# ALLUVIAL FANS

Thesis by

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# ABSTRACT

Alluvial fans were studied in the field, largely in the desert regions of California, and in the laboratory. Field study consisted of detailed mapping of ages and sizes of debris, channel patterns, and deposits of different types on parts of four fans, and reconnaissance work on over 100 additional fans. Reconnaissance generally consisted of outlining the fan, noting material size and channel patterns, and measuring a few slopes. In the laboratory small alluvial fans were built of mud and sand transported through a channel into a five-foot square box under controlled conditions.

Material is transported to fans by debris flows or water flows which follow the main channel. This channel is generally incised at the fanhead, because there water is able to transport on a lower slope the material deposited earlier by debris flows. Since the main channel at the fanhead has a lower slope than the adjacent fan surface, it emerges onto the surface near a midfan point herein called the intersection point. On the laboratory fans most deposition above the intersection point is by debris flows that exceed the depth of the incised channel. Fluvial deposition dominates below the intersection point. This is also inferred to be true on natural fans.

Fans deficient in fine material may have so high an

infiltration rate that even moderately large discharges are completely absorbed before reaching the toe of the fan. Under these conditions the coarse debris in transport is deposited as lobate masses on the fan. In many respects these deposits resemble and may, in the past, have been mistaken for debris-flow deposits.

The empirical relationship between fan area, $A_f$, and drainage-basin area, $A_d$,

$$A_f = cA_d^{\,n}$$

has been recognized previously (Bull, 1964; Denny, 1965). The present study suggests that this relationship results from a tendency toward a quasi steady-state between coalescing fans in the same lithologic, tectonic, and geographic environment. The quasi steady-state exists when all fans are increasing in thickness at the same rate. If rates differ, the areas of the fans will change to approach a quasi steady-state. The rate of deposition is determined by the influx of debris, which is a function of drainage-basin area. The exponent $\underline{n}$ is less than unity because a storm of a given recurrence interval is less likely to envelop a large drainage basin than a small one. The coefficient $\underline{c}$ is a function of the lithologic, tectonic, and geographic environment.

Rates of deposition on fans may be estimated from this relationship using Langbein and Schumm's (1958) data on sediment yield as a function of precipitation. A typical average rate is on the order of one foot per 1,000 years. If a long-term tectonic process is superimposed upon the quasi steady-state relationship between fans in the same lithologic and geographic environment, the rate of deposition may be used to estimate the rate and nature of the tectonic process. As an example, the difference in depositional rates on opposite sides of Death Valley suggests a present rate of eastward tilting of 0.018 degrees/1000 years.

The slope of an alluvial fan is determined primarily by debris size and water discharge. Large fans have larger drainage basins and hence larger discharges than small fans. Consequently fan slope generally decreases with increasing fan area.

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# INTRODUCTION

## Previous Work

Until recently alluvial fans have not received the attention deserved by so prominent a feature of the arid landscape. Most early papers are descriptive and contain little quantitative data on processes or surface features. Recent papers by Lustig (1963), Bull (1964), and Denny (1965) are notable exceptions. Only Denny and Lustig (in press) did detailed geomorphic mapping on fans.

## Purpose and Methods of Investigation

The object of this study was to achieve an understanding of processes acting on fans and the morphologic consequences of these processes.

The conclusions reached are based on reconnaissance and detailed field work, and on a concurrent model study. The reconnaissance work consisted of qualitative observations on channel pattern, form of the main channel, lithology and size of fan material, and other unusual or interesting features, supplemented by quantitative measurements in some instances. In this cursory manner, data were taken on more than 100 fans in California (Fig. 1).

Six of these fans were selected for detailed field work. The locations and names of five of them are shown in Figure 1, and exact locations are given in the Appendix.

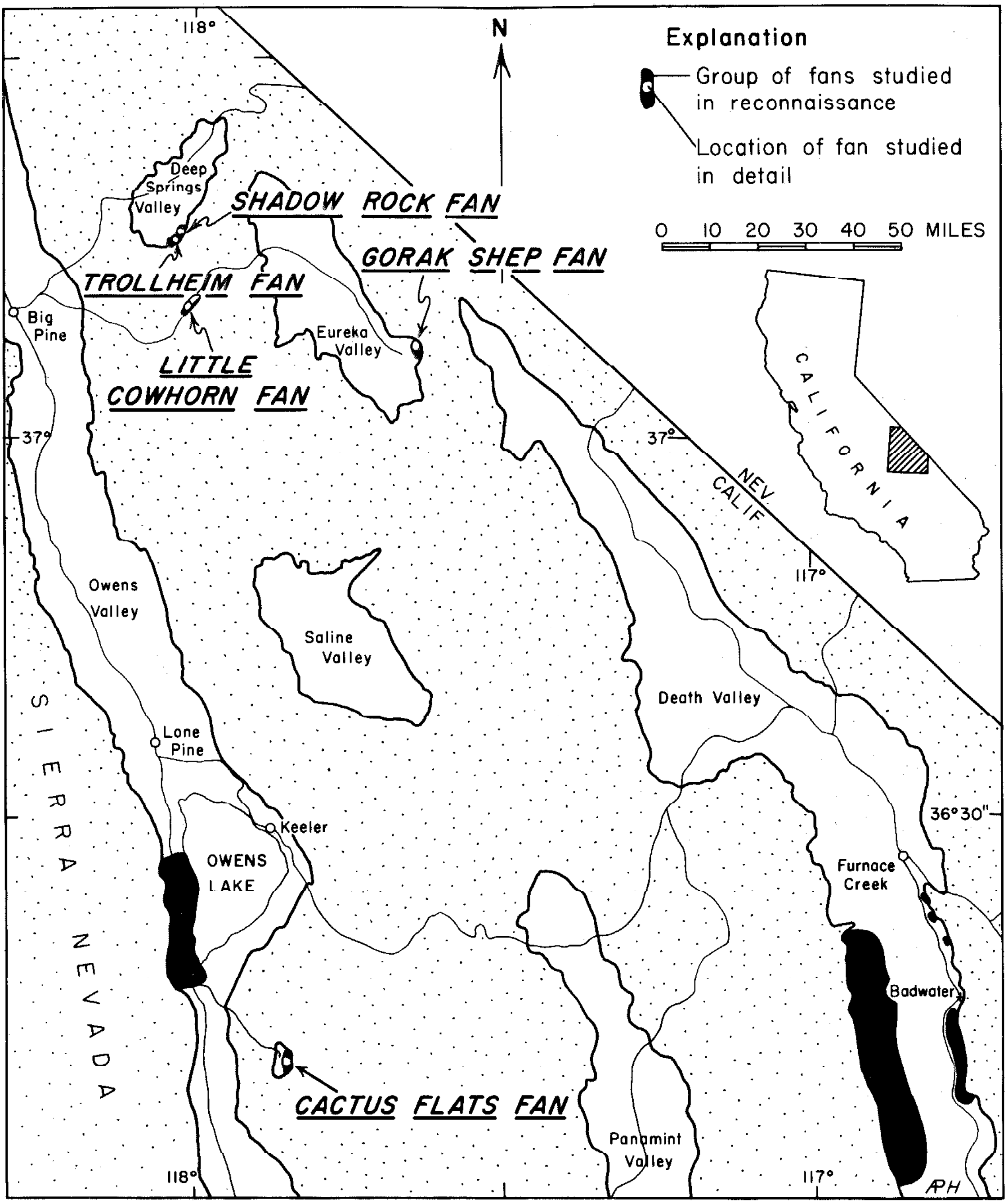


Figure 1. Index map showing locations of fans discussed in this paper. Sand Fan is several miles south of the area covered by this map and hence is not shown. Detailed locations of all fans are given in the Appendix.

The nature of these detailed studies was determined by the characteristics of the fan and by specific objectives. Detailed geomorphic mapping, and measurement of channel cross sections and of weathering phenomena, were the most commonly used procedures. Mapping was done by plane-table methods or on large-scale aerial photographs.

The model studies were designed to supplement, and to answer questions raised by the field investigation. Observation of processes and features on laboratory fans focused attention on field features that might otherwise have been overlooked or mis-identified. The experiments were designed to yield qualitative data on processes rather than to model a particular fan.

Because of the diversity of fans studied, many of the conclusions are believed to be applicable not only to these fans, but to active fans throughout arid regions.

## Terminology

It is convenient, at this stage, to define several terms, some being used for the first time.

### Intersection point

The slope of major channels on most fans is less than the slope of the adjacent fan surface (Fig. 2). As a result the channels are deeper upstream and shallow gradually downstream until they merge with the fan surface at a place

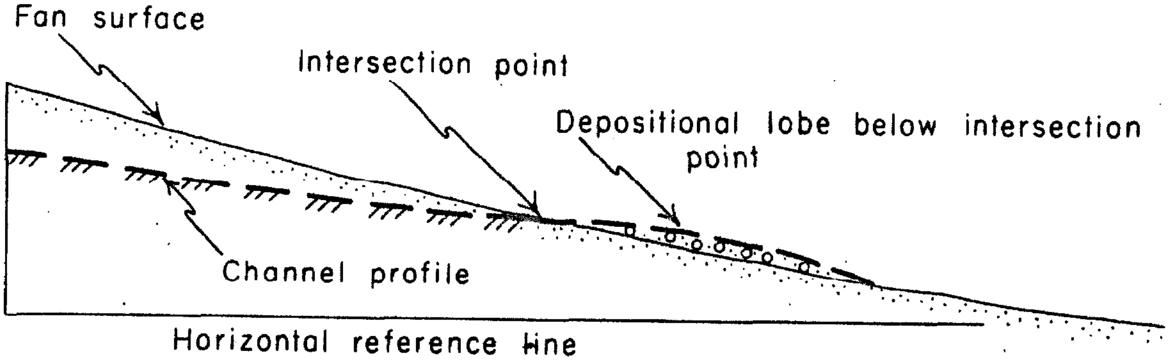


Figure 2. Idealized sketch of intersection-point relationships.

herein called the intersection point. This is usually a locus of deposition and the material deposited is commonly coarser than the average material found in the channel. In some instances this deposit forms a secondary lobe on the fan surface below the intersection point (Figs. 2 and 3B).

Sieve deposition

In a flow of water transporting material of pebble size and larger, an abrupt decrease in slope, a large stationary stone, or loss of water by infiltration, can cause deposition. This results in a decrease in slope and further deposition upstream. If there is little material of sand size or smaller in transport, the voids in the deposit of coarse material will not be filled and the deposit will be very permeable. The permeability may be so

Figure 3A. Geomorphic map of Little Cowhorn Fan.

The cobble- and boulder-sized material was probably transported to the fan by debris flows. Swales are poorly-defined, shallow, linear depressions with indistinct banks. On the south, inactive, half of the fan they are either old channels filled by creep, or linear topographic depressions which carry some runoff.

Age designation of channels is based on topographic relationships. Thus channel 3 is cut about three feet below channel 4 near the 180-foot contour. Channel 5 exists as a terrace remnant above channels 3 and 4 but below the level of the adjacent fan surface (see 200-foot contour).

