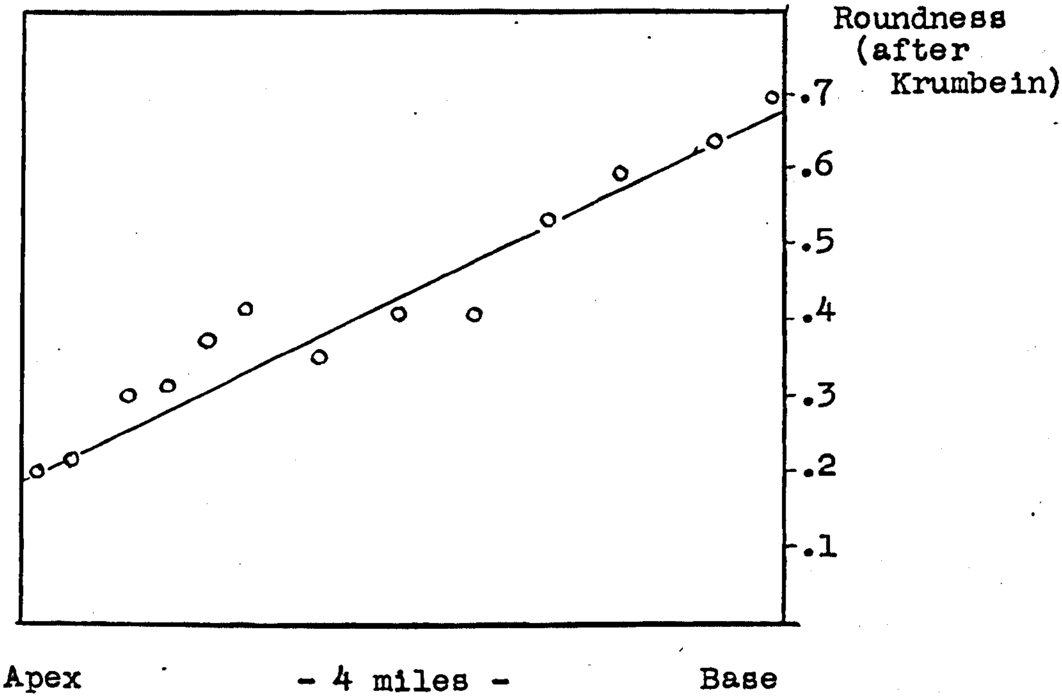


Fig.11. Distribution of roundness of alluvial fan particles along the same radial profile as figs.7 and 10; base of Santa Catalina Mountains, Arizona.

The minimum roundness of fragments in these fan deposits was 0.2, at the point closest to the apex of the fan; the maximum roundness amounted to 0.7 at the point closest to the base (fig.11). The distribution curve (fig.11) suggests that the function between the roundness found at any point and the distance of this point from the apex is of linear nature. The mathematical expression of this distribution curve (fig.11) is :

$$P = axd + c \;;$$

wherein P is the roundness (after Krumbein), a is a constant denoting the rate of change in roundness, d the distance from the apex and c the initial roundness at the apex. It is not known whether similar, simple functions between roundness and distance from apex prevail on other alluvial fans.

Fragments are rounded fast if the rock material of which they are composed is soft. Limestone gravels serve as an example. At the base of alluvial fans in the Aubrey Valley, limestone fragments are much better rounded than sandstone fragments. In contrast, resistant rocks, such as quartzites and cherts, may retain a high degree of angularity for a long time.

Gneisses form more than 90 per cent of the fragments in the deposits of the Santa Catalina Mountain fans. As gneiss occupies an intermediate position between the extremely resistant rocks and the highly soluble and friable rocks, a distribution curve of the roundness of fragments in the Santa Catalina Mountain fans (fig.11) may serve as illustration for the normal increase in roundness with distance from the apex.

Based on the classification of roundness by Short and McKee (1951,table 12) fragments in alluvial fan deposits of the Santa Catalina Mountains, Arizona, may be described as angular, subangular and subrounded. On the basis of these findings, the common conception of alluvial fan deposits being necessarily characterized by angularity of their fragments (Chawner,1935,p.259) must be abandoned.

In a recent study (1951) the writer describes Pliocene gravel deposits at Blue Mountain, northwest Arizona, which probably were deposited on alluvial fans. These gravels have been derived from a distant source (Koons,1948). They attained a high degree of rounding due to long transport. Later faulting brought these floodplain gravels into a position from where they could be redeposited as fan gravels. Thus, the high degree of rounding of the Blue Mountain gravels was not accomplished on an alluvial fan but results from long transport in the floodplain environment.

SPHERICITY.

Sphericity in detrital sediments is a property inherited from the parent rock therefore it is not expected to show different values in fan deposits along any par-

TABLE IV.

Rounding of sedimentary particles as function of the distance of transport from the apex, on an alluvial fan of the Santa Catalina Mountains, Arizona.

Distance of transport from apex in miles	0 - 0.5	0.5 - 2	2 - 4
Degree of rounding of fragments (descript. term)	angular	subangular	subrounded
Degree of rounding of fragments (numerical value)	.2-.25	.25 - .45	.45 - .70

ticular radial profile. The sphericity may change, however, if changes in the composition of a fan deposit occur. A change in the sphericity may also be expected if platy fragments derived from well-layered rocks, such as sandstones or gneisses, break down to the individual constituents which commonly have a different degree of sphericity.

Sphericity measurements in alluvial fan deposits of the Santa Catalina Mountains, Arizona, were made from samples obtained for the determination of roundness of the fragments, described in the previous chapter. Krumbein's sphericity charts (1941) were employed. The mean sphericity of alluvial fan particles was found to be 0.65 (after Krumbein,1941). The maximum and the minimum values of the sphericity along a radial extent of four miles on this fan deviated but 7 per cent from the mean value (fig.12).

MATRIX.

Particles in the matrix of alluvial fan gravels range from sand to mud size. Finer particle sizes predominate in the matrix of mudflow deposits. A typical sample from the matrix of a mudflow deposit of a small alluvial fan (pl.II) of the Santa Catalina Mountains, Arizona, showed an average particle size of 0.15 millimeter. Deposits laid down by streams on alluvial fans tend to have a coarser-grained matrix. The average particle size of the matrix of a stream

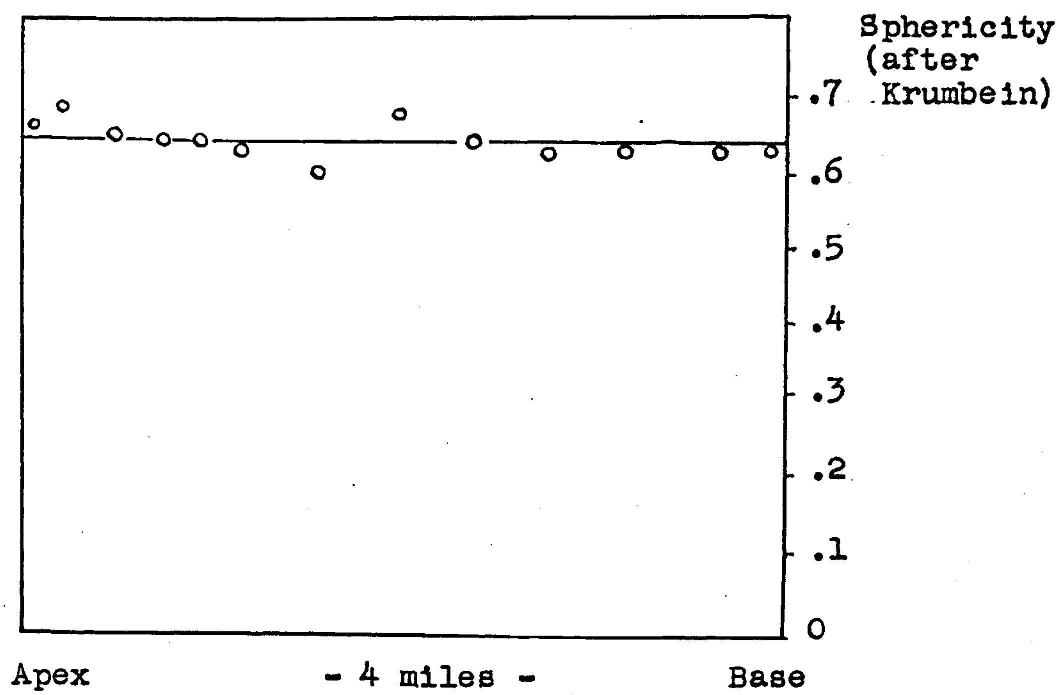


Fig.12. Sphericity of alluvial fan particles along the same radial profile as figs.7,10 and 11; base of Santa Catalina Mountains, Arizona.

deposit of the small alluvial fan (pl.II), described before, is 0.7 millimeter.

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

A secondary matrix is a common feature in fan gravels. This results from removal of an original interstitial fill between fan gravels and filling out of interstitial space at a later stage. An illustration of this process is seen in a deposit of the Santa Catalina Mountain fans. This deposit is a mass of boulders without interstitial fill. The original matrix has probably been removed. Future floods may be expected to fill the interstitial space between individual boulders with sediments and thus give the deposit a secondary matrix.

CEMENT.

Calcium carbonate is the commonest cement in alluvial fan deposits in most areas. It is precipitated from ascending or descending groundwater (Breazeale and Smith,1930) and develops as a coating around alluvial fan particles, as solid layers or concretions, or dissiminated as minute calcite crystals in the matrix.

In some places calcium carbonate will fill all available pore space in a fan deposit and the resulting sediment may therefore have a content in calcium carbonate of 10 - 20 per cent or even more.

Alluvial fan deposits, now in process of accumulation in Nevada, Utah and California are mostly incoherent or but feebly cemented; in parts of Arizona and New Mexico and over a large part of Mexico, fanglomerates are to a varying depth strongly cemented by carbonate of lime (Lawson,1913, p.332).

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. Most alluvial fan deposits are gray or yellow; in semi-arid climates there may be red and brown colors. There are local occurrences of sediments with black colors (Twenhofel,1926,p.564).