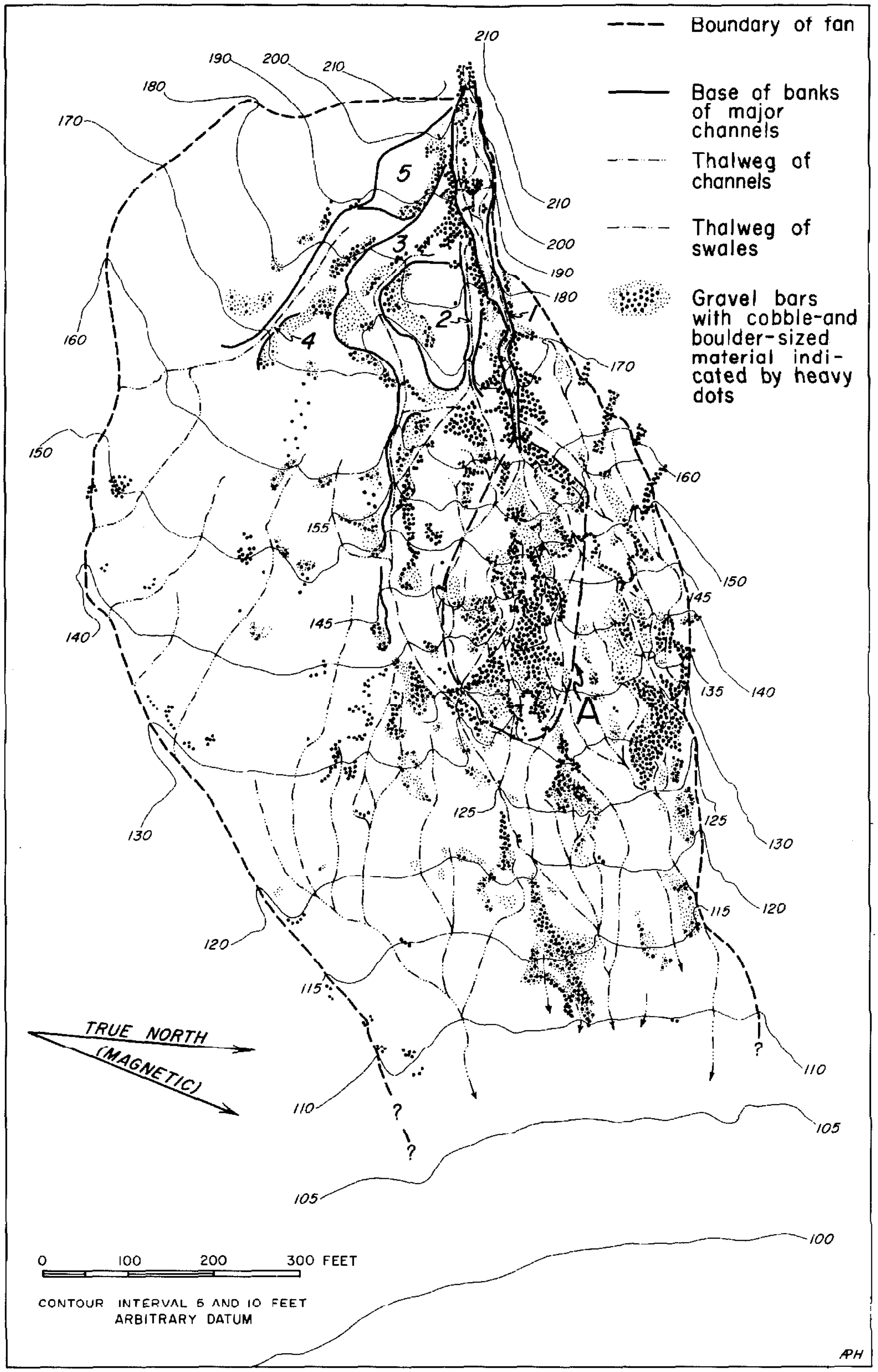

Boundary of fan
Base of banks of major channels
Thalweg of channels
Thalweg of swales
Gravel bars with cobble-and boulder-sized material indicated by heavy dots
210
190
200
210
180
170
160
150
140
130
120
115
110
105
100
155
145
125
135
1
2
3
4
5
A
?
TRUE NORTH
(MAGNETIC)
0 100 200 300 FEET
CONTOUR INTERVAL 5 AND 10 FEET
ARBITRARY DATUM
APH

Figure 3A.

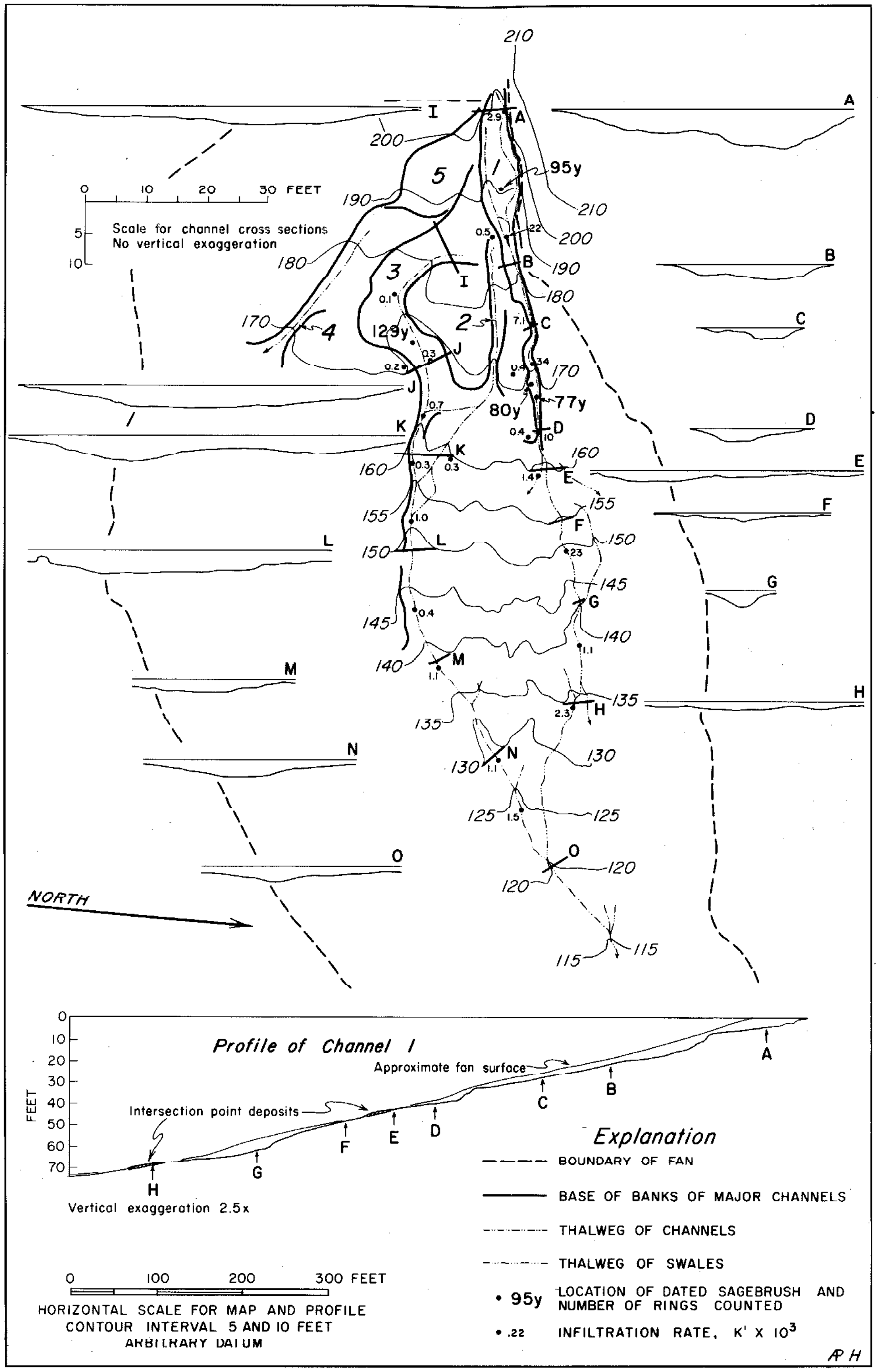


Figure 3 B. Map of part of Little Cowhorn Fan showing five main channels, channel cross sections, and longitudinal profile of channel 1.

high that most or all of the subsequent water flow passes through rather than over the deposit. The deposit thus acts as a strainer or sieve by permitting water to pass while holding back the coarse material in transport. I call the lobate mass thus formed a sieve lobe or sieve deposit while the mode of formation is sieve deposition.

### Overall fan slope

This is defined as the slope of a straight line from a point at or near the toe of the fan to the fanhead (Bull, 1964, p. 94).

### Overall drainage-basin slope

In a similar way this is defined as the slope of a straight line from the fanhead to the highest point in the drainage basin.

### Dominant size

The dominant size is the size of material that controls the slope of the fan surface. If all coarser material were reduced to the dominant size, the fan slope would remain unchanged. Field estimates suggest that the dominant size is approximately $d_{75}$; that is, 75 percent by weight of the material on the fan surface is smaller than the dominant size and 25 percent is larger.

### Dominant discharge

Conceptually, the dominant discharge is the discharge responsible for the gross morphology of an alluvial fan. Larger discharges are too infrequent and smaller discharges lack the competence and capacity to affect the fan morphology as much as the dominant discharge. In comparing fans with different-sized drainage basins, the recurrence interval of the dominant discharge must be used, much as the bankfull discharge is used in comparing different reaches of a perennial river (Leopold and Maddock, 1953, p. 9-19).

## Fanhead incision

In this report a fanhead will be considered incised if it seems unreasonable to expect overbank flooding by water flows at least once in a few decades. The discharge required to produce overbank flooding may be approximated by means of the Manning equation if the width, depth and slope of the channel are measured and the hydraulic roughness estimated. In most cases of fanhead incision the discharge so calculated will be totally unreasonable in terms of the area and hydrologic characteristics of the drainage basin. For example, a discharge of approximately 33,000 cfs would be required for overbank flooding at channel cross-section A on Gorak Shep Fan (Figs. 1 and 9B) which has a drainage area of less than one square mile. On the basis of this definition a wide or steep channel need not be especially deep to be incised.

### Quasi Steady-state

The term steady-state is used to describe a system, certain aspects of which (e.g., fan area, and fan slope) remain constant while other aspects (e.g., thickness of fan, and position of the intersection point) vary. In a quasi steady-state system the "constant" factors fluctuate about a mean during geologically short periods of time, but over a much longer time interval the mean changes gradually in response to net denudation of the source area or to secular climatic change.

## Similarity of Process

Alluvial fans have comparatively low slopes and either straight or concave radial profiles. In addition morphologic features on fans tend to radiate from the fanhead. These similarities reflect common influences in fan development. Most important among these influences are two hydraulic transport phenomena, debris flows and fluvial flows. This duality of hydraulic processes on fans has been recognized previously (Blackwelder, 1928, p. 480; and Blissenbach, 1954, p. 177-178; among others).

The present study relies upon the similarity of process concept in two important ways. First, it is assumed that detailed study of a few fans will lead to conclusions generally applicable to most fans. Study of fans from widely diverse climatic, lithologic, and tectonic environments should reveal the influence of these factors on fan processes, and errors resulting from too limited a range of observation can thus be avoided. Secondly, to avoid difficult, if not insoluble, scaling problems, fans built in the laboratory must be treated as small fans in their own right, not as scale models of existing fans. The best way to demonstrate the basic validity of this treatment is to show that processes acting on laboratory fans are similar to those acting on natural fans. For these purposes the concept of similarity of process must be carried much farther than radial symmetry and low slope by considering surface morphology. In this section natural fans alone will be considered, leaving the extension to laboratory fans until the laboratory apparatus and procedures have been described.

Most fans have a main channel which heads in the source area and ends at an intersection point on the fan. In rare cases the channel may end at the fanhead. Small secondary channels typically head in the intersection point deposit (Fig. 3 A). These channels commonly coalesce and divide, forming a braided pattern. When two secondary channels join, the resulting channel may be much deeper than either of the branches.

Most surficial features of primarily depositional origin are products of debris flows. Debris-flow levees and lobate debris-flow tongues are the most common and most important features. Sieve deposits generally take the place of debris-flow features on fans lacking fine material, and are, of course, of fluvial origin.

These depositional features and channel patterns appear on fans of otherwise diverse character. Fans with extensively channeled surfaces and fans with large areas of subdued relief have basically the same morphologic characteristics. Fans on the east side of the Sierra Nevada, west of Olancha, California, have an unusually large number of boulders greater than three to four feet in diameter yet they show basically the same features as fans composed of finer detritus. Fans with channels incised to depths of 100 feet in Death Valley (Johnson Canyon Fan) are morphologically similar to those with only moderate fanhead incision.

As with most generalizations there are some exceptions. On some fans the intersection point may be so near the fanhead that a main channel is almost non-existent. This is usually the result of tectonic disturbance. In other instances the source rock may not produce much cobble- and boulder-sized material. In such situations debris-flow levees and tongues will not retain their distinctive form, and coarse material will not accumulate at the intersection point. On fans composed dominantly of sandy material, creep and down-slope movements may be so active as to erase all but the largest and most recent surface features. But even on these fans scattered boulders testify to the importance of debris flows. These morphologic similarities support the concept of similarity of process, a basic premise of this study.

# THE MODEL

## Introduction

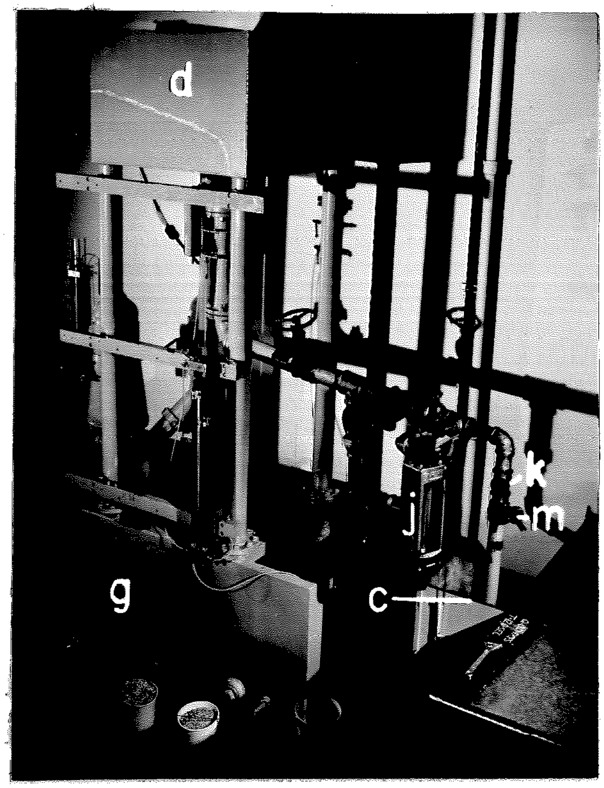
Geologists have speculated on aspects of alluvial-fan morphology, but few have observed the processes of deposition and erosion by which a fan is made. Laboratory study enables the geologist to observe these processes and focuses attention on aspects of fan morphology which might otherwise be neglected. Semi-quantitative information on relationships between fan slope, water discharge, debris-flow behavior, and the depth of fanhead incision can be obtained, if the reasons for these relationships on laboratory fans are thoroughly understood, and if the same reasons can be applied logically to natural fans.