Mudflow deposits of the Santa Catalina Mountain fans are light yellow; the interbedded stream deposits are a somewhat darker shade of yellow. Where calcium carbonate cement is abundant, the color of an alluvial fan deposit ranges from gray to pure white.

POROSITY.

Porosity and permeability are probably the most-studied properties in alluvial fan deposits. This is due, in part, to the fact that alluvial fans are the greatest water producers in the western United States (Tolman,1937,p.364). Uncemented alluvial material may have a porosity as high as 50 per cent, according to Tolman (1937,p.112). The porosity of alluvial fan deposits rarely reaches such an extreme value. The porosity in pebble lenses with loose packing, observed in a small alluvial fan (pl.II) at the base of the large Santa Catalina Mountain fans, was estimated to be 30 per cent. Due to cementation the porosity in the deposits of the large Catalina fans does not exceed approximately 15 per cent.

The porosity of alluvial fan deposits may attain any value between the above extremes and zero. Porosity in general is controlled by the following factors :

(a) sorting,
(b) degree of packing,
(c) roundness of particles,
(d) compaction,
(e) cementation.

Poorly-sorted mudflow deposits have low porosity; well-sorted stream deposits high porosity, other factors being the same.

PERMEABILITY.

Permeability probably is more important than porosity from the economic standpoint because the permeability of fan deposits directly controls the movement of groundwater. The permeability of alluvial fan deposits depends on their porosity and, in addition, is a function of the size of the interstitial void space.

In addition to their low porosity, mudflow deposits have extremely small interstitial openings. Molecular forces therefore tend to retain water and though the sediment may be soaked, groundwater cannot move freely. Thus, mudflow deposits are ideal aquicludes.

In contrast, stream deposits on alluvial fans have comparatively large pore spaces which account for the ease with which groundwater can move through them. Stream deposits therefore are good aquifers.

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

Alluvial fans of the Santa Catalina Mountains and the Black Hills of Arizona tend to confirm the concept of alternating aquifers and aquicludes, though other unfavorable conditions do not permit the recovery of much groundwater.

SEDIMENTARY STRUCTURES.

Sedimentary structures were studied first in a small alluvial fan (pl.II) at the base of the large Santa Catalina fans (pl.I). Comparison with sedimentary structures in other alluvial fans suggest that the results may be applied to alluvial fans in general.

Original dip of strata. Alluvial fan deposits are laid down in rude beds approximately parallel to the surface of the fan (Lahee,1941,p.65; this report, Pl.VI,A,B). Thus, the surface angles as treated in a previous chapter (Part I, Morphologic shape) are repeated within the strata of the fan deposits.

Dipping angles greater than 10 degrees are exceedingly rare in the beds of fans; angles between 5 and 10 degrees are infrequent. Commonly the dip of alluvial fan strata will range from about 5 degrees to almost horizontal. These angles do not apply to cross-stratification within individual fan strata.

The classification adopted for the angles of dip of the fan surface (Part I, Morphologic shape) may also be applied to the dip of the fan strata and the original dip of alluvial fan strata may be called steep, gentle or flat.

Stratification. Statements by various investigators concerning the character of stratification in alluvial fans differ widely. It is described as indistinct bedding by Eckis (1928,p.232), as irregular stratification by Chawner (1935, p.259) and as apparently absent by Blackwelder (1928,p.465).

All alluvial fans studied by the writer were distinctly stratified. This finding does not necessarily contradict the results obtained by previous investigators. Alluvial fan deposits appear to lack or have but little stratification when observed at close range. Only when seen from some distance does the stratification become apparent. Photographs furnish ample proof for this (Tolman,1937,fig.137, p.366; this report,pl.VIII,A;pl.IX,A).

Many mudflow deposits show distinct contacts with stream deposits (pl.X,A,B). The impression that a body of alluvial fan deposits is well-stratified is amplified if mudflow and stream deposits are of different colors and if pronounced imbrication is present in stream deposits but absent in underlying or overlying mudflow deposits. In general mudflow deposits form one solid layer without being subdivided into a number of thinner layers.

Deposits laid down by streams and moderate streamfloods show good stratification. Many of them are subdivided into a more or less large number of thinner layers. Where the average particle size of the deposits allows such development, lamination is a common feature.

Thus, series of well-stratified or cross-stratified deposits, laid down by the action of streams and moderate streamfloods, alternate with single thick beds produced as mudflows during violent streamfloods and sheetfloods and lacking any sub-stratification.

The overall stratification of most alluvial fans is fair to good. On the other hand, in alluvial fans built up through their entire vertical and radial extent by mudflow deposition, stratification may be absent.

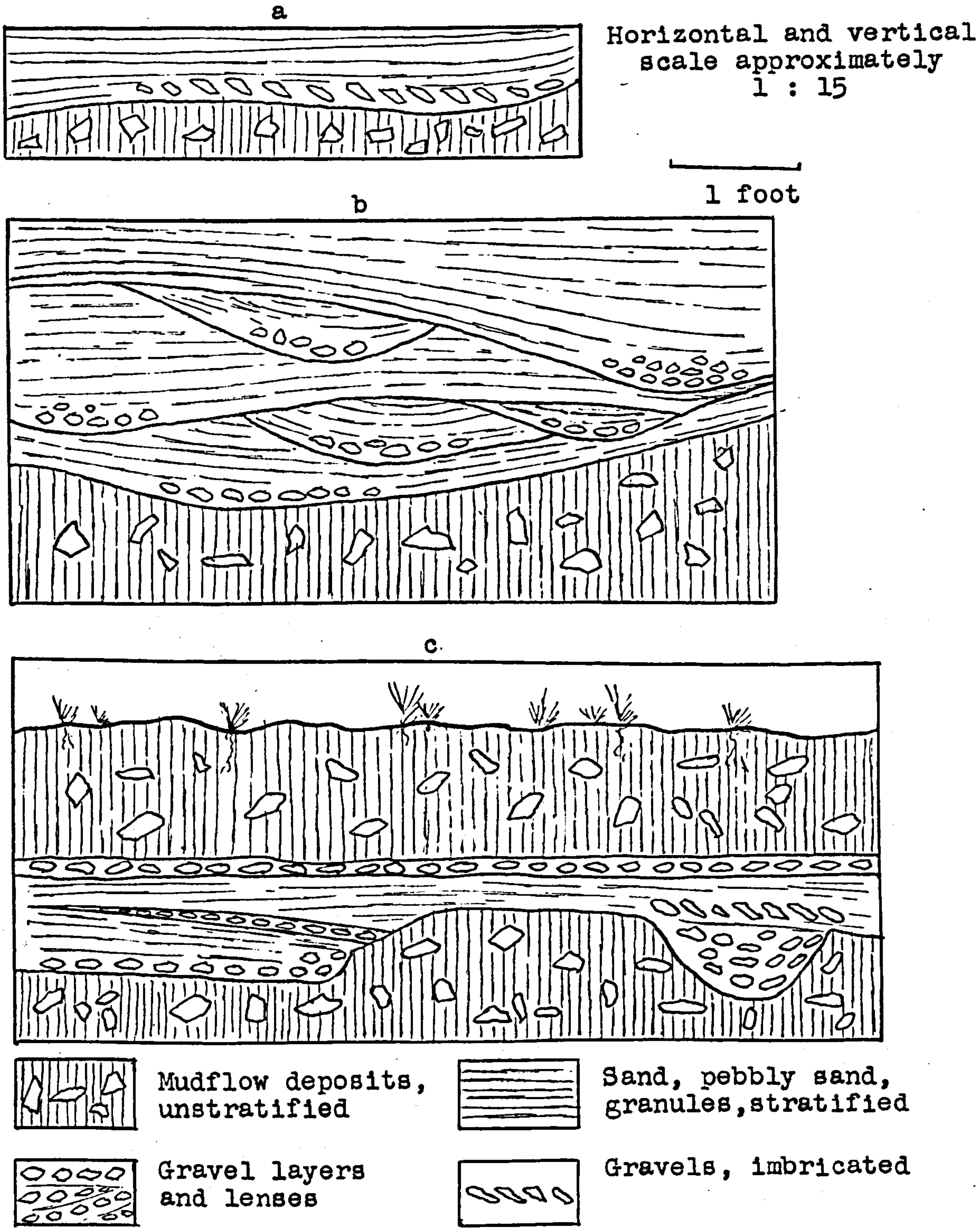
<u>Cross-stratification.</u> This structure is well developed in deposits formed by streams. Current ripple marks may be present in these deposits (Twenhofel,1950,p.71).

The most common and conspicuous type of cross-stratification is due to the filling of channels that have been cut into the underlying deposit (pl.IX,A; pl.X,A,B; fig.13). Frequently the fill in these channels is comparatively coarse near the bottom and the packing of the deposits is loose so that in such places the maximum porosity of fan deposits is encountered.

<u>Thickness of strata.</u> The thickness of individual strata in alluvial fans ranges from a fraction of an inch to fifteen or twenty feet. Most stream deposits are in beds from one inch to one foot thick. Successive series of stream deposits may attain a vertical extent of several tens of feet. Mudflow deposits range in thickness from one foot on small fans to fifteen or twenty feet on large fans. These figures, based on observations by the writer, compare well with the findings by other investigators (*). Alternating mudflow deposits frequently are of a thickness comparable to that of stream deposits.

---

* E.Blackwelder and J.P.Buwalda: Oral communication.



Fig,13. Characteristic sedimentary structures in a small alluvial fan (pl.II). Detailed sections a and c are located along line of flow between points 1 and 2, section b between points 5 and 6 as per plate II. Main direction of deposition from right to left.

Preferred orientation of particles. Mudflow deposits do not show any preferred orientation of their fragments. Particles frequently stand on edge (pl.IX,B; pl.X,A,B) and in all other normal positions of repose.

Imbrication is pronounced in deposits laid down by streams and moderate streamfloods wherever the shape of the fragments permits such development. The gneissic bedrock of the Santa Catalina Mountains tends to break down into platy or disc-shaped fragments therefore imbrication is distinct in fan deposits at the base of these mountains. The disc-shaped fragments are inclined towards the site of derivation as might be expected within the fluviatile environment. The angle of inclination reaches a maximum of 30 degrees and is pronounced among fragments of pebble and cobble size. Boulders, 100 to 200 centimeters in diameter, were found to have inclinations not greater than 25 degrees (pl.XI,A,B).