An exact model of a specific fan would give information regarding the rate of formation of that fan, and might answer other specific quantitative questions. However, many of the pertinent factors such as sediment transport by debris flows and streams are not well enough understood to permit accurate modeling; others such as weathering cannot be modeled owing to the time factor; and still others, such as proper size-grading of sediment, would be very time consuming to model. Thus it seemed advisable to model processes instead of individual fans.

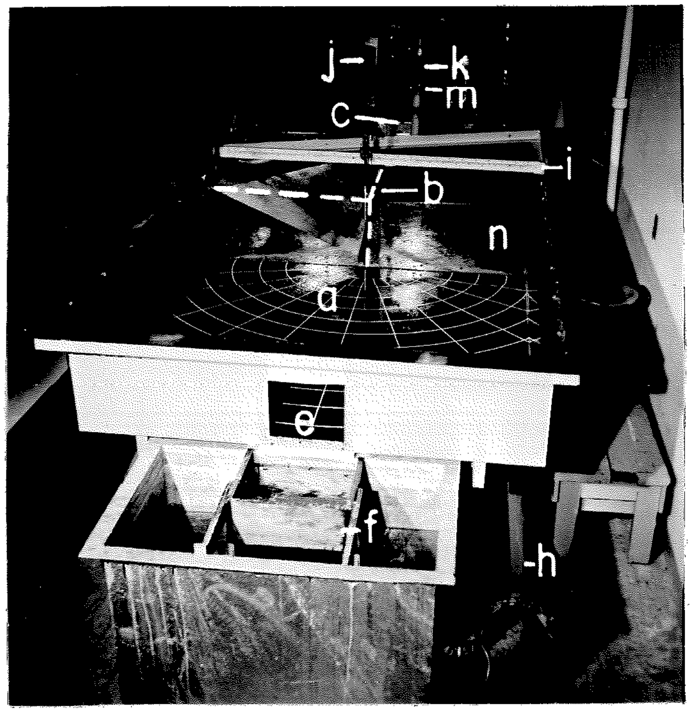
## Apparatus

The modeling apparatus is shown in Plate 1. Water is pumped into the constant-head tank, d (Plate 1A), from whence it flowed through a series of pipes and valves, into the inlet box, c. The inlet box was 43" deep and the inlet pipe was submerged to a depth of about 30". Thus the water surface at the entrance to the sheet-metal channel, b, was comparatively free of disturbance. The channel was 4" wide and 50" long, and had a slope of 0.162. Both channel banks were vertical and about 3½" high at the inlet. However the banks varied in height uniformly downstream, the left bank (Plate 1B) being about 1½" and the right bank 12" high at the bulkhead, n. The channel bottom was artificially roughened by cementing to it a mixture of coarse sand and granules, but flow was still generally supercritical above the limit of backfilling from the aggrading fan. Debris was picked up in the channel and deposited as a fan in the working area, a, which was 59½" wide and 60" long. Water left the working area through the outlet gate, e, and sediment trap, f, and returned to the reservoir, g, below the constant-head source via the return pipe, h.

The working area had a slope of 0.0076 toward the outlet. However, the instrument carriage, i, carrying the point gage, rode on horizontal rails. Thus all elevation measurements were made with respect to a horizontal datum



A. Water source.



B. Working area.

Plate 1. Experimental apparatus. Letters and dashed lines are referred to in text.

plane. Discharge was measured with a Fischer and Porter Company precision-bore flowrator tube*, j, and was regulated with the plug valve, k. Discharges on the order of 0.002 to 0.02 cfs were used. The fast-action valve, m, was used to turn the flow on and off so the setting of the plug valve could be left unchanged during a run.

## Procedure

### Series A

The first series of model experiments comprised twelve runs. Each run consisted of eight to twelve or thirteen episodes. Each episode involved packing the channel (b in Plate 1B) with a fixed amount of material, and then opening the fast-action valve for a fixed length of time, T, with the discharge, Q, entering the inlet box determined by the setting of the plug valve. During each run Q and T were held constant. However, owing to storage in the inlet box as the water surface rose to the level of the debris in the channel, discharge at the bulkhead varied in a manner similar to a natural hydrograph. The discharge was high immediately after erosion started, but decreased to a constant value when debris in the channel had been eroded to the level of the channel inlet. Runs were made with four different discharges, and three runs with

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*Keck Laboratory number Q-29.

different values of T were made at each discharge, making a total of twelve runs (Fig. 6). Following the eighth episode in each run a contour map of the resulting fan was made and morphological features were mapped (Fig. 6). The values of Q and T for each run are given on the left side and at the top of Figure 6.

The quantity of material used in each event was held constant for the entire series of runs, and amounted to roughly 17 lbs. dry weight. This debris was in the coarse-sand to granule range on the Wentworth scale and was poorly sorted (Fig. 4).

## Series B.

Use of finer sediment and lower discharges during the Series B experiments necessitated certain changes in the apparatus. A new flowrator tube* with a lower capacity was installed to obtain greater accuracy in measuring the lower flows. To avoid recycling of fine material and possible damage to the valves and flowrator (j, k, and m in Plate 1A), the return pipe, h, was eliminated, and turbid water leaving the model discarded. Finally, the inlet channel b was narrowed to 2 inches by placing a partition down the middle of the previous channel, and the bulkhead n was extended, as shown by dashed lines on Plate 1 B. This last modification eliminated undesirable effects caused by asymmetry of the earlier arrangement.

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*Fischer Porter Number FP-1-35-G-10/80.

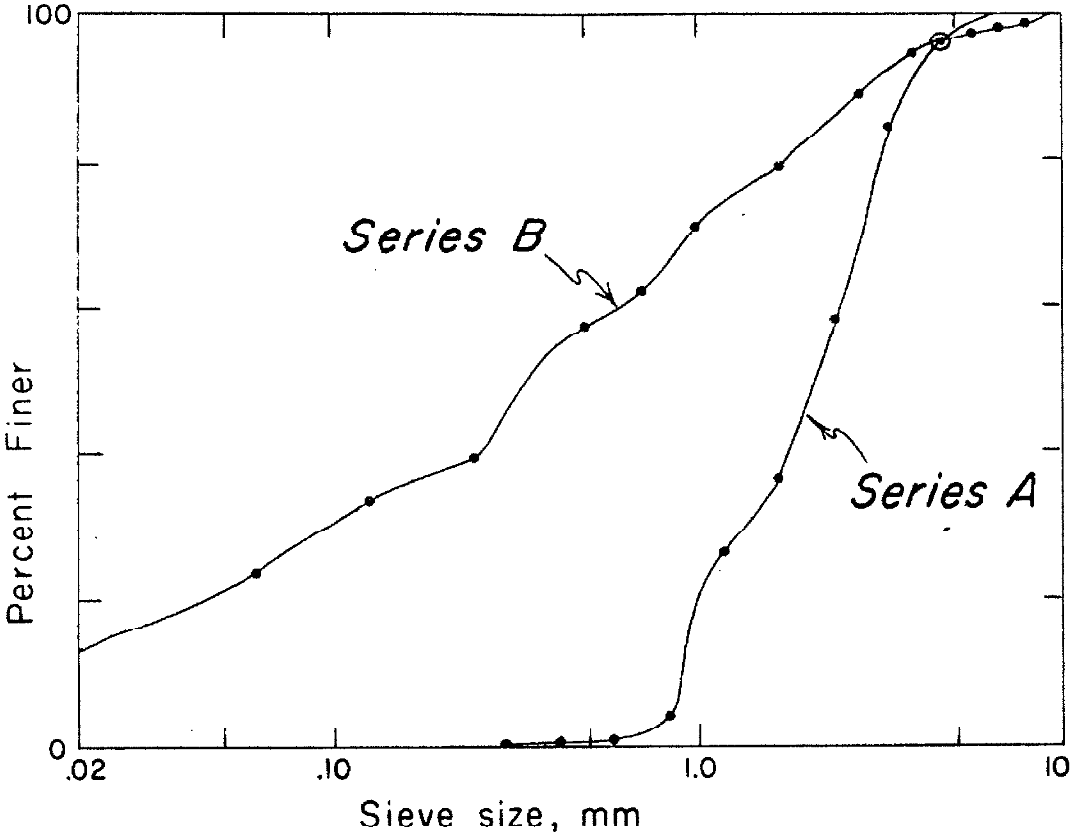


Figure 4. Size distribution of material used in the model experiments.

Series B consisted of three runs, each involving 35 or more episodes. An episode usually consisted of a debris flow followed by a water flow, but in several episodes only one type of flow was used (Table I). A small amount of dry sediment was usually added to the channel before each water flow. This provided material for transport by the water flow and for backfilling of the channel to keep it graded to the level of the rising fanhead.

The material was a mixture of that used in Series A, some fine sand, a few pebbles, and a large amount of silt and clay (Figure 4). The size distribution was not constant as sorting took place on the fan and some fine material was lost in the waste water. Thus debris from one fan that is reused without thorough mixing and addition of fines will vary slightly in composition.

Debris flows were made by first mixing a slurry of water and sediment in a bucket and then transferring one or one and one-half liters of this slurry to a can from which it was easily poured into the channel just above the bulkhead. The density of the flow could be determined readily by weighing the can containing the known volume of sediment. This method of determing the density was used during the last half of Run B-2 and during Run B-3. Earlier density measurements, made on volumes of 5 to 10 cubic centimeters, are less reliable.

Table I

Range of Variation of Parameters between Episodes in Each Run of Series B

| | | Debris-flow data | | | Water-flow data | | |
|---|---|---|---|---|---|---|---|
| Run | No. of Episodes | Volume, liters | Density gm/cm3 | Yield Thickness, cm | Discharge, cfs | Duration, minutes | Amt. of dry debris added, lbs. |
| B-1 | 35 | 0.5-4.0<br>aver. 1.5 | 1.49-1.85 | .25-.95 last 5 episodes only | No water flows | | |
| B-2 | 43 | 0.5-1.5 | 1.52-1.69 | .25-.95 | 0.002 | 2 | 1.5 |
| Run<br>B-3, episodes 1-34 | | No debris flows | | | 0.002-0.004 | Usually 2 or 4; rarely 6 or 12 | 2 |
| B-3, episodes 35-66 | | 0.75-1.5 | 1.54-1.73 | .40-.70 | 0.002-0.004 | " | .5 |

Owing to a finite yield strength, debris flowage will not occur on a slope, S, unless a certain critical depth, $d_o$, is exceeded. For low slopes the yield strength, $\tau_0$, is given by

$$\tau_o = \rho g d_o S$$

where $\rho$ is the density of the slurry and g is the acceleration of gravity. In order to estimate the yield strength of a sample, a small quantity of mud was poured onto an aluminum plate with a slope of 7.1°. After flowage had ceased the depth of the puddle was measured to the nearest half millimeter. This depth will approximate the critical depth. These measurements suggested a rough correlation between density and depth (Fig. 5); the scatter in the plot is attributed to inaccurate depth measurements and to variations in the amount of coarse material in the mud. Coarse material increases the average density of the mud but probably does not appreciably alter the yield strength.

Viscosity measurements were made on two samples, using a Stormer Viscometer. The results are summarized in Table II. After the yield strength of the material was exceeded the viscosity decreased, at first slowly and then more rapidly, finally approaching a constant value at an applied stress slightly less than twice the yield strength. Unfortunately the viscometer was not calibrated in a way that permitted easy conversion from the driving weight on

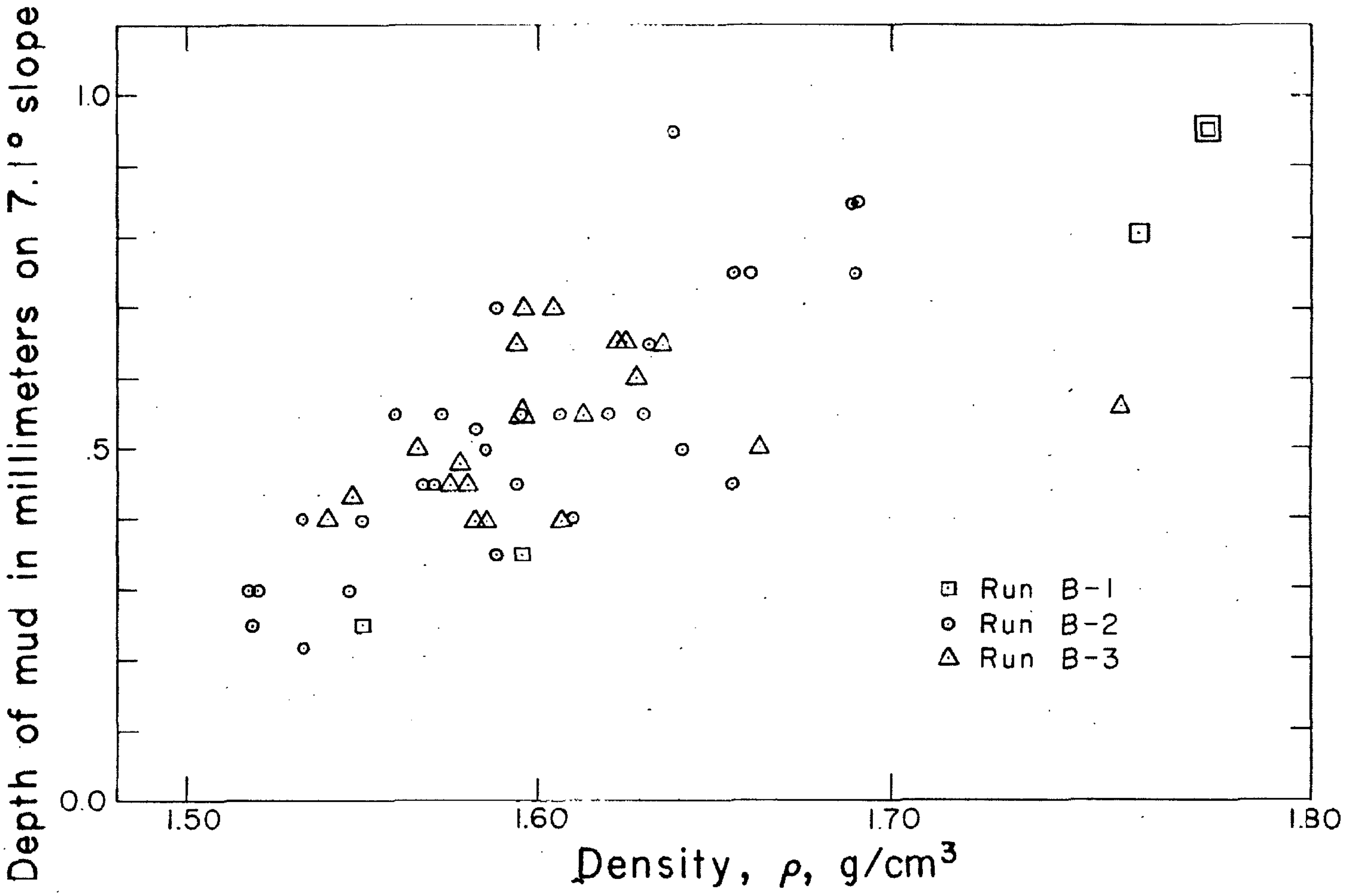


Figure 5. Relationship between density of mud and the critical depth required for flow on a 7.1° slope.

Table II

Results of viscometer test

| $\rho$ g/cm$^3$ | $\tau_o$ from plate test (dynes/cm$^2$) | $\tau_o$ estimated from viscometer test (dynes/cm$^2$) | $\mu$ at $\tau = 2\tau_o$ poises |
|---|---|---|---|
| 1.42 | 70 | 35 | 0.42 |
| 1.48 | 136 | 110 | 0.92 |
| | | 134* | 1.02 |

*Viscosity increased during the test for unknown reason

the viscometer to the applied stress on the fluid. Thus an accurate value of $\tau_o$ could not be obtained directly from these tests.

## Model Verification

In engineering parlance model verification implies a comprehensive series of tests during which scale factors are adjusted until the model accurately reproduces an observed behavior of the prototype. Such detail is not warranted in the present study in which processes are emphasized. For the purposes of this study, model verification will therefore involve an extension of the earlier discussion of similarity of process (p. 10) to include laboratory fans. In general processes were observed only on laboratory fans and the comparison will be based more on the products than on the processes themselves.

The most obvious similarity between laboratory fans and natural fans is the radial symmetry and gentle slope. The mean slope of a well-developed laboratory fan in Series A, measured along the longest radial profile, ranged between $4^{\circ}$ and $7^{\circ}$ prior to initiation of sieve deposition. The channel slopes, measured just above the intersection point, generally ranged from $2^{\circ}$ to $5^{\circ}$. In Series B, Runs B-2 and B-3, slopes ranged from $5^{\circ}$ to $8^{\circ}$ on the upper half of the fan. These values are about average for natural fans with a high percentage of cobble- and boulder-sized material. Under conditions of sieve deposition, slopes of laboratory fans range from about $7^{\circ}$ to $13^{\circ}$. Average slopes on Shadow Rock and Gorak Shep fans (Fig. 1 and Plate 5) in regions of sieve deposition are $13.5^{\circ}$ and $9^{\circ}$ respectively, in good agreement with the laboratory data.

Details of laboratory fan development further confirm this basic similarity. During Series A, each episode began with a debris flow and was followed by a water flow. The water flow lasted substantially longer than the debris flow and, owing to storage in the inlet box, varied in discharge in a manner similar to a natural hydrograph. Episodes in Series B were similar except that storage did not occur and the water discharge following the debris flow did not vary appreciably. Similarly, natural debris flows described by Beaty (1963, p. 520-21) and Pack (1923, p. 355) were followed by long periods of water runoff.

Earlier water-cut channels on laboratory fans were commonly filled with debris-flow material and, in Series A, with material carried by the subsequent overloaded water flow. These channels disappear beneath such deposits upstream in the same way that many natural channels do (Fig. 6, Runs A-1, 9, 10). In the erosional phase of an event an intersection point is formed, commonly near midfan, and sometimes several small channels head in the intersection-point deposit (Plates 2 H and 3 H). Abandoned main channels commonly end upstream at the banks of deeper channels (Fig. 6, Run A-12, channel above sieve lobe). These channel patterns are observed in nature.

Sieve deposition is a process first recognized in the laboratory. Lobes, thought to be the product of sieve deposition, were later identified in the field. The similarity of these natural lobes and the laboratory features is further evidence for the basic similarity of process.

Debris flows in the Series B experiments behaved in much the same way as natural flows. The laboratory flows had steep, rounded fronts. The deeper parts of the flow

Figure 6. Maps of laboratory fans, Series A.

Each map depicts a separate fan composed of material accumulated during eight episodes of deposition. For any one fan each of the eight episodes had a fixed discharge in $ft^3/sec$ and lasted for a fixed length of time in seconds, as indicated on the left margin and at the top of the figure respectively. For example, after the map of fan A-6 was drawn, the model was completely cleaned. A new fan, A-7, was then built, using eight episodes of 120 seconds duration each, and a discharge of 0.019 $ft^3/sec$.

The coarse sand is usually deposited near the end of the episode. During episodes of high discharge or long duration this sand was deposited and subsequently eroded (See Run A-8).

The fan surface prior to the 8th episode was identified by a thin coat of spray paint. Erosion around the edge of the fan (Run A-3) is, in part, the result of floating of grains attached to a film of paint. In runs labeled "No age distinction" the surface was not painted prior to the 8th episode.

Small patches of older material are exposed locally in recent channels by erosion (Run A-4).

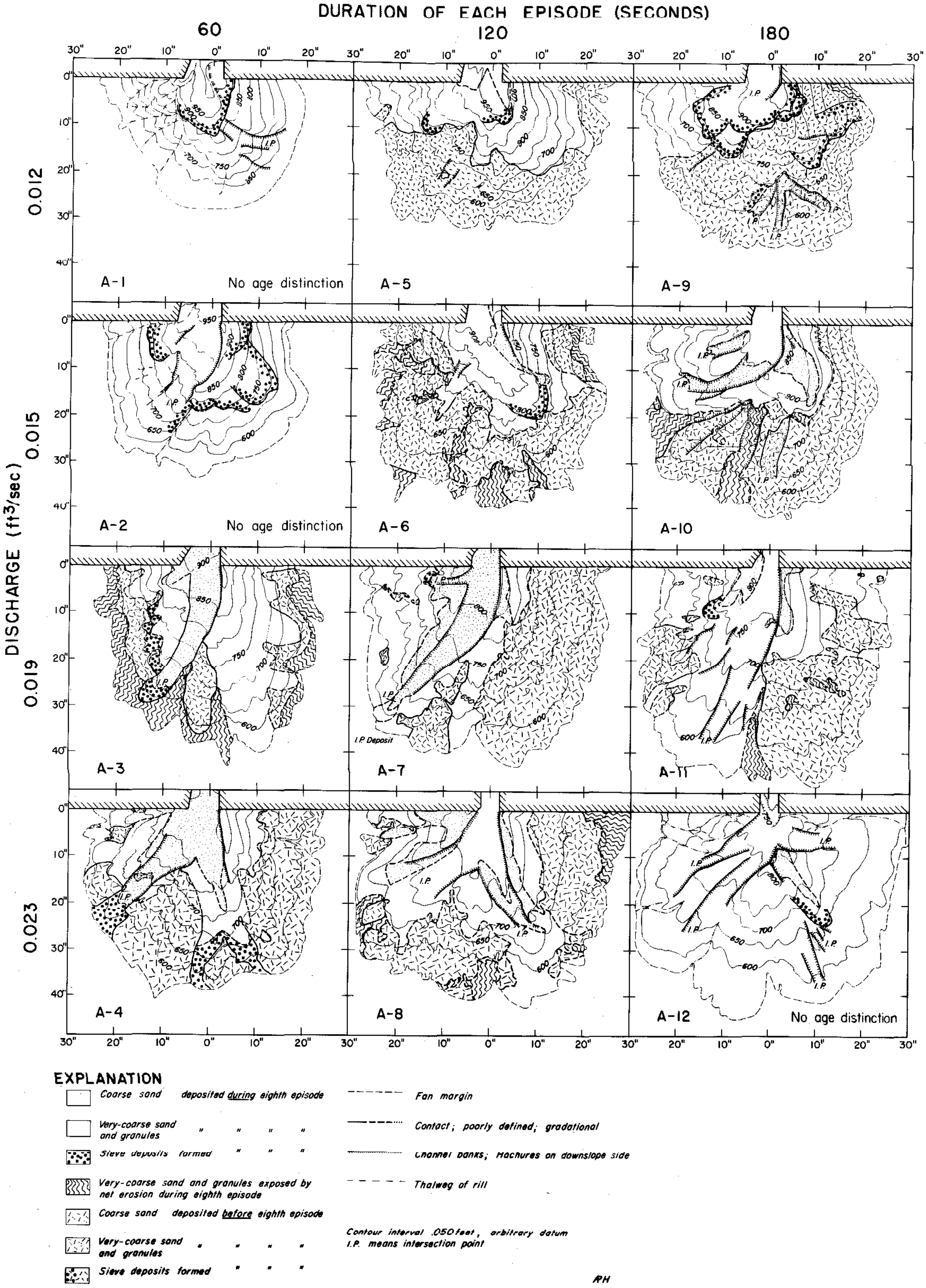

DURATION OF EACH EPISODE (SECONDS)
60
120
180
DISCHARGE (ft³/sec)
0.012
0.015
0.019
0.023
30"
20"
10"
0"
10"
20"
30"
0"
10"
20"
30"
40"
A-1
No age distinction
A-5
A-9
A-2
No age distinction
A-6
A-10
A-3
A-7
I.P. Deposit
A-11
A-4
A-8
A-12
No age distinction
I.P.
950
900
850
800
750
700
650
600
EXPLANATION
Coarse sand deposited during eighth episode
Very-coarse sand and granules " " " "
Sieve deposits formed " " "
Very-coarse sand and granules exposed by net erosion during eighth episode
Coarse sand deposited before eighth episode
Very-coarse sand and granules " " " "
Sieve deposits formed " " "
Fan margin
Contact; poorly defined; gradational
Channel banks; Hachures on downslope side
Thalweg of rill
Contour interval .050 feet, arbitrary datum
I.P. means intersection point
RH

Figure 6.

moved faster than shallow parts, and following surges moved more rapidly than the front of the flow. If the front stopped and was not remobilized by the following surges, small pressure ridges developed parallel to the borders of the flow. Jahns (1949, p. 12-13) has described natural flows which behaved in the same way. Although the main body of laboratory flows followed the existing main channel, (Plate 2, A and B) small lobes of material diverged from the channel when the flow became deep enough to overtop the banks (Plate 2, B). Below the intersection point the laboratory flows formed wide lobes. Beaty's (1963, p. 520) maps of debris flows at the base of the White Mountains of California exhibit similar characteristics. Fresh mud of laboratory flows was remobilized by the next flow if insufficient drying time was allowed between episodes. Remobilization of natural flows has been described by Sharp and Nobles (1953, p. 551). Contacts between fresh laboratory flows and the older fan surface were always sharp (Plate 2, B, E, and G), as in natural flows unmodified by flood waters (Jahns, 1949, p. 13; Blackwelder, 1928, p. 470). When the laboratory flows overtopped the channel banks without forming diverging lobes, lateral ridges or levees were left as the flow receded (Plate 2, G). Such lateral ridges are common on natural fans.