Shape of individual strata. Stream and streamflood deposits are rudely lenticular (Chawner,1935,p.260). They are deposited in channels and follow in their extent the winding course of the former channels. Sheetflood deposits, in contrast, are laid down in definite sheets (pl.V,B). They terminate, however, with sharp, abrupt edges (Chawner,1935, p.256).

Even on large alluvial fans, like those of the Santa Catalina Mountains, Arizona, where comparatively thick beds are well exposed, no layer could be traced for more than one hundred feet. Series of beds, several tens of feet thick, could be traced for a somewhat greater lateral distance.

The areal extent of a mudflow deposit, i.e. whether it was deposited in a definite channel or spread out in a sheet, appears to constitute the only valid criterion by which its origin can be determined. Thus, a streamflood deposit may be distinguished from a sheetflood deposit by its overall shape.

ORGANIC CONTENTS.

Fossils are more often absent than present in alluvial fan deposits, but there may be local occurrences of abundant fossils, due to sudden floods which caused wholesale killing and rapid burial according to Twenhofel (1939,p.67). Fossil animals were not found within the alluvial fan deposits studied by the writer. Fossil plants or plant fragments, however, are not uncommon in certain places.

INFLUENCE OF PARENT ROCK.

Certain types of rock such as shale, limestone, numerous kinds of schist, and most lavas furnish no sand, but only silt and clay upon weathering. In an area where such parent rocks occur, the resulting alluvial fan deposits have an abundance of fine-grained constituents (Tolman,1937,p.367). An illustration for this is given by alluvial fans of the volcanic Tucson Mountains. Mud-sized particles predominate in the matrix of these fan deposits. In contrast, the matrix of alluvial fan deposits of the Santa Catalina Mountains, Arizona, derived from a parent rock of gneiss shows an abundance of sand-sized particles. The matrix of fan deposits derived from a parent rock of limestone and sandstone, such as the one of the Aubrey Cliffs, occupies an intermediate position in its predominant particle size.

The composition of a fan deposit depends largely on the composition of the parent rock as described in the chapter on the composition of alluvial fan deposits.

ANCIENT ALLUVIAL FAN DEPOSITS.

Occurrence. A number of occurrences of ancient alluvial fan deposits are listed by Twenhofel (1950,p.72). The earliest recorded alluvial fan deposits, according to him, are some of the coarse sediments in the Huronian, some of the Keweenawan conglomerates and sandstones of the Lake Superior Region, the Doré series of western Ontario, and parts of the Great Smoky and Cochran conglomerates of the southern Appalachians described by Barrell. Parts of the Old Red Sandstone of Great Britain may be of this origin, some of the Pennsylvanian sediments of the Appalachians, and the New Glasgow conglomerate (Permian) of Nova Scotia.

The Triassic Newark series has alluvial fan deposits along most of the fault basins in which the sediments accumulated. Parts of the Flysch and Molasse of the Alps certainly accumulated as alluvial fan deposits, and such also is the origin of parts of the Siwalics of northern India. Tertiary alluvial fan deposits have extensive distribution over western United States, and to this origin may be referred most of the extensive clastic deposits that flank the Rocky Mountains on the east.

A conglomerate of Late Miocene age, 500 to 1000 feet thick, flanking the Alps on the north and covering the whole area of Lower Bavaria has been examined by the writer. Though detailed work on this deposit is lacking, all indications point to an origin on a compound alluvial fan of the Alps.

In a recent study (1951) the writer describes gravel deposits exposed at Blue Mountain, north of the Aubrey Valley, Arizona. These gravel deposits are of early Pliocene (?) age. They indicate by their stratification, the alternation of mudflow and stream deposits, imbrication of particles and the abundance of channels that they were probably formed on alluvial fans.

Relative abundance. The failure to recognize alluvial fan deposits in the geologic column to the extent they are known in Recent may be explained by the following factors:

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

(b) A combination of bold relief and aridity was not common in the geologic past (Lawson,1913).

(c) The period of time extending through the Quaternary with its dominance of land is exceptional in geologic history (Lawson,1913).

(d) 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 features such as extensive down-faulting, like that involving the Newark series, has protected the alluvial fan deposits from further erosion can they be expected to be preserved.

(e) Alluvial fan deposits may not always have been described as such but have been classified as angular conglomerates or sedimentary breccias (Lawson,1913). The misconception common in literature that fan deposits are necessarily (1) unstratified, (2) of highly angular gravels, (3) poorly sorted and (4) without distinctive sedimentary structures, may in part be responsible for such results, in the opinion of the present writer.

Part III. RELATION OF PARTICLE SIZE DISTRIBUTION TO SURFACE ANGLE DISTRIBUTION.

Barrell (1925,p.329) states that both size of gravels and gradient of a single stream are related, under the same general law. Krumbein (1937,pp.577-601) was able to demonstrate that both a distribution curve of particle sizes and a distribution curve in respect of surface angles followed exponential functions which finding proves a relationship of particle size to the slope formed by the respective deposits.

The distribution curves in respect of particle sizes and surface slope of the Santa Catalina Mountain fans (fig.7

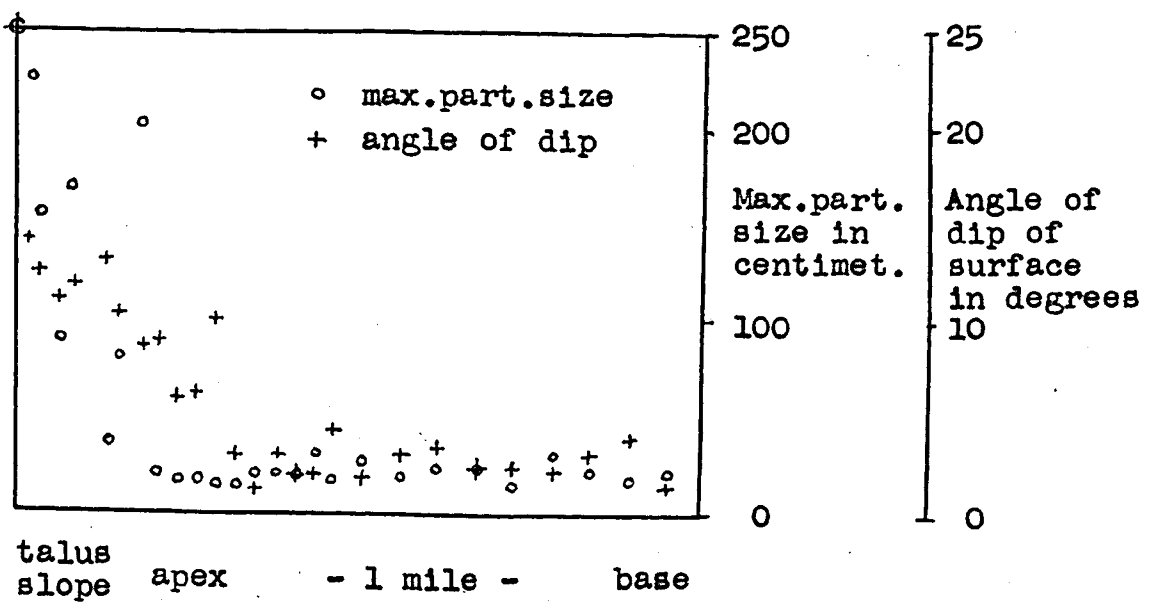


Fig.14. Relation between maximum particle size and angle of dip on an alluvial fan of the Tucson Mountains, Arizona.

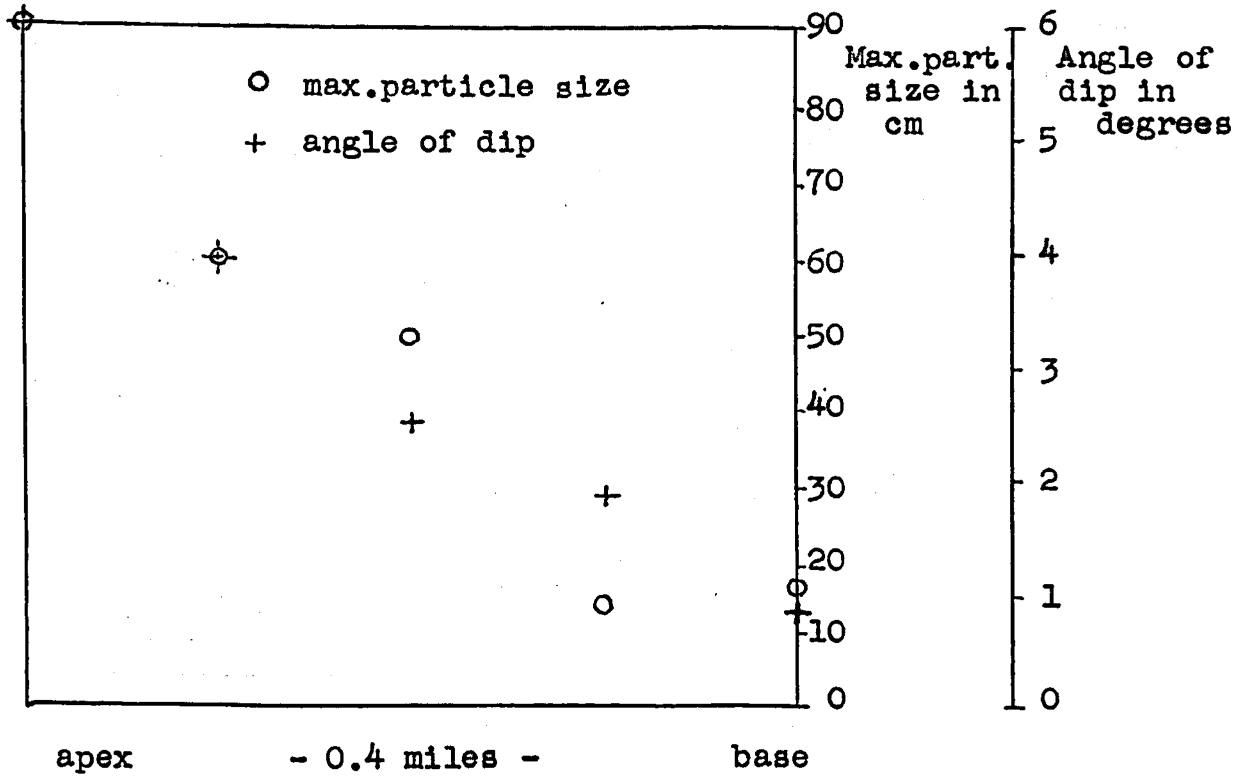


Fig.15. Relation between maximum particle size and angle of dip of fan surface on an alluvial fan of the Aubrey Cliffs, Arizona.

and 10) were similar. To investigate whether such a relation is applicable to other alluvial fans, studies were carried out on an alluvial fan of the Tucson Mountains, Arizona (fig.14), and on two alluvial fans of the Aubrey Cliffs, Arizona (fig.15 and 16).