Plate 2. Stages of development of laboratory fan B-2

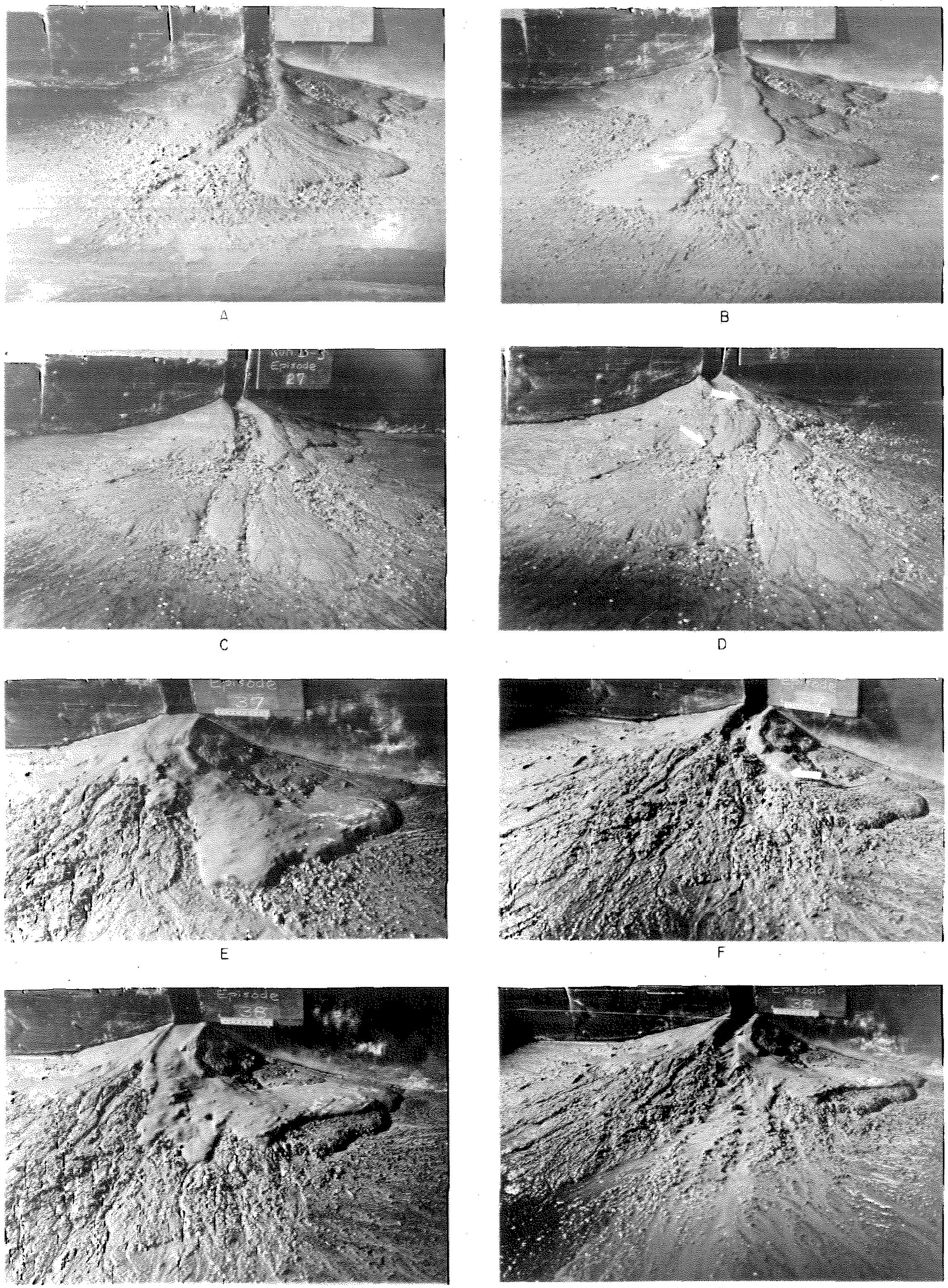
Scale in Figures E, F, G, and H is graduated in centimeters.

A & B. Channel after episode 17 (Fig. A) and debris flow of episode 18 that followed this channel (Fig. B). Note lobe of debris that left channel at bend.

C & D. Channel after episode 27 (Fig. C), and diversion from that channel during episode 28 (Fig. D). Arrows in Figure D indicate snout of debris flow that caused diversion and position of new channel.

E & F. Lobe of debris from debris flow of episode 37 (Fig. E), largely destroyed by water runoff at end of episode 37 (Fig. F). Part of the flow, mantled with gravel, is visible below and to the right of the arrow in Figure F. Most of this gravel was eroded from the debris flow higher on fan, but some may have been exposed by winnowing of the lobe on which it rests. Arrow indicates intersection point.

G & H. Debris flow of episode 38 (Fig. G) followed channel in Figure F, and is being eroded by flow in Figure H. Note levees formed by debris flow in Figure G, and note distributary flow pattern below intersection point in Figure H.



A B C D E F G H

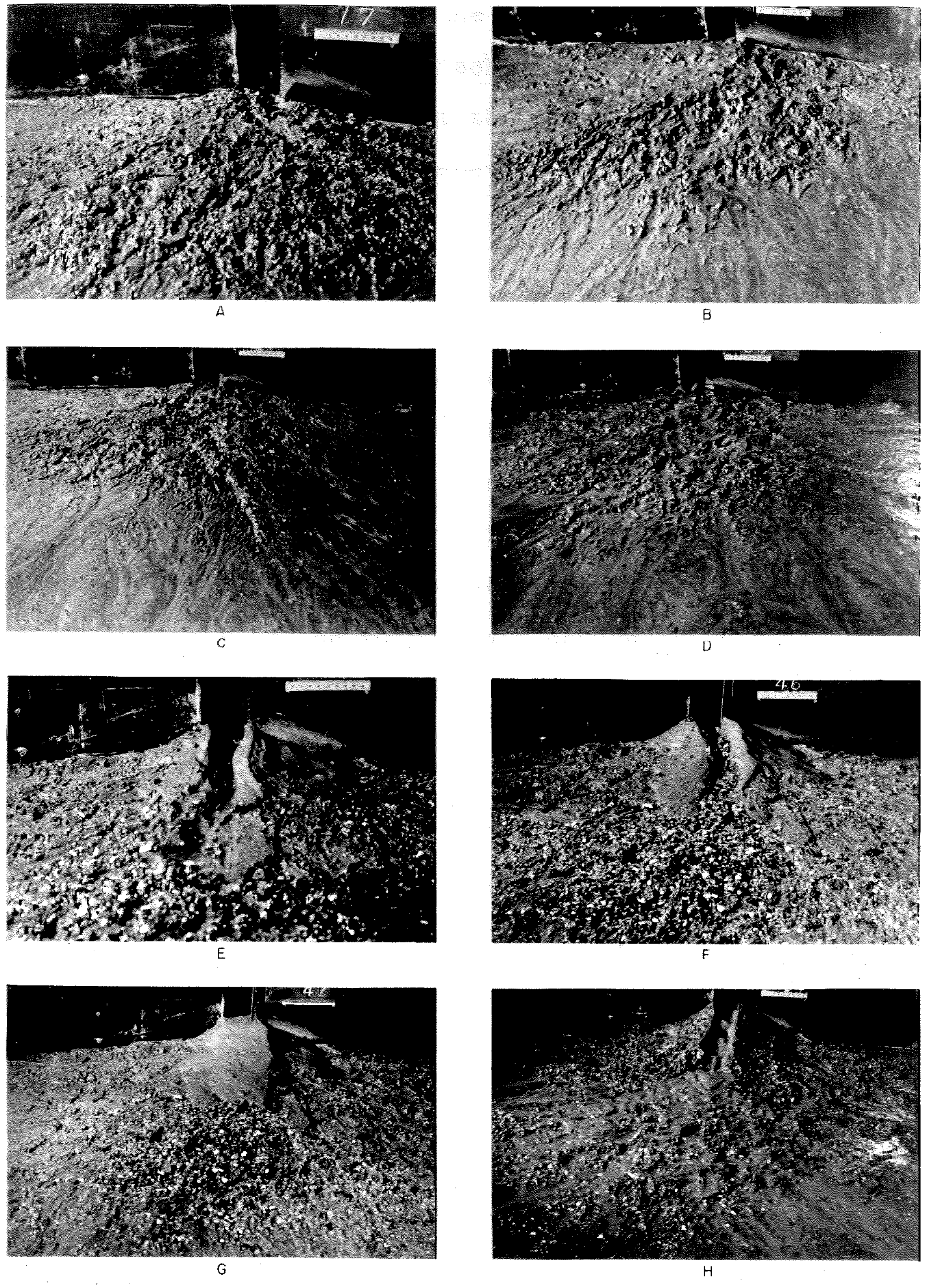
Plate 2.

Plate 3. Stages of development of laboratory fan B-3.

Scale is graduated in centimeters.

A, B, C, and D. Fan at or near end of episodes 17, 23, 24, and 30 respectively. Owing to the absence of debris flows, existing channels at the fanhead are not cut down below bankfull stage as shown by the water levels in Figures B and D. Coarse material is concentrated in the upper part of the fan where the slope is higher. Both fine and coarse deposits are extensively braided.

E, F, G, and H. Fan at or near end of episodes 43, 46, 47, and 54 respectively. With the onset of debris-flow deposition the fanhead has become incised. The locus of deposition by braided fluvial flow is now below the intersection point (Fig. H). The position of the intersection point does not vary because the volume and yield strength of the debris flows was held nearly constant (Fig. G). Debris-flow levees are well-developed in Figure E.



A B C D E F G H

Plate 3.

Finally, the area of the laboratory fans proved to be roughly proportional to discharge (Fig. 6). In a later section it will be shown that the areas of natural fans are likewise proportional to discharge.

These similarities in surficial morphology and debris-flow behavior suggest that both laboratory fans and natural fans are products of the same basic processes. Many of the differences may be related to grading of material composing the laboratory fans, to the absence of weathering in the laboratory, and to the extreme resistance of congealed laboratory debris flows to erosion by low discharges. Results of the laboratory study may be applied to natural fans if the morphologic consequences of these factors are taken into account.

# DEBRIS FLOWS AND FLUVIAL PROCESSES

Hydraulic processes which transport material from the drainage area to and across the fan are of prime importance in fan morphology. Early workers (Gilbert, 1882, p. 183-4; Trowbridge, 1911, 738-744) assumed that fan morphology was a product of fluvial processes alone. The significance of debris flows was not widely recognized prior to Blackwelder's (1928) revealing discussion of this process.

## Characteristics of Debris Flows and Fluvial Processes

### Mechanics of sediment transport

Differences in physical properties are responsible for fundamental differences in the mechanics of sediment transport by debris flows and water flows. Natural debris flows have viscosities on the order of 1,000 poise and densities of 2.0 to 2.4 (Sharp and Nobles, 1953, p. 552-3). In contrast, the viscosity of water is about 0.01 poise, and the density of a stream carrying suspended sediment is only slightly greater than unity. Furthermore, water is a Newtonian fluid; its response to an applied stress, $\tau$, can be represented by

$$\tau = \mu \frac{du}{dy}$$

where $du/dy$ is the rate of shear and $\mu$ is the coefficient of viscosity. In contrast a debris flow behaves as a quasiplastic substance, and its rate of deformation under stress is represented by

$$(\tau - \tau_o)^n = \mu(\tau)\ du/dy \qquad n > 1$$

where $\tau_o$ is the yield strength, and $\mu(\tau)$ indicates that the viscosity is a function of the applied stress (Leopold, Wolman, and Miller, 1964, p. 31). No flow occurs until the yield strength is exceeded and motion begins, but then the viscosity decreases gradually with increasing applied stress until a constant value is reached. The values of n and $\tau_o$ and form of the function $\mu(\tau)$ differ between flows owing to differences in flow density and in mineralogy of the silt-clay fraction. The behavior described above is that observed in laboratory debris flows, but natural flows are probably not basically different.

Owing to the high density of mud, forces on rocks in debris flows are substantially different from those on comparable rocks in a stream. The submerged weight of a rock is reduced, perhaps by more than 60 percent, relative to its submerged weight in water, and bed shear forces are increased. Furthermore, the combination of low density contrast between rocks and mud, and high density of mud reduces the settling velocity (Vanoni, 1962, p. 84). Thus gravity forces tending to prevent motion are reduced and drag forces are increased.

The ability of a stream to transport sediment in suspension is closely governed by a balance between settling velocity of the sediment and upward transport of material by turbulent eddies (Vanoni, 1963). With the reduced settling velocity in debris flows, coarser material can be maintained in suspension. The yield strength of the mud may also prevent settling of many fragments, but the importance of this effect in a moving flow, the yield strength of which has already been exceeded, is not clear.

Nevertheless, it is instructive to estimate the maximum diameter of spheres that will remain suspended in mud that is not flowing. This can be done by extrapolating the laboratory data on yield strengths of mud of various densities (Fig. 5) to obtain a yield strength $\tau'$ of mud in a natural flow of higher density. If a sphere of diameter d just barely remains suspended in this mud, the upward components of the shear stress integrated over the surface of the sphere, must equal the gravitational force. If uniform shear over the surface is assumed, the resulting equation is

$$\int_0^{2\pi}\int_0^{\pi} \tau' \operatorname{Cos}\theta \left(\frac{d}{2}\right)^2 \operatorname{Sin}\theta \; d\theta \; d\phi = \frac{4}{3}\pi\left(\frac{d}{2}\right)^3 \Delta\rho g$$

where $\theta$ and $\phi$ are the angular directions in a spherical coordinate system, $\Delta\rho$ is the density contrast between the sphere and the fluid, and g is the gravitational acceleration. Integration gives

$$d = 3\frac{\tau'}{\Delta\rho g}.$$

Reasonable average values for $\tau'$ and $\Delta\rho$ are 500 dynes/cm$^2$ (Fig. 5) and 0.5 g/cm$^3$ (Sharp and Nobles, 1953, p. 552) respectively, giving a diameter of 3 cm. Mr. Arvid Johnson (written communication, 4/2/65) has made a similar calculation. His laboratory research on debris flows indicates that values of $\tau'$ up to 18,000 dynes/cm$^2$ are reasonable.

The reduction in settling velocity suggests the possibility that dispersive pressure forces (Bagnold, 1954, 1955) may play a more important role in debris-flow mechanics than does the settling velocity. It is logical that Bagnold's experiments with low density grains in water should be more applicable to debris flows than to streams.

These considerations suggest one fundamental difference between water flows and debris flows. Whereas streams vary their sediment load readily by deposition or erosion and will continue to flow as long as a slope exists, debris flows cannot selectively deposit any but the coarsest fragments. This means that a debris flow cannot turn into a stream flow by deposition. Both types of flow are formed by water moving over and entraining loose sediment, but at some point sediment entrainment becomes irreversible. Perhaps this is the best distinction between stream flows and debris flows.

## Conditions promoting debris-flow formation

Lithology, climate, and topography are three important independent variables controlling the formation of debris flows.

Lithology. A substantial amount of silt and clay in the regolith is conducive to debris-flow formation. In the absence of fines, evidence for debris-flow action is sparse. For example, the drainage area of Gorak Shep Fan is underlain by carbonate rocks, mostly dolomite, with less than 3 percent insoluble residue in the silt-clay size range. Furthermore, slopes in the drainage area are steep and loose material is quickly transported to the fan with little pre-transport weathering. Similarly the drainage area of Shadow Rock Fan is underlain predominantly by hard, resistant quartzite of the Campito Formation (Nelson, in press (b)). Unequivocal evidence of debris-flow transport on these two fans is lacking. In contrast, Trollheim Fan, about a mile southwest of Shadow Rock Fan, shows good evidence of debris-flow action (Fig. 12). This is attributed to exposures of readily weathered sandy dolomite in the Reed Formation which underlies a large part of the drainage basin (Fig. 10). Climatic and topographic factors do not vary significantly between Trollheim and Shadow Rock Fans. Similarly, a large part of the drainage basin of Little Cowhorn Fan is covered by unconsolidated alluvium. Fines are abundant and extensive debris-flow deposits on the fan reflect this influence. The drainage basins of fans in southern Owens Valley are underlain by granitic rocks of the Sierra Nevada Batholith. In this environment the granite readily decomposes to gruss which in turn weathers to clay, providing sufficient fine material for debris flows. Evidence for lithologic control of the type of deposition on fans is convincing and unambiguous. Fine material, produced by weathering or derived from unconsolidated alluvium greatly facilitates generation of debris flows.

Climate. In arid regions where the regolith is not stabilized by vegetation, most authors agree that copious water rapidly applied, as in a summer thunderstorm, is essential to debris-flow formation (Blackwelder, 1928, p. 478; Beaty, 1963, p. 531-532). Observations of debris flows during Series A of the model experiments suggest that the resulting high rate of runoff is able to entrain sediment by some process other than the processes active in rivers. This might account for the aforementioned irreversibility of the entrainment process. Debris flows resulting from rapid snow melt have also been described (Sharp, 1942; Sharp and Nobles, 1953; Rickmers, 1913, p. 194-198). Prolonged frontal rains are either too rare to be effective in arid regions, or do not produce the requisite high runoff-rate. The frequency of major storms is also important; if storms occur too frequently, the period of weathering and debris accumulation may be too short to supply material for a debris flow. (Blackwelder, 1928, p. 479).

Topography. Slopes of the drainage basin must be steep enough to permit flow of a viscous material with a finite yield strength, and to produce a high runoff velocity with a concurrent high rate of sediment entrainment, but not so steep that sufficient loose material to form a debris flow never accumulates. A narrow canyon that concentrates flow and produces mixing and temporary damming may also be important in some instances (R. P. Sharp, written communication, 11/64).

Summary. The conditions which promote debris-flow formation are: (1) intense episodic rainfall, (2) unconsolidated fine material, (3) sparse vegetation, and (4) reasonably steep slopes. As Blackwelder has pointed out (1928, p. 478) a deficiency in one of these conditions can be compensated by an excess in another. For instance, a drainage basin with gentle slopes may require a more intense rainfall to produce debris flows than a basin with steep slopes.

## Recognizing debris-flow deposits

Old debris-flow deposits are most easily recognized in vertical section by poor sorting, the absence of stratification, and especially by the matrix of fine material in which cobbles and boulders are embedded. On fan surfaces comparatively recent debris flows also can be identified by their flat-topped, steep-sided, lobate form, and by their abrupt contact with the underlying material. Subsequent rain, erosion, deposition, and weathering will modify this distinctive morphology and internal character, making these surface deposits more difficult to recognize. Cobble and boulder trains or arcs with low relief may be the only remaining evidence.

Deposits formed by creep may resemble debris-flow deposits in cross section. During creep the coarse and fine material become thoroughly mixed (Gilluly, Waters, and Woodford, 1959, p. 173); pebbles, cobbles, and boulders become embedded in a matrix of sand, silt and clay, with no recognizable sorting. A deposit having these characteristics was observed on a fan west of Gorak Shep Fan (Fig. 1). This deposit is thought to be due to creep because it truncates bedding in the underlying fan material at an angle of about 15 degrees and because it appears to be continuous with the material on the sloping channel bank above it.

## Effect of Debris Flows on Fan Morphology

Differences in the physical properties of fluvial flows and debris flows have important consequences in terms of fan morphology.

## Transportation of coarse material

One characteristic feature of many alluvial fans is a large amount of cobble- and boulder-sized material. Fahnstock's data (Leopold, Wolman, and Miller, 1964, p. 170) suggest that such coarse debris could be transported by water. However, the occurrence of cobbles and boulders in levees and lobes and the association of this coarse debris with material recognized, on the basis of other criteria, to be of debris-flow origin, suggest that much of it is transported to the fan by debris flows. The high competence and capacity of debris flows for coarse material support this conclusion.

## Debris-flow levees

Boulders moved by debris flows frequently accumulate at the snout of the flow and are rolled under (Jahns, 1949, p. 12) or shoved aside (Sharp, 1942, p. 225) by the advancing snout. Boulders that are shoved aside in this fashion form levees which confine the remainder of the flow. Sharp (1942, p. 225) has given an interesting description of the formation of debris-flow levees:

> "If the flow was viscous, slow moving, and relatively uniform, the entire mass reached the foot of the slope without building levees or hardened before reaching the bottom leaving a tongue-shaped deposit of mud and boulders. If the flow, however, had a degree of fluidity permitting it to move one to two feet per second, levees were built. At the start mud and boulders were evenly distributed through the mass, but boulders rapidly accumulated near the

> snout by sliding and rolling through the slower moving mud. This concentration of boulders retarded the movement and built up pressure in the more fluid material behind. Eventually, the fluid material pushed with such force on the snout that part of the boulders and mud were shoved aside in snowplow fashion. This continued over a considerable distance as the flow moved downslope and embankments of mud and boulders were left along the borders of the channel. The more fluid part of the mud and following muddy waters cleaned out and deepened the channel between the embankments. The boulders in all newly formed levees were covered with mud, but a few rains washed them clean and removed the mud in the surface layer."

Such levees also form when a debris flow at peak discharge overflows channel banks leaving a ridge of material along the top of the bank as the discharge subsides. Levees of this type were observed on laboratory fans (Plate 2, G, H) and on debris flows on Surprise Canyon Fan in Panamint Valley, California. Mr. Arvid Johnson (written communication 1/30/65) has studied the mechanics of debris-flow movement and believes that this process of levee formation may be the more common one on alluvial fans.

One interesting characteristic of some debris-flow levees observed in the field is a distinct sorting of clasts with pebble-sized material on the inside (toward the flow) and coarser material on the outside. This sorting is probably not due to selective deposition of coarser material by slower flow because the size difference is not large and the coarser material is probably not heavy enough to stop independently of the flow. It is surmised instead that coarser material selectively migrates to the surface, perhaps because of dispersive pressure forces (Leopold, Wolman, and Miller, 1964, p. 211-212). The higher surface velocity then moves it to the front and edges of the flow where it is concentrated when the edges stop moving and form levees.

## Areal extent of debris flows

As a consequence of the finite yield strength of mud, a debris flow will stop when

$$\frac{\tau_0}{ds} > \rho g$$

where $\tau_0$ is the shear strength, $\rho$ is the density of the flow, g is the gravitational acceleration, d is the flow depth, and s is the hydraulic gradient ($\doteq$ fan slope). This relationship follows directly from balancing gravitational forces with shear forces on the bottom of the flow. The above condition can be satisfied by (1) decreasing either the hydraulic gradient or the depth of flow; (2) by loss of water to underlying dry fan material, thus increasing the yield strength; or (3) by a combination of these changes. All of these processes were observed on laboratory flows. The areal extent of a debris flow is thus limited by the volume of the flow, by its yield strength, and by the slope of the fan surface. Whereas water flows frequently reach, and transport material to the toe of a fan and beyond, debris flows rarely transport material this far.

Since most fans have a main channel which is incised at the fanhead, debris flows commonly follow this channel to the intersection point where they spread out over the fan surface (Plate 2, E). Thus, the down-fan extent of debris flows is determined in large part by the degree to which existing channels prevent lateral spreading at the fanhead.

Radial variations in alluvial fan stratigraphy. As a consequence of the limited areal extent of debris flows, most deposition at the toe of fans probably results from water action rather than debris-flow action. The material deposited may be derived by erosion from debris-flow deposits higher on the fan, or it may come directly from the drainage area, but regardless of the process by which it reached the fan, the last stage of its progress across the fan is the result of fluvial processes. In contrast much of the deposition at the fanhead is probably caused by debris flows overtopping the channel banks and depositing material on the fan surface. Thus the stratigraphy of fans on which debris-flow deposition has been important should be non-homogeneous; debris-flow deposits will dominate at the fanhead and water-sorted material will be most abundant at the toe. The midfan region should consist of interfingering debris-flow and stream-flow deposits. This variation was observed on laboratory fans B-2 and B-3.

The Pliocene Ridge Basin Group (Crowell, 1954), 75 miles north of Los Angeles, is probably an ancient example of radial gradation from debris-flow to stream-flow deposition on fans. The Violin Breccia (Crowell, 1954) an unbedded to poorly-bedded cobble and boulder conglomerate with a matrix of sand- to clay-sized material represents the debris-flow deposits near the fanhead or mountain front. Outward from the mountain front this unit grades into bedded conglomerate with smaller clasts and thence into well-bedded, rarely cross-bedded, sandstone with interbedded shale.

Erosion by debris flows. A second consequence of the limited areal extent of debris flows is that each flow deposits some material in the channel near the fanhead. It is inconsequential for the present argument that this material may be immediately eroded by water flows generated by the same storm. The significant fact is that for debris flows to accomplish net erosion of the channel, the amount of material removed by debris-flow scour must exceed the amount deposited at the same place when the debris flow comes to rest.

Evidence for entrainment of material by debris flows is not unknown. Jahns (1949, p. 13) mentions "dry soil and rocks...sheared" from canyon walls by a debris flow he observed, and Pack (1923, p. 355) reports "broadly U-shaped" channels cut by mudflows. Boulders resting on a surface over which a flow moves may also be entrained, but much of the erosion attributed to debris flows is probably due to water runoff that commonly follows such flows. For instance Blackwelder (1928, p. 469) reports that a concrete highway at the base of the Wasatch Range, Utah, was covered by a debris flow without damage to the road, while at another point a water flow following the debris flow tore a gap in the highway, apparently by undermining its foundations.