From these diagrams (figs.14, 15 and 16) it appears that the rate of change in maximum particle size equals the rate of change in the angle of surface dip of an alluvial fan. Such a relation between the rates of change in particle size and surface slope may constitute one of the fundamental

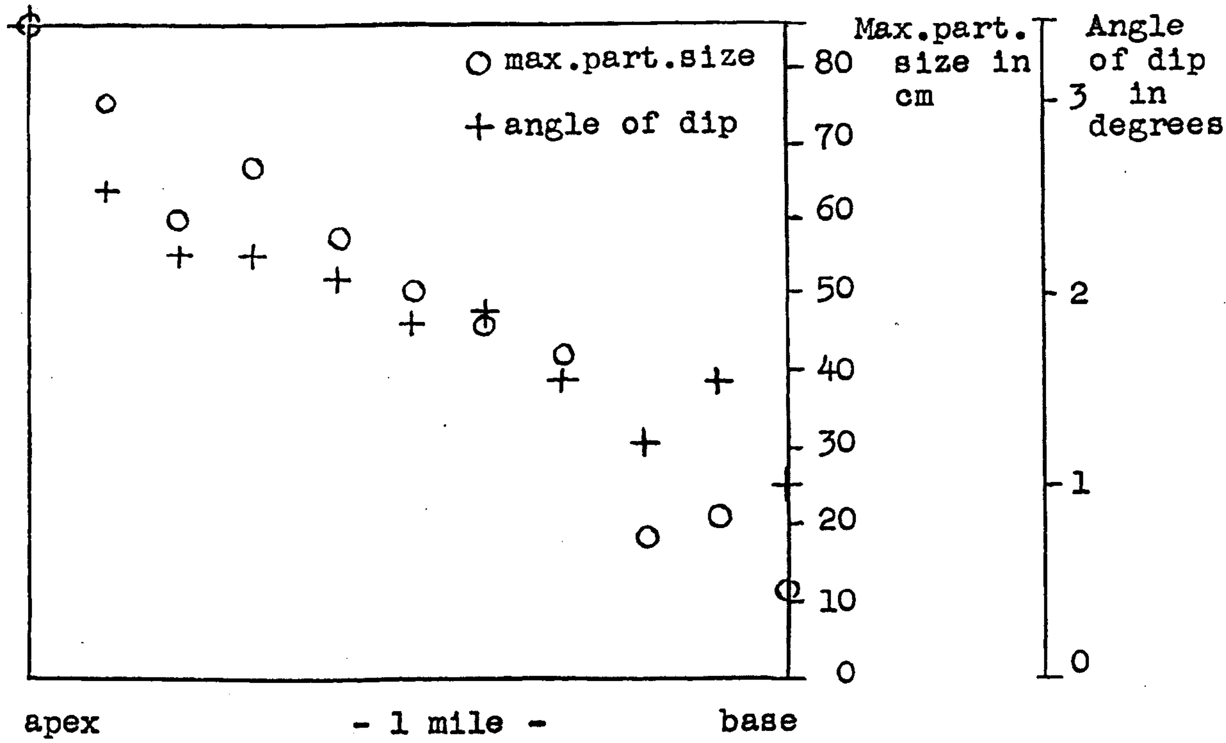


Fig.16. Relation between maximum particle size and angle of dip of fan surface on an alluvial fan of the Aubrey Cliffs, Arizona.

principles of sedimentation. The practical importance of this close relationship rests in the possibility to assign a certain surface slope distribution to a given particle size distribution, and vice versa. Such procedure might help to reconstruct a surface of deposition in cases where erosion or tectonic movements later obscured the original gradient.

Part IV. CLASSIFICATION OF ALLUVIAL FANS.

BASIS OF CLASSIFICATION.

Alluvial fans are classified on the basis of the following characteristics :

(a) morphologic shape,

(b) overall structure,

(c) properties of the fan deposits.

CLASSIFICATION.

Morphologic shape. The descriptive characteristics employed to classify alluvial fans include the dimensions of an alluvial fan, its radial extent, thickness at the apex and the base, and the total difference in elevation between apex and base of the fan.

The angle of dip of a fan surface may be steep, gentle or flat. Single alluvial fans may interfinger laterally to form compound alluvial fans.

Overall structure. Alluvial fans may be in the stage of aggradation, the stage of maturity, or in late stage development. Late stage development may be reflected in dissection of fans, or in telescoped or superimposed structure.

Dissection of alluvial fans results from changes in the normal course of the cycle. Telescoped structure in small alluvial fans is effected by a rhythmically degrading base-level, or by the lateral swinging of a river at the base of the fan. On large alluvial fans telescoped structure results from the influence of climatic changes or tectonic movements. Fan-mesas are characteristically developed.

Superimposed structure results from tectonic movements. The development of fan-bays is conspicuous.

Changes in the normal course of a cycle are ever-present once the maturity of a fan is reached. Other influences are merely superimposed. Different development of single alluvial fans within the same compound fan may be due to tectonic movements or to the different sizes of streams on the respective single fans.

Properties of the fan deposits.

(a) Facies. Fan gravels, fan sands and fan muds constitute the facies of unconsolidated fan deposits. Their lithified equivalents are fanglomerates, fan sandstones, and fan mudstones.

(b) Particle size and distribution. The particle sizes at apex and base of the fan and their rate of change are characteristic.

(c) Depositing agents. Sheetfloods, streamfloods and streams constitute the transporting and depositing agents on alluvial fans. Mudflow deposits are formed by sheetfloods if laid down in definite sheets, they are due to the action of streamfloods if they occupy a stream channel. The relative abundance of certain types of deposits is characteristic for a fan.

(d) Composition. Alluvial fan deposits commonly are of either arkosic or graywacke composition.

(e) Sorting. Sheetflood deposits have poor sorting, stream deposits have fair to good sorting and streamflood deposits have an intermediate degree of sorting. Good sorting may also result either from a breakdown to homogeneous particle sizes of the parent rock or from a comparatively long distance of transport.

(f) Roundness. Fragments in alluvial fan deposits may be angular, subangular, subrounded or rounded. The rate of change in roundness is characteristic for fragments in alluvial fan deposits.

(g) Sphericity. This property tends to remain rather constant on fans if no changes in composition or facies occur.

(h) Matrix. The matrix may be predominantly sand or mud; it may be primary or secondary. The composition of the matrix commonly is either arkosic or graywacke.

(i) Cement. The composition of the cement and its percentage are characteristic for fan deposits.

(j) Color. Alluvial fan deposits commonly are gray or yellow. In semi-arid climates there may be red and brown colors.

(k) Porosity. The degree of porosity of alluvial fan deposits ranges from a maximum of 30 per cent or more to zero.

(l) Permeability. This property will vary with the relative abundance of comparatively impermeable mudflow deposits and permeable stream deposits.

(m) Sedimentary structures. The original dip of fan strata is comparable to the dip of the fan surface. Thus, the dip of the strata may be steep, gentle or flat. Deposits have poor to good stratification depending on the participation of unstratified mudflow deposits or stratified stream deposits. Cross-stratification is common in in stream deposits; it is absent in mudflow deposits. The thickness of individual fan strata ranges from a fraction of an inch to 15 or 20 feet. Deposits are rudely lenticular. Imbrication is conspicuous in stream deposits, preferred orientation of particles is absent in mudflow deposits.

(n) Organic contents. Fossil animals are rare. Fossil plants are locally abundant.

APPENDIX "A". GEOLOGIC HISTORY OF AN ALLUVIAL FAN OF THE SANTA CATALINA MOUNTAINS, ARIZ.

INTRODUCTION.

The area covered by this report (pl.I) is approximately six miles north of Tucson, Arizona, at the southern base of the Santa Catalina Mountains. The east-west extent of the area studied is about two miles; its north-south extent about four miles. Natural boundaries of this area are formed by the present front of the Santa Catalina Mountains in the north and the floodplain of the Tucson basin in the south. The area selected for study lies between Campbell Avenue in the west and Pontiac Road in the east(pl.I;pl.XII).

The trend of the Santa Catalina Mountains is east-west and swings to the southeast northeast of Tucson. The northern part of the range drains to the San Pedro River, a tributary of the Gila River, Arizona. Drainage of the southern part of the range heads southward to the Tucson basin. Alluvial fans extend from the northern front of the Santa Catalina Mountains into the San Pedro Valley and from the southern mountain front into the Tucson basin. Single alluvial fans interfinger laterally to form compound alluvial fans (p.9).

The area covered by this report is a sector of the compound alluvial fan at the southern base of the Santa Catalina Mountains. From the present mountain front the fan surface dips gently to the south (p.8). The difference in elevation between apex and base of the compound fan is about 600 feet. The surface of the fan is strongly dissected. Some of the dissecting streams are 50 feet deep; the walls of these washes are steep. All streams are of the intermittent type.

GENERAL GEOLOGY.

Structures. The most conspicuous structure within the area covered by this report is the fault separating the Catalina Mountain block on its southwestern side from a basin block . It strikes west-north-west about parallel to the present mountain front (pl.I). The name Catalina fault is proposed for it. This fault is well exposed in the wash east of Campbell Avenue running north from Tucson (pl.I;pl.XIV,A). The fault zone is several feet wide. Mineralization is encountered in various places along the mountain or north side of this fault. Specularite is the most common mineral found in this zone of mineralization.

The Catalina fault is believed to represent the normal type of fault. No conclusive evidence for this assumption could be found. Open cracks and fissures running parallel to the Catalina fault were observed. If these open cracks can be taken as criterion for the action of tensional forces, a normal type of fault of the Catalina fault appears more probable.

No definite indication by which the amount of displacement in the Catalina fault can be determined is known. It probably is somewhere between six hundred and several thousand feet.

The abnormal course of Rillito Creek is believed by Davis (1931,p.302) to be due to tectonic disturbance along the course taken by this river. Section a-b, plate I, however, compiled from surface exposures and well data, does not give any indication as to the presence of a tectonic line along the course of the Rillito Creek.

Small faults with displacements around several centimeters are found in the redbeds in the area of study. In no place were structures in the redbeds seen to continue into the overlying fan deposits.

Formations. Most of the Santa Catalina Mountain range is composed of the Catalina gneiss. Outcrops of the Catalina gneiss are found on the up-thrown or north side of the Catalina fault. The only occurrence of this rock south of the Catalina fault is reported from a drill several miles east of the area of study. In this drill the Catalina gneiss was struck at a depth of 600 feet.

The Catalina gneiss comprises a wide variety of igneous and metamorphic rocks. The intrusives vary from granodiorite to alkaline granite in composition (Hernon,1932). In many places their texture is pegmatitic. The texture of the metamorphic rocks is gneissic along the outer zone of the range, granitic in the central parts of the range. Quartzites are encountered in many places within the Catalina gneiss. Along the southern margin of the range the Catalina gneiss shows a pronounced dip towards the Tucson basin.

The Catalina gneiss was ascribed pre-Cambrian age by earlier investigators (Darton,1925). In the light of more recent studies it appears that the intrusions and the metamorphism of earlier sediments may have taken place in Cretaceous (?) (Hernon,1932). In the opinion of B.S.Butler (*) the Catalina gneiss represents an example of granitization of sediments, at least in part.

South of the Catalina fault clastic deposits are found in patchy exposures which, because of their reddish and brown color, are referred to as <u>redbeds</u>. These redbeds form the base of alluvial fans in the area of study.

The redbeds are developed in two facies, a conglomeratic facies and a mudstone facies. The conglomerate overlies the mudstone. The conglomerate beds dip at a low angle and in many places truncate the lower mudstones which dip at a higher angle. An unconformity between rocks of these facies has been suggested (Smith,G.E.P.,1938) but seems improbable in view of an exposure near Hacienda del Sol, in the center of the area studied, in which some of the conglomerate beds merge into the lower, steeply dipping mudstone beds. Thus, the conglomerates appear to constitute topset beds and the mudstone beds are the foresets of delta formation.

---

* B.S.Butler: Oral communication.

The redbeds are composed of exotic constituents, including volcanic rocks, red and bluish quartzites, pink granites, gray fossiliferous limestones and quartzitic, cross-bedded sandstones. Outcrops of such rocks are not known along the southern front of the Santa Catalina Mountains. Some of them are exposed along the northern slope of the Catalinas, however.

Towards the present mountains particle sizes in the redbed conglomerates appear to increase slightly. This, however, is not sufficiently pronounced to be taken as conclusive evidence of the direction from which the sediments were derived. All redbed deposits are distinctly bedded; imbrication is absent. The type of transport and deposition seems to have been very different from those represented in the overlying alluvial fan deposits.

Several miles to the east of the area studied the entire thickness of the redbeds was penetrated by a drill. The thickness of the redbeds at this place is 600 feet. Catalina gneiss was encountered below.

In the area studied redbed deposits have been subjected to tectonic disturbance. Faults with little vertical displacement are a conspicuous feature. Small synclines and anticlines with gently dipping flanks are developed in the redbeds in the area of study.

The redbeds probably are of Pliocene age (Kirk Bryan,1925, p.66).

The top of the redbeds is a well developed erosion surface (pl.XVI,A,B).

Most of the area studied is covered by <u>alluvial fan deposits</u> (pl.I). The surface slope of these alluvial fans and characteristics of their deposits have been dealt with in part I and II of this paper.

Ninety per cent or more of the fragments in the alluvial fan deposits of the area studied are platy gneiss particles derived directly from the Santa Catalina Mountains. The rest are made up of schists, quartzites and pegmatite fragments, also known to occur in the mountain range, and of exotic constituents derived from the underlying redbeds.

The thickness of the Santa Catalina fan deposits in the area studied ranges from zero to one hundred feet at the apex and from two to three hundred feet at the base of the fan (pl.I,profile a-b).

The conspicuous development of the erosion surface on top of the redbeds suggests that there has been a considerable time interval between their deposition and that of the alluvial fans. Some alluvial fan deposits indicate in their high degree of consolidation that they were formed considerably earlier than others. Small alluvial fans at the base of the large alluvial fans of the Santa Catalina Mountains are in the process of aggradation (pl.I;pl.II;pl.VII,B). In general the large fans in the area of study undergo a process of degradation. The development of the alluvial fans in the area studied may have started in early or middle Pleistocene. Aggradation and degradation has gone on ever since.

Wash fill. These deposits occupy the bottoms of dry washes (pl.I). They consist of sand and gravels and show marked resemblance to older alluvial fan deposits. The wash fill is of very Recent age.

Floodplain deposits. In the area of study the floodplain deposits are well developed between the base of the alluvial fans and the course of the Rillito Creek in the extreme south (pl.I). Muds and sands with occasional pebble and granule lenses are the principal types of sediments involved. The floodplain deposits are of very Recent age.

FAN STAGES.

In the area examined three different levels predominate on the alluvial fans. The surface of alluvial fans, which is composed of separate fan-mesas, can be correlated with one of these three levels.

The difference in elevation between any two fan levels is greatest in the fanhead area and decreases toward the base of the fan (pl.I,profile a-b). Recognition of any particular fan level becomes progressively more difficult in the lower parts of the alluvial fan. These fan levels correspond to deposition stages on the alluvial fan.

The question of the relative age of the three fan stages in the Santa Catalina fans cannot be answered in the area examined because exposures showing the relations between deposits of all three fan stages are missing. Further east, along the Sabino Canyon Road, however, such exposures exist (fig.17;pl.XVII,A,B).

The highest fan level corresponds to the oldest stage of deposition (pl.I,stage "A"), the intermediate fan level to an intermediate stage (pl.I,stage "B"), and the lowest fan level to the youngest stage (pl.I,stage "C"). The three deposition stages are separated by surfaces formed during two stages of profound erosion.

The presence of younger alluvial fans spreading out between fan-mesas of older fans gives this fan an overall telescope structure (p.25;fig.4).

The effects of the lateral swing of a river at the base of the fan or rhythmically degrading base-level are discarded as likely explanations for the development of telescope structure in alluvial fans of the area examined because they do not produce this type of fan structure on a large scale.

Tectonic influences are favored by Davis (1931,p.299) in explanation of changes on alluvial fans of the Santa Catalina Mountains. This assumption, however, cannot be accepted on the basis of findings in the area examined. Thus, if the slope of upper surfaces of fan-mesas of stage "A" is projected across the area dissected by erosion, the fan slope meets the surface of a rock pediment developed adjacent to the present mountain front on the Santa Catalina Mountain gneiss. It is concluded that rock pediment and fan-mesas of stage "A" belong together (pl.I,profile a-b;pl.VIII,B;pl.XV,A,B). As rock pediment and fan-mesas of stage "A" are on different sides of the Catalina fault and as the surfaces of rock pediment and these fan-mesas are in line, no movement seems to have occurred along the Catalina fault since the time of deposition of alluvial fans of stage "A". The development of later stages "B" and "C" cannot result from tectonic movements along the Catalina fault. Other structural lines along which movement could have occurred later are not known in the area studied (pp.70-71).

An alternative explanation for the development of telescope structure is found in climatic changes. Such a hypothesis for the Santa Catalina Mountain fans was proposed by G.E.P.Smith (1938,p.83) who correlated fan stages with definite Pleistocene stages. No evidence was offered by Smith, nor could the present writer find indications which would allow such exact dating. Nevertheless, alternating periods of aggradation and degradation on alluvial fans of the Santa Catalina Mountains are believed to have resulted from changes between arid and humid.

Aggrading periods represented in fan levels of stages "A","B" and "C" may correspond to arid periods, degrading periods between these stages to humid periods. The assumption of climatic changes being the responsible factor for the development of telescope structure in the Santa Catalina Mountain fans is favored by the fact that much of the development of these fans probably took place during Pleistocene times when climatic changes must have occurred in this area contemporaneously with the advance and retreat of glaciers in the north.

Each alluvial fan stage shows a flatter gradient than that developed by the preceding stage(pl.I,profile a-b). Such development probably results from the continuous lowering of the mountains and the building up of the base-level of the fans.

GEOLOGIC HISTORY OF SANTA CATALINA MOUNTAIN FANS.

Pliocene epoch marks the time of deposition of redbeds in the area of study (p.73). The present Santa Catalina Mountains were not in existence then because the redbeds contain little or no gneissic material and because the type of deposition and particle size distribution of the redbeds do not indicate a gradient such as develops on a mountain front.