Blackwelder's observation suggests two possible explanations for the general lack of net erosion by debris flows. First, most debris flows are of short duration and the time available may be insufficient for erosion to exceed deposition. For instance some flows on fans at the base of the White Mountains, California, lasted only 45 minutes to an hour (Beaty, 1963, p. 520).

Secondly, owing to high viscosity, many debris flows may have a thick laminar sublayer, and the flow in others may be entirely laminar. In the absence of turbulence near the bed scour would be substantially reduced. A laminar sublayer, or perhaps a zone of no flow, could also develop near the bed if the yield strength and viscosity in this region were increased, through a combination of loss of water to and incorporation of the dry surface material beneath the flow. Jahns (1949, p. 13) dug beneath the outer margin of a flow he observed and found patches of dry gravel, indicating that such dry material is incorporated, and suggesting that turbulence near the bed was insufficient to break it up, or that the gravel was incorporated shortly before the flow stopped.

## Mudless Debris Flows

Thus far only the classical type of debris flow, composed of a slurry of mud in which pebbles and boulders are transported, has been discussed. It is interesting to consider how coarse the fine material may be and still permit mass transport. Flows composed wholly of coarse sand- and granule-sized material were observed in the laboratory during the first series of experiments. While in motion these flows confined themselves with levees and had a sediment concentration two or three times that of the subsequent high stream flows. The ensuing stream flow easily removed the debris-flow material so levees were not left, although they existed while the debris flow was in motion. Whether levees would have remained had coarser material been available is not known.

The absence of a muddy matrix, the possibility of sorting owing to the fluidity of the transporting fluid, and the possible absence of levees, make sediment deposited by this type of debris flow difficult to recognize in nature.

Even if levees are left, distinguishing between mudless flows and muddy flows will not be easy.

However, such flows apparently do occur. Mr. Arvid Johnson (written communication, 4/2/65) believes that some flow deposits he has observed are of this type. An eyewitness account by Terzaghi (Bagnold, 1954, p. 62-63) of a flow of gravel "up to the size of hens' eggs" without visible supporting fluid is also interesting. If the voids of this flow were filled with mud, one would expect to see mud-coated pebbles that had arisen to the surface through the flow.

The possibility of mudless debris flows is pertinent to Gorak Shep and Shadow Rock fans. Clearcut evidence of debris-flow action, either in the surficial morphology or in rarely exposed stratigraphic sections, is lacking. Furthermore both fans are composed of fairly coarse, sorted material (Table III). Most fines present are of secondary origin, and could not have acted as a lubricant for debris flows. Consequently most material on these fans must have been transported either as mudless debris flows or in the normal fluvial manner. Fahnstock's data (Leopold, Wolman, and Miller, 1964, p. 170) indicate that even the largest boulders on these fans could have been transported by fluvial processes. At this point it is thus impossible to draw conclusions regarding the possible role of mudless debris flows in building these fans.

## TABLE III

SIZE DISTRIBUTION* OF MATERIAL FROM GORAK SHEP FAN AND LITTLE COWHORN FAN. EVIDENCE OF DEBRIS FLOWS IS ABSENT ON THE FORMER BUT ABUNDANT ON THE LATTER.

| Sieve opening, mm. | 13.33 | 2.79 | .351 | .117 | Pan |
|---|---|---|---|---|---|
| Percent retained Gorak Shep Fan | 41 | 33 | 13 | 7 | 6 |
| Percent retained Little Cowhorn Fan | 24 | 32** | 25** | 9** | 10 |

* Based on an average of 16 sieve analyses, each involving 8-10 kilograms of material.

** These numbers are based on interpolation of data from a different series of sieves. The interpolation was done graphically on logarithmic-probability paper.

## Relative Significance of Debris Flows and Water Flows

Blackwelder (1928, p. 473-4) realized that the relative importance of debris-flow deposition compared to stream deposition varied from one fan to another. "Some fans," he wrote, "may contain no mudflows [debris flows]. In most of the fans in arid regions there is an interlamination of mudflows and washed gravel sheets...Many alluvial fans, especially those of steeper gradient, consist largely of mudflows." Blissenbach (1954, p. 179) found that debris-flow deposits comprised 5-10 percent of the fan material in a region of 19 inches of precipitation and 20-40 percent in a region of about 11 inches. Beaty (1963, p. 535) in his study of some fans at the base of the White Mountains of California and Nevada, concluded that:

> "Alluvial fans of the White Mountains, and, by analogy, those of other Great Basin ranges, appear not to have been built by the ordinary processes of stream deposition. Instead, spectacular episodes of debris-flow deposition have been irregularly interspersed with periods of quiescence..."

As these divergent viewpoints suggest, the proportion of recognizable debris-flow material on fan surfaces and in fan stratigraphy varies widely. On Little Cowhorn Fan evidence of stream deposition is minor. Gorak Shep and Shadow Rock fans have practically no recognizable debris-flow deposits, but Trollheim Fan, about a mile south of Shadow Rock Fan appears to be predominantly of debris-flow origin. Likewise Olancha Creek Fan and many other fans on the western side of southern Owens Valley appear to be composed predominantly of debris-flow material.

For several reasons, volumetric estimates of the role of debris flows in transporting material to a fan are difficult to make. One of the most useful criteria for identifying debris-flow deposits is the heterogeneous nature of the material and the fine matrix in which coarser fragments are embedded. Unfortunately this characteristic is susceptible to destruction by other fan processes. Rain falling directly on the fan will wash out the fine matrix. Stream flows occurring either immediately after debris flows or in intervening intervals, can rework the debris-flow material, removing fines and producing greater sorting and stratification. Fluvial runoff following debris flows is common and often lasts longer than the debris flows. Beaty (1963, p. 521) reports that high water continued for 24 to 48 hours after debris flows which he studied, although the flows themselves lasted less than an hour. Pack (1923, p. 355) notes "well-washed and well-sorted boulders and gravels...strewn along the water channels..." which were cut in a debris-flow deposit by this following water flow. A high proportion of the relatively well-sorted material found on fans may be debris-flow material reworked by subsequent fluvial processes. It is possible that the lower proportion of debris-flow deposits recognized by Blissenbach (1954, p. 179) in areas of relatively high precipitation is due to greater modification of debris flows by fluvial processes and not to the lesser importance of debris flows in transporting material to the fan.

The inhomogeneous distribution of debris-flow material in a fan is another source of difficulty. The best exposures of fan stratigraphy are usually in the main channel above the intersection point. Since debris-flow deposition is likely to be more common near the head of the fan than near the toe, field estimates of the volumetric importance of debris-flow deposition will often be biased in favor of debris flows.

It is constructive to consider morphologic characteristics of fans built entirely by one type of flow. A laboratory fan built entirely with debris flows was steep and strongly concave (Plate 4). This was because laboratory debris flows, owing to their yield strength and limited erosional capabilities, always deposited some material at the fanhead. If natural debris flows behave similarly, natural fans composed entirely of debris-flow material would also be steep and concave and erosional channels would be

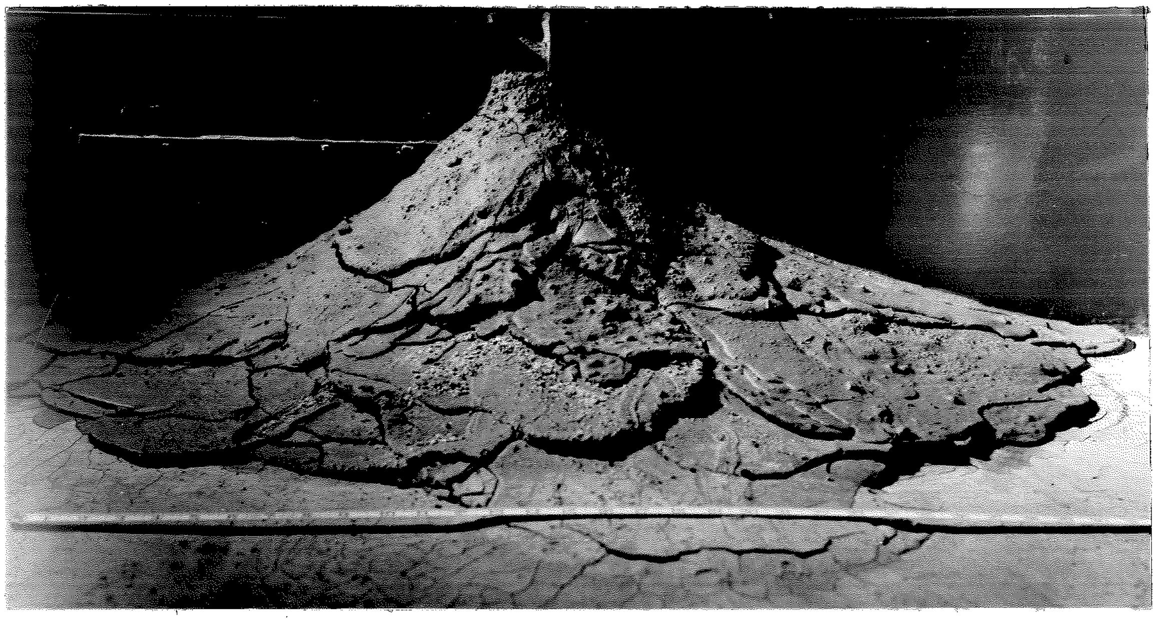


Plate 4. Laboratory fan B-1, a fan built entirely with debris flows.

absent. Steep concave fans with no channels are rare in nature. The fan northeast of Little Cowhorn Fan is steep, has a very small main channel, and has many debris flow lobes on its surface. This is the only fan seen that has these characteristics.

Laboratory fans built entirely by fluvial processes (Plate 3, A-D) usually do not have incised fanheads. The entire fan surface has the characteristic morphology of a braided stream bed. When debris flows are intermixed with fluvial episodes the braided pattern is restricted to the fan surface below the intersection point (Plates 2 and 3). This last type of channel pattern has been observed in the field by the author and is also described by Bull (1964, p. 93). Natural fans whose entire surface is braided have been observed on the east side of Death Valley. In this case tectonic disturbance may be responsible for aggradation over the entire fan surface, but a dearth of debris flows could have the same effect.

In conclusion, the relative importance of debris-flow and fluvial processes is determined by the lithologic, climatic, and topographic factors which control debris-flow formation. Qualitative estimates of the relative volumetric significance of the two processes on any one fan can be made using morphologic characteristics, but accurate quantitative estimates are impossible at present.

# INFILTRATION AND SIEVE DEPOSITION

Earlier students of alluvial fans have remarked upon the significance of infiltration in reducing the sediment carrying capacity of fluvial flows and instigating deposition (Trowbridge, 1911, p. 738; Eckis, 1928, p. 237; Blissenbach, 1954, p. 178). However, Bull (1964, p. 104) has shown that water on fans in the San Joaquin Valley does not percolate below the root zone of vegetation.

## Consequences of a High Infiltration Rate

Deductively, there are two morphologic consequences of high infiltration on alluvial fans. Consider a channel in quasi-equilibrium from which an appreciable amount of flow is lost owing to infiltration. In order to maintain equilibrium the capacity for sediment transport of the remaining water must increase downstream. To visualize the process by which this may occur consider a perturbation of the system. If deposition occurs in a given reach owing to infiltration, the slope of the channel upstream would be decreased and the slope in this reach increased. The increased slope resulting from deposition would increase the velocity, and hence the capacity of the remaining flow. Velocity could also be increased by decreasing the width and increasing the depth of the channel. Thus, deductively, high infiltration should result in a channel which becomes steeper and perhaps narrower downstream. Such channels have been observed in the laboratory (Fig. 6, Runs A-3 and A-7). The convexity of the channels is shown by the contours (Fig. 6) and by the channel profile in Figure 7.

The second morphologic consequence of high infiltration is deposition of a lobe of debris at the point where the water is finally unable to effect further transport. The profiles of laboratory fans A-1 and A-2 (Fig. 7) and of Gorak Shep and Shadow Rock fans (Plate 5) reflect this occurrence, herein called sieve deposition. Current understanding of this type of non-steady state process does not permit a meaningful theoretical or deductive discussion. An observational description of the process follows.

## Sieve Deposition

Extensive sieve deposits have been observed on seven fans in the field. Four are in the southeast corner of Deep Springs Valley, California, one of which, Shadow Rock Fan (Plate 6A and Fig. 11 A), has been mapped in detail. Two others, including Gorak Shep Fan (Plate 6 B and Fig. 9 A), are in the southeast corner of Eureka Valley, California. The last is about 2800 feet N. 16 E. of Badwater in Death Valley. Sieve deposition may be due to permanent loss of discharge or to temporary loss of discharge. Both processes have been observed in the

Figure 7. Longitudinal and transverse profiles of laboratory fans in Runs A-1, A-2, A-3, and A-4 (Fig. 6) after eighth episode.

A. Longitudinal profiles along the zero ordinate (axis) of the fans. The stepped nature of these profiles and of the transverse profiles in Figure C is the result of sieve deposition. Reverse slopes on the fans are at channel banks.

B. Profile of main channel in Run A-3. Note the convexity of the profile above the sieve deposit. This is the result of a high infiltration rate.