After consolidation of the redbed deposits tectonic movements occurred as evidenced by numerous faults and folds within the redbeds. Profound erosion transformed the surface of the redbeds into a landscape of gentle hills and valleys. Development of this erosion surface may have gone far into the Pleistocene epoch. The change from deposition of the redbeds to their erosion may have resulted from a regional up-warping

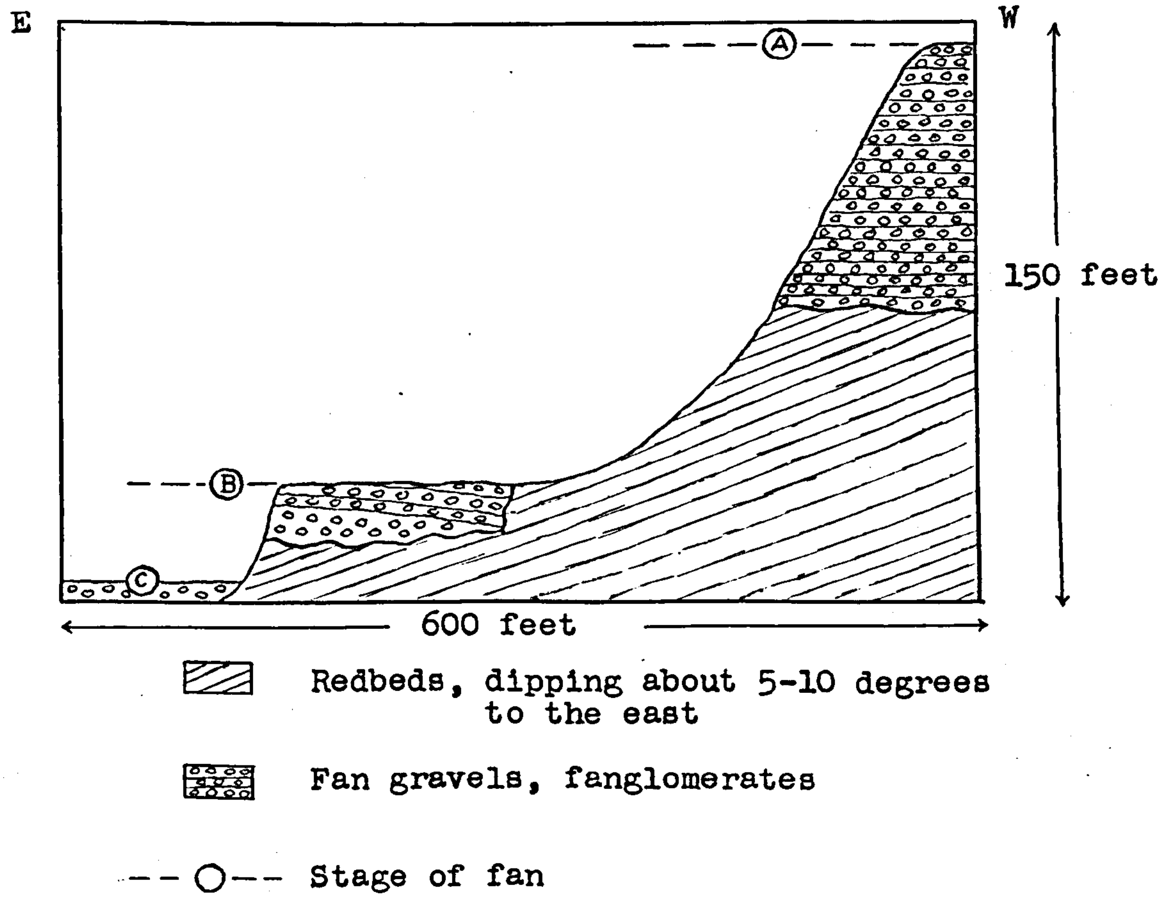


Fig.17. Relation of fan stages "A","B" and "C" in exposure at Sabino Canyon Road, east of the area studied (pl.I); base of the Santa Catalina Mountains, Arizona.

preceding the Santa Catalina Mountain orogeny.

The development of alluvial fans starts with the up-lift of the Santa Catalina Mountains. Fans of gneissic composition were formed at the base of the up-thrown Santa Catalina block. They were deposited on the erosion surface of the redbeds. These alluvial fans mark stage "A" in the development of fans. The gradient of the fan level of stage "A" is steeper than those developed during later stages. It is assumed that most of the building up of fans of stage "A" was accomplished under arid conditions. Since the up-lift of the Santa Catalina Mountains the mountain front receded leaving a comparatively smooth rock floor, the rock pediment. At the time of optimum development of stage "A" the apeces and fanhead areas of this stage may have covered the rock pediment adjacent to the mountain front. The thickness of alluvial fan deposits laid down during stage "A" has not been equaled during later stages. The rock pediment developed at the then mountain front is several hundred feet wide. It does not have counterparts of this magnitude during later stages. It may be concluded therefore that the time involved in building up stage "A" greatly exceeded the duration of the later stages "B" and "C".

Dissection of the fans of stage "A" probably resulted from a climatic change to more humid conditions. Erosion did not only remove part of the alluvial fan deposits laid down during stage "A" but also cut deeply into the underlying redbeds (fig.17). Degradation must have lasted for considerable time as stage "A" fans are preserved in only a few fan-mesas. The duration of post-stage "A" erosion may be comparable to the time involved in building up stage "A" fans.

Stage "B" was initiated by a change to arid climate. Degradation of the stage "A" fans stopped and aggradation set in again. Alluvial fans of stage "B" were built up around the fan-mesas of stage "A". The gradient of stage "B" fans is considerably flatter than that of the preceding stage. This is due probably to the lowering of the mountains and the building up of the base-level of the fans. The duration of stage "B" was considerably shorter than that of stage "A". The fan deposits of stage "B" are thinner and cover less area than those of the preceding stage.

Heavy dissection of stage "B" fans results from another change to more humid conditions. Erosion removes part of the stage "B" deposits and, in some places, cuts channels in the underlying redbeds. Post-stage "B" erosion of the fans did not last as long as the degradation phase after stage "A". In the area studied stage "B" deposits are still interconnected and the development of fan-mesas of "B" stage was not accomplished during the post-stage "B" erosion phase.

Stage "C" began with a change to more arid climate. Aggradation set in again and started to lay down fan deposits in the north of the area studied while at the base of the dissected fans small alluvial fans began to spread out. It is believed that stage "C" is still in a youthful phase and that optimum development of alluvial fans of stage "C" has not been accomplished yet.

Stage "C" is of very Recent age. This phase in the development of alluvial fans on the south flank of the Santa Catalina Mountains may have started several tens or hundreds of years ago. Stages "B" and "A" could be earlier Recent. Considering the time factor, however, involved in the aggradation and following degradation of these fan levels it appears more logical to ascribe Pleistocene age to the fan stages "A" and "B".

From the probable Pliocene age of the redbeds in the area studied deposited before the Santa Catalina Mountains were in existence and the probable Pleistocene age of the earlier fan deposits in this area laid down after the Santa Catalina orogeny it may be inferred that the up-lift of the Santa Catalina Mountains occurred in Pleistocene, possibly between Early and Middle Pleistocene.

BIBLIOGRAPHY.

Barrel, J. (1925) Marine and terrestrial conglomerates, Geol. Soc.Am.Bull.,Vol.36,No.2,pp.279-342

Blackwelder, E. (1928) Mudflow as a geologic agent in semi-arid mountains, Geol.Soc.Am.Bull.,Vol.39, No.2,pp.465-483

-------------- (1931) Desert plains, Jour.Geol.,Vol.39

Blissenbach, E. (1951) Geology of the Aubrey Valley, north-western Arizona, Plateau (in press)

Breazeale, J.F. and Smith, H.V. (1930) Caliche in Arizona, Univ.Ariz.,Agr.Exp.Station Bull.,No.131

Buwalda, J.P. (1951) Transportation of coarse material on alluvial fans, Abstract Cord.Sect., Geol. Soc.Am., Los Angeles

Bryan, K. (1925) The Papago Country, U.S.Geol.Survey, Water Supply Paper 499

Chawner, W.D. (1935) Alluvial fan flooding: The Montrose, California, flood of 1934, Geogr.Review, Vol.25,pp.255-263

Dana, J.D. (1894) Manual of geology. New York

Darton, N.H. (1925) A résumé of Arizona geology, Univ.Ariz., Ariz.Bur.Mines Bull.,No.119,Geol.Ser.No.3

Davis, W.M. (1898) Physical geography. New York

---------- (1931) The Santa Catalina Mountains, Arizona, Am. Jour.Sci.,5th ser.,Vol.22,pp.289-317

---------- (1938) Sheetfloods and streamfloods, Geol.Soc. Am.Bull.,Vol.49,pp.1337-1416

Drew, F. (1873) Alluvial and lacustrine deposits and glacial records of the upper Indus basin, Quart.Jour. Geol.Soc.,Vol.XXIX

Eardley, A.J. (1938) Sediments of Great Salt Lake, Utah, Am. Assoc.Petr.Geol.Bull.,Vol.22,No.10,pp.1305-1411

Eckis, R. (1928) Alluvial fans in the Cucamonga District, Southern California, Jour.Geol.,Vol.36,No.3, pp.224-247

Emmons,W.H., Thiel,G.A., Stauffer,C.R., Allison,I.S. (1949) Geology, principles and processes,3rd ed., New York

Gilbert, G.K. (1928) Studies of the Basin-Range structure, U.S.Geol.Survey, Prof.Paper 153

Grabau, A.W. (1913a) Principles of stratigraphy. New York

----------- (1913b) Early Paleozoic delta deposits of North America, Geol.Soc.Am.Bull.,Vol.24,pp.399-528

Hernon, R.M. (1932) Pegmatitic rocks of the Catalina-Rincon Mountains, Arizona, Master's thesis, Univ. Ariz.

Jahns, R.H. (1949) Desert floods, Engineering and Science Monthly, Cal.Inst.Tech.Alumni Assoc.,Contribution No.499

Johnson, D. (1932) Rock fans in arid regions, Am.Jour.Sci., 5th ser.,Vol.XXIII,No.137,pp.389-416

Koons, D. (1948) Geology of the eastern Hualpai Reservation, Plateau,Vol.20,No.4,pp.53-60

Krumbein, W.C. (1937) Sediments and exponential curves, Jour. Geol.,Vol.XLV,No.6,pp.577-601

------------ (1941) Measurement and geologic significance of shape and roundness of sedimentary particles, Jour.Sed.Petr.,Vol.11,No.2,pp.64-72

Lahee, F.H. (1941) Field geology, 4th ed. New York

Lawson, A.C. (1906) The geomorphogeny of the Tehachapi Valley System, Univ.Cal.Publ.Bull.,Dept.Geol.,Vol.IV

----------- (1913) The petrographic designation of alluvial fan formations, Univ.Cal.,Dept.Geol.,Bull.7

----------- (1915) The epigene profiles of the desert, Univ. Cal.Publ.,Geol.,Vol.9,pp.23-48

Longwell, C.R. (1930) Faulted fans west of the Sheep Range, South Nevada, Am.Jour.Sci.,5th ser., Vol.20

------------- , Knopf,A., Flint,R.F., (1932) Geology, Part I, New York

McGee, W.J. (1897) Sheetflood erosion, Geol.Soc.Am.Bull., Vol.8,pp.87-112

Miller, W.J. (1926) Geology. New York

Oldham, R.D. (1893) Manual of the geology of India, 2nd ed., Calcutta

Pack, F.J. (1923) Torrential potential of desert waters, Pan-Am.Geol.,Vol.40,pp.349-356

Payne, T.G. (1942) Stratigraphic analysis and environmental reconstruction, Am.Assoc.Petr.Geol. Bull.,Vol.26,No.11

Penck, A. (1894) Morphologie der Erdoberflaeche,Vol.I

Petermann, A. (1867) Ein Flussdelta im Innern von Australien und die neuesten Entdeckungen von Waburton und der deutschen Missionare Walder, Kramer und Meissel, 1866-1867, Petermann's Geographische Mitteilungen, pp. 437-447

Scott, W.B. (1932) An introduction to geology. New York

Short, M.N. and McKee, E.D. (1951) Hand specimen petrology, McGraw-Hill Book Co., New York (in press)

Smith, G.E.P. (1938) The physiography of Arizona valleys and the occurrence of groundwater, Univ.Ariz. Agr.Exp.Station, Tech.Bull.,No.77

Smith, H.V. (1945) The climate of Arizona, Univ.Ariz.,Agr. Exp.Station,Bull.197

Thompson, H.D. (1947) Fundamentals of earth science, New York

Tolman, C.T. (1937) Groundwater, 1rst ed. New York

Trask, P.D. (1932) Origin and environment of source sediments of petroleum, Gulf Publ.Co.,Houston, Texas

Trowbridge, A.C. (1911) The terrestrial deposits of Owens Valley, California, Jour.Geol.,Vol.19, pp.706-747

Troxell, H.C. and others (1942) Floods of March 1938 in southern California, U.S.Geol.Survey, Water Supply Paper 844

Twenhofel, W.H. (1926) Treatise of sedimentation. New York

-------------- (1939) Principles of sedimentation, 1rst ed., New York

-------------- (1950) Principles of sedimentation, 2nd ed., New York

Vaughan, F.E. (1922) Geology of the San Bernardino Mountains north of San Gorgonio Pass, California, Cal.Univ.Publ.,Dept.Geol.Sci.Bull.,Vol. 13,No.9,pp.319-411

Walther, J. (1924) Das Gesetz der Wuestenbildung in Gegenwart und Vorzeit, 4th ed., Leipzig

Plate IV. A and B. Compound alluvial fans on the south flank of the Santa Catalina Mountains, Arizona.

Plate V. A. Coalescence of two single alluvial fans to form a compound fan, Black Hills, Ariz.

B. Mudflow deposit (M) laid down by sheet-flood fills the depression where the two fans in A. meet.

Plate VI. A and B. Small alluvial fan with telescope structure, Black Hills, Arizona.

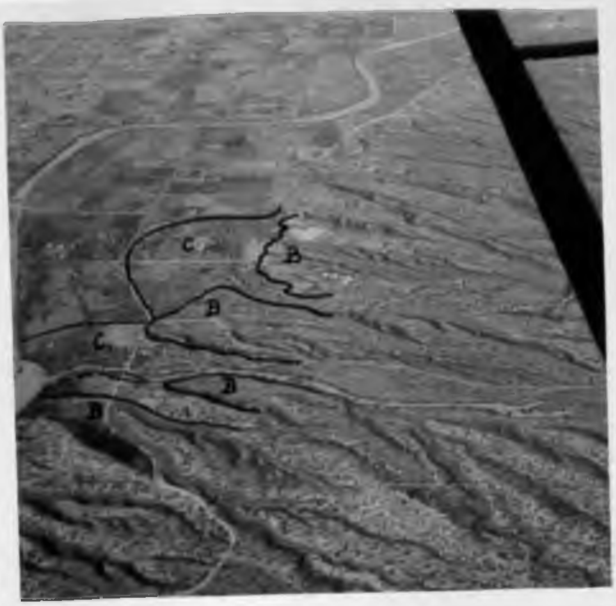


Plate VII. A. Fan-mesas on compound alluvial fan of Santa Catalina Mountains, Arizona; near Sabino Canyon Road.

B. Secondary alluvial fans C and C_1 (pl.II) at the base of primary fans B (pl.I), Santa Catalina Mountains, Arizona.

Plate VIII. A. Stratified alluvial fan deposits on top of river deposits; base of a small alluvial fan (pl.II), Santa Catalina Mountains, Arizona.

B. Rock pediment (gneiss) adjacent to the mountain front (extreme left) of the Santa Catalina Mountains, Arizona (pl.I); drop is to the right to present fan level.

Plate IX.A. Fanglomerate deposited by stream or moderate streamflood. 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, Ariz.

B. Fanglomerate deposited by mudflow; poor sorting, random orientation of particles. Large particles are 10 centimeters in diameter. Santa Catalina Mountain fans, Arizona.

Plate X. A and B. Stratified fanglomerate (Fs) laid down by stream or streamflood on top of unstratified fanglomerate (Fn) deposited by mudflow. Ruler is 15 centimeters. Alluvial fan of the Santa Catalina Mountains, Arizona.

Plate XI.A. Imbrication in large particles (up to 150 centimeters). Direction of transport from right to left. Close to the apex of an alluvial fan of the Santa Catalina Mountains, Ariz.

B. Imbrication in medium-sized particles (up to 10 centimeters). Direction of transport from left to right. Midfan area, Santa Catalina Mountain fan, Arizona.

Plate XII. Aerial view of alluvial fan studied at the base of the Santa Catalina Mountains, Arizona. Inked line to the west is Campbell Ave., to the east Pontiac Road (pl.I). Scale approximately 1:100000.

Plate XIII.A. Injection gneiss of the Santa Catalina Mountains, Arizona; at Sabino Canyon Road.

B. Apex of alluvial fan, stage "B" (pl.I). Front of Santa Catalina Mountains, Arizona.

Plate XIV.A. Exposure of Catalina fault, east of Campbell Ave., base of Santa Catalina Mountains, Arizona. G - Catalina gneiss, RB - Redbeds, AF - Alluvial fan deposits, FZ - Fault zone.

B. View of fan levels "A" and "B" at fan-mesa "A_1" (pl.I), alluvial fan of Santa Catalina Mountains, Arizona.

Plate XV. A. Surface of gneiss pediment (inked line) seen from fan-mesa "A_1" (pl.I), Santa Catalina Mountains, Arizona.

B. View from gneiss pediment (Gp) to fan-mesa "A_1" (pl.I), Santa Catalina Mountain fans, Arizona.

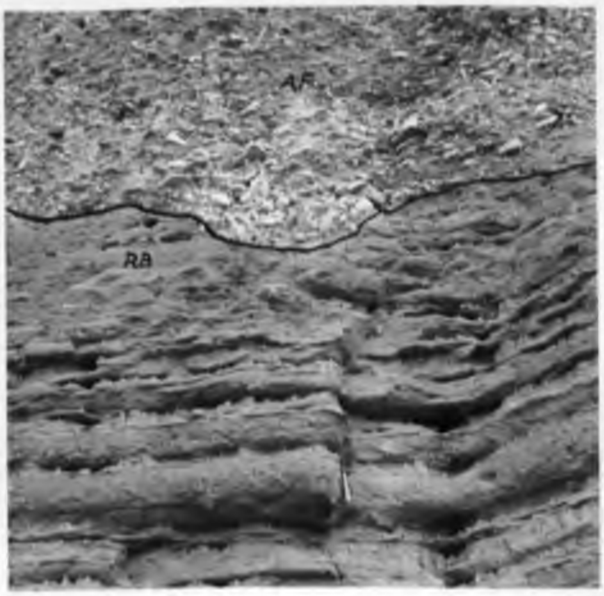


Plate XVI.A. Alluvial fan deposits (AF) unconformably overlying redbeds (RB). Deposits formed by slumping (S) along side of former channel. Hacienda del Sol, base of Santa Catalina Mountains, Arizona.

B. Contact of alluvial fan deposits (AF) on top of redbeds (RB). Hacienda del Sol, base of Santa Catalina Mountains, Arizona.

Plate XVII. A. Contact of fanglomerate of fan stage "A" with underlying redbeds. Alluvial fan deposits (AF), redbeds (RB). Exposure near Sabino Canyon Road.(fig.17), base of Santa Catalina Mountains,Ariz.

B. Same; close view of contact.

Plate XVIII. A. Poorly stratified fanglomerate on top of well stratified fanglomerate, alluvial fans, Santa Catalina Mountains, Arizona.

B. Base of small alluvial fan (pl.II) cut by the Rillito Creek, Santa Catalina Mountain fans, Arizona.

(3 pieces)

PLATE II.

MAP OF ALLUVIAL FAN C1.

SCALE 1:3000

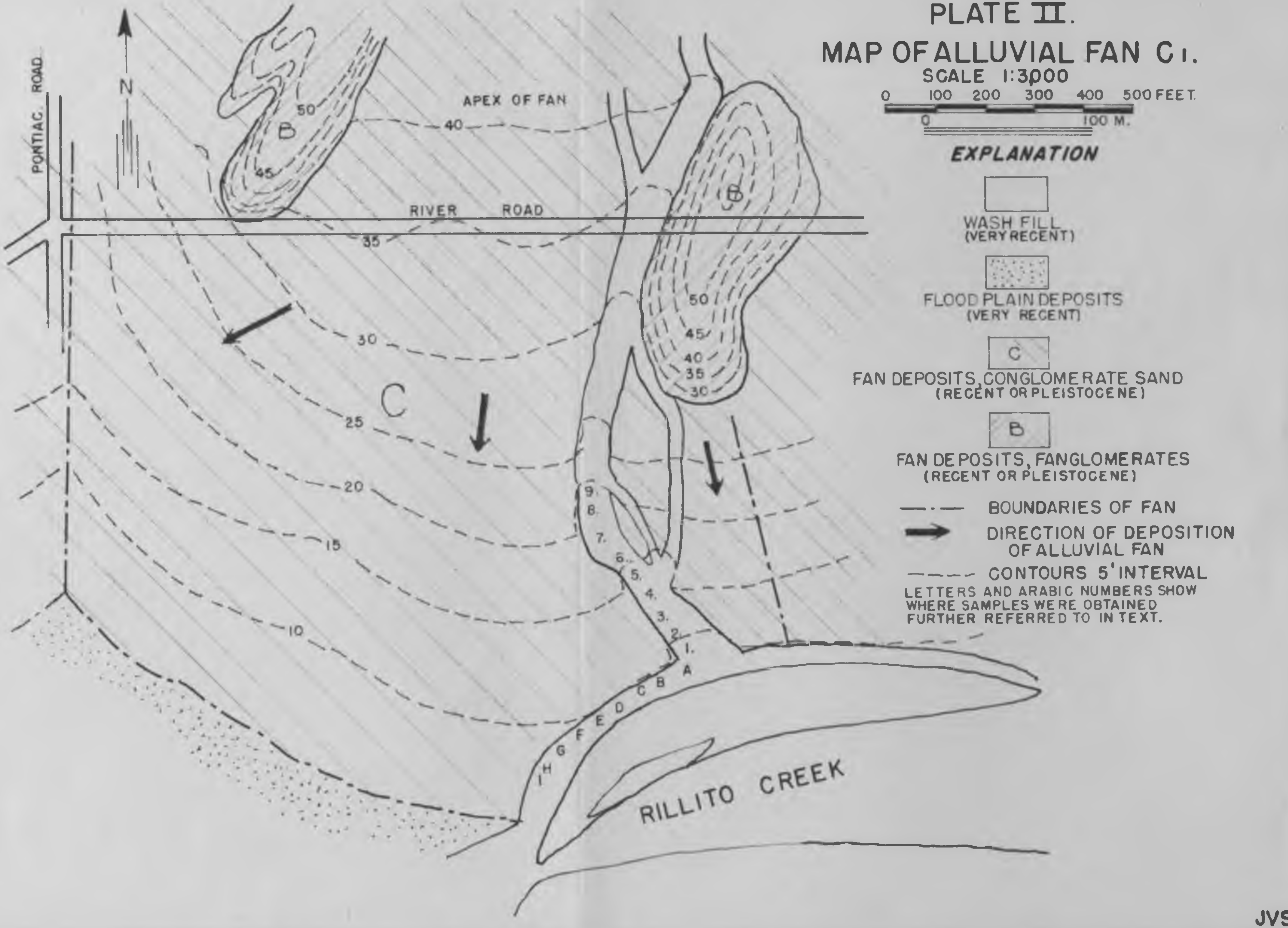


PLATE I.
SHOWING FAN DEPOSITS CATALINA FOOTHILLS.

SCALE 1:29500

0 1000 2000 3000 FEET

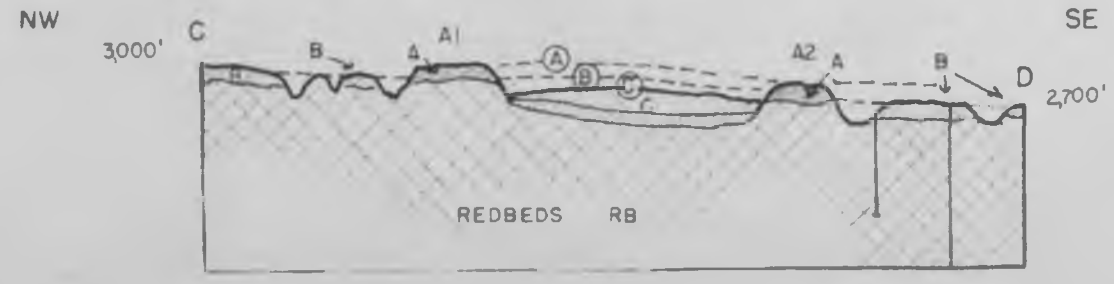
0 1 KM.

EXPLANATION

FLOOD PLAIN DEPOSITS (RECENT)	QUATERNARY
WASH FILL (RECENT)	QUATERNARY
C — ALLUVIAL FAN DEPOSITS STAGE-C (RECENT)	QUATERNARY
B — ALLUVIAL FAN DEPOSITS STAGE-B (RECENT OR PLEISTOCENE)	QUATERNARY
A — ALLUVIAL FAN DEPOSITS STAGE-A (EARLY RECENT OR PLEISTOCENE)	QUATERNARY
RB — RED BEDS	TERTIARY (?)
G — CATALINA GNEISS	CRETACEOUS (?)

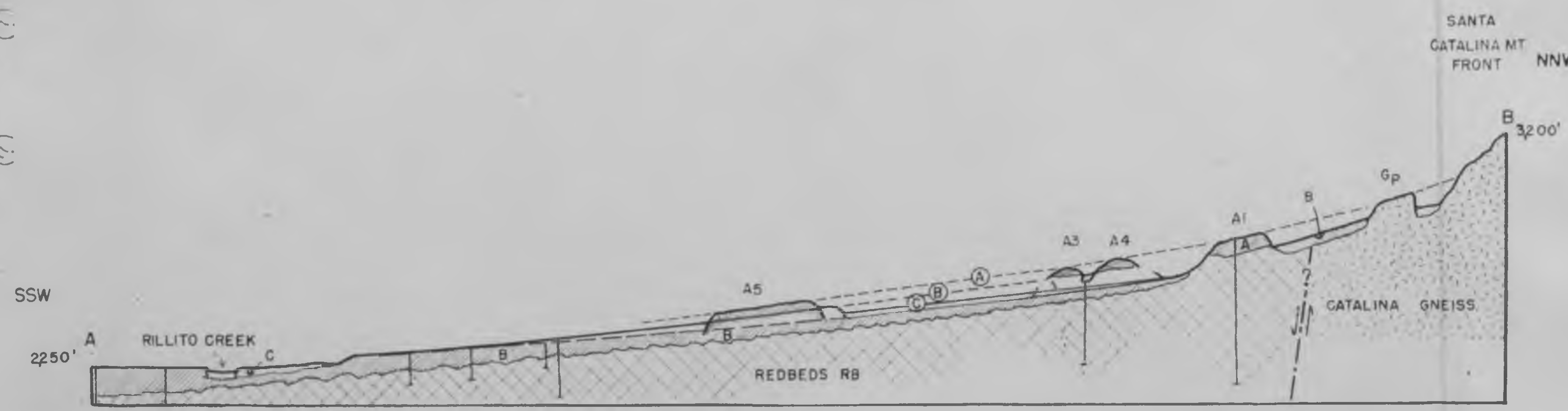
- —Gp— GNEISS PED
- ROADS
- STREAMS
- FAULT
- ◎ WELLS
- | WELL LOG IN PROFILE
- CONTOUR LINES 100' INTERVAL
- --Ⓐ-- --Ⓑ-- --Ⓒ-- SURFACE OF ALLUVIAL FANS IN PROFILE

SHADED AREA IN SE CORNER, ILLUSTRATING ALLUVIAL FAN C1 ENLARGED APPROXIMATELY 10 TIMES IN PLATE II.



SECTION CD.

VERTICAL SCALE ENLARGED THREE TIMES



SECTION AB

VERTICAL SCALE ENLARGED THREE TIMES

JVS

TABLE V.

Classifying properties of alluvial fans.

MORPHOLOGIC SHAPE	CLASSIFYING TERMS	CAUSES
Dimensions	Radial extent; Thickness; Difference in elevation apex-base	
Surface slope	steep (5 degr.and more) gentle (2-5 degrees) flat (less than 2 degr.)	
Lateral arrangement	Compound alluvial fan	Lateral interfingering of single alluvial fans
	Chessboard pattern	Lateral alternation of large and small alluvial fans
OVERALL STRUCTURE		
Simple structure		Young age and maturity stages
Complex structure	Dissection	Changes in normal course of cycle (old age)
	Superimposed structure	Tectonic movements; Climatic changes (?); mainly on large fans
	Telescoped structure	Degrading base-level; Lateral swing of river at base; on small fans Climatic changes; Tectonic movements; on large fans
	Pseudo-telescope structure	Slumping of fan deposits
ALLUVIAL FAN DEPOSITS		
Facies	Fan gravel - Fanglom. Fan sands - Fan ss. Fan muds - Fan ms.	
Particle size	Particle sizes at apex and base; distribution	
Deposit.agent	Sheetflood Streamflood Stream	Volume of detritus,water: big moderate small
Composition	arkosic	Parent rock : abundance of megascopic feldspars
	graywacke	without megascopic feldspars
Sorting	poor fair good	Detritus Dist.of Agent transp. heterog. short sheetf. intermed. inter. streamf. homogen. long stream
Roundness	angular sub-angular sub-rounded rounded	Dist. of transport : short long
Sphericity	constant changes	Change in composition or facies
Matrix	Sand - Mud primary-secondary arkosic-graywacke	
Cement	Calcium carbonate, Limonite, etc. (percentage)	
Color	yellow, gray; red, brown; locally black	
Porosity	high - low (30% - 0)	
Permeability	high low	Abundance of : Stream deposits Mudflow deposits
Sedimentary structures		
Dip of strata	steep (5 degr.and more) gentle (2-5 degrees) flat (below 2 degrees)	
Stratification	good poor	Abundance of: Stream deposits Mudflow deposits
Cross-stratif.	Channel cut-and-fill none	Stream deposits Mudflow deposits
Thickness of individ.strata	thick 15 - 20 feet thin fraction of inch	
Shape of strata	lenticular sheetlike	Stream,streamfl.dep. Sheetflood deposits
Preferred orientation	imbrication present " absent	Stream deposits Mudflow deposits