C. Transverse profiles of the fans 6 inches from the fanhead.

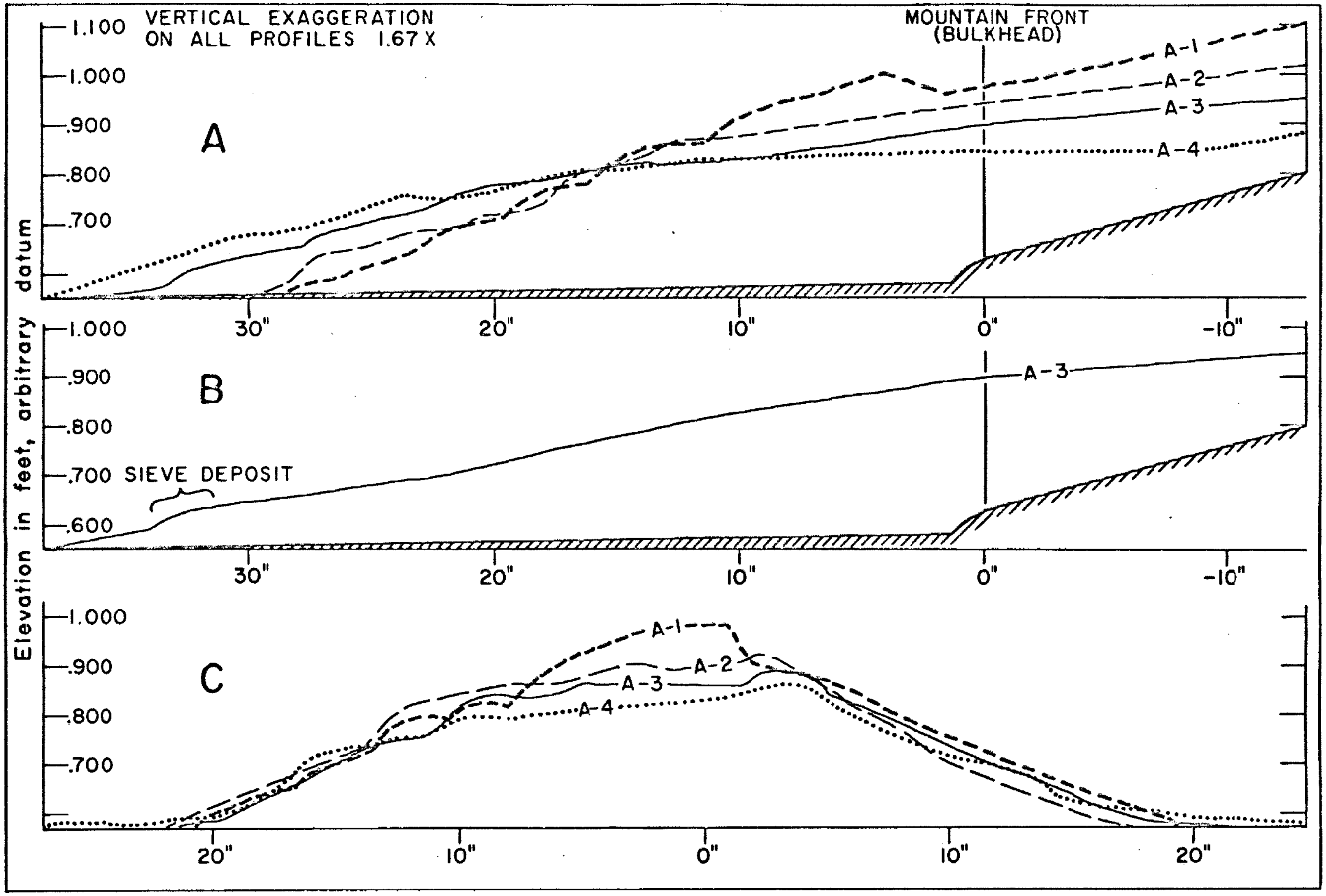

VERTICAL EXAGGERATION ON ALL PROFILES 1.67 X
MOUNTAIN FRONT (BULKHEAD)
Elevation in feet, arbitrary datum
A
1.100
1.000
.900
.800
.700
A-1
A-2
A-3
A-4
30"
20"
10"
0"
-10"
B
1.000
.900
.800
.700
.600
SIEVE DEPOSIT
A-3
30"
20"
10"
0"
-10"
C
1.000
.900
.800
.700
A-1
A-2
A-3
A-4
20"
10"
0"
10"
20"

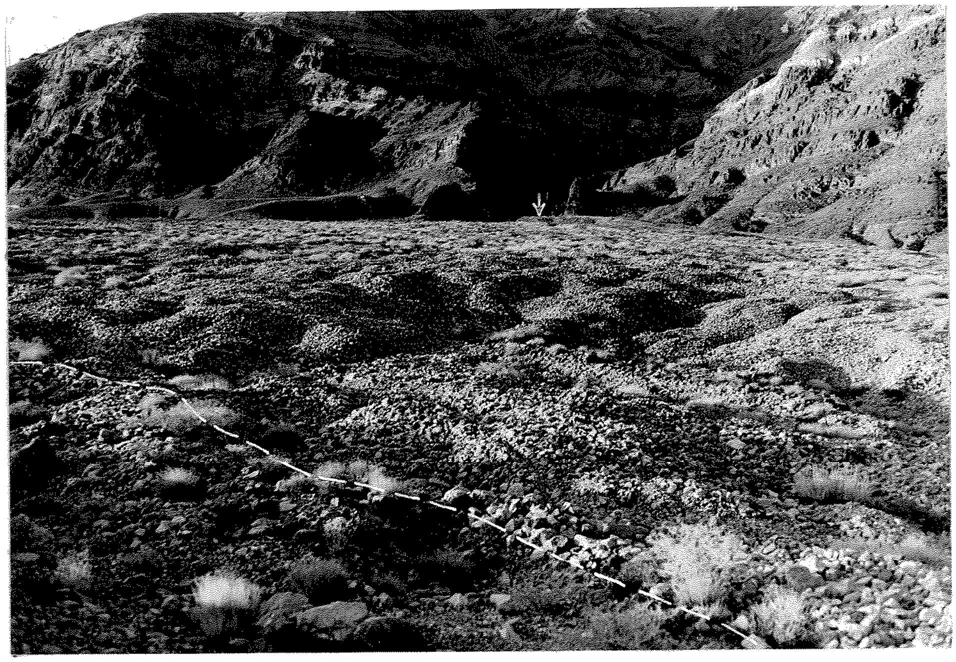
Figure 7.

Plate 6. Field examples of sieve deposition.

Figure A. Shadow Rock Fan. In this instance the hummocky surface results from sieve deposition, but similar topography can be formed by debris-flow action.

Figure B. Gorak Shep Fan. Note the bank in the foreground (outlined) emerging from beneath the sieve lobes. This bank is the "youngest fan surface material" in the vicinity of the number "7" on Figure 9 A. It also appears below the sieve deposits on the left side of Figure 9 B. Note also the fault scarp (arrow) on the right side near the fanhead and the older terrace on the left side.

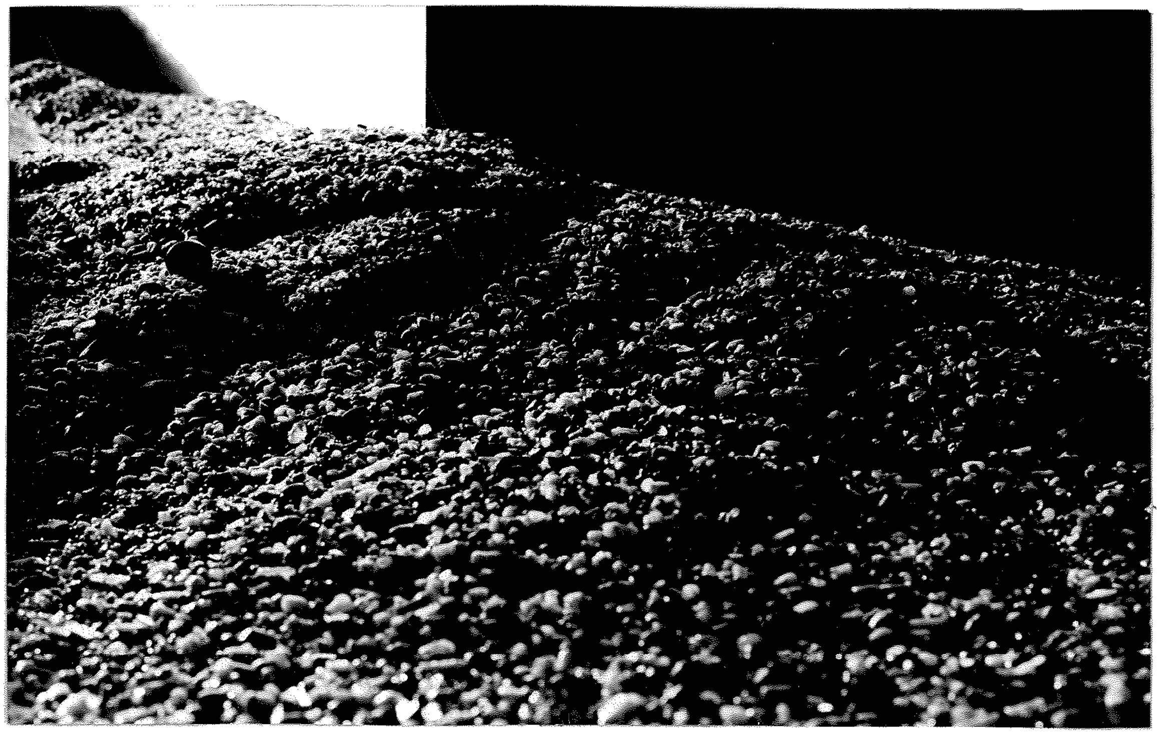
A.



B.

Plate 6.

A. Fan A-2 after 10th episode. Duration of flow, 60 sec. Discharge, 0.015 cfs.



B. Fan A-1 after 8th episode. Duration of flow, 60 sec. Discharge, 0.012 cfs.

Plate 7. Laboratory examples of sieve deposition.

laboratory, and field relationships suggest that both have occurred in nature. Sieve deposition was first recognized in the laboratory, so laboratory observations will be considered before describing the natural examples.

## Laboratory Observations

On laboratory fans, sieve deposition at midfan is the result of permanent loss of flow by infiltration. Deposition of granules, when the discharge becomes too small, forms an initial debris barrier. The channel slope immediately upstream from this barrier is reduced by backfilling (Fig. 8). Further deposition ensues as a result of infiltration and of the decrease in slope. Deposition does not actually occur in layers as represented in Figure 8, but schematically this provides an easy way to visualize the process. When regrading of the channel above one barrier is complete water is again able to transport material to the front of the lobe, and a new barrier is formed. Owing to the decreased slope, each new debris barrier is successively slightly farther upstream, resulting in lobe fronts which are convex in cross-section and fairly steep (Fig. 8).

Adjustment of the laboratory channel above the snout of a sieve lobe may occur in the same way that a stream channel adjusts upstream from a dam. Over a few years, significant aggradation is usually observed behind

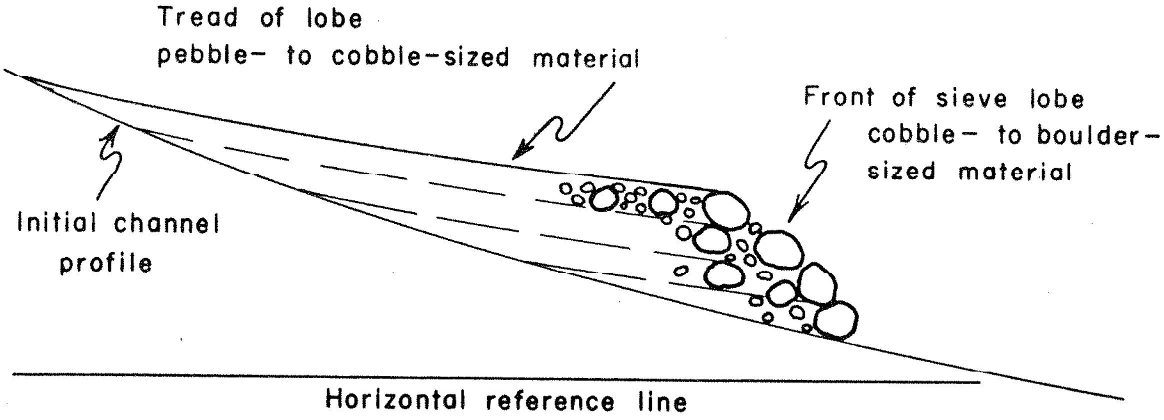


Figure 8. Schematic sketch of growth of a sieve lobe.

the dam but the amount of deposition decreases to zero within a few hundred to a few thousand feet upstream (Leopold, Wolman, and Miller, 1964, p. 258-266). Leopold, Wolman, and Miller (1964, p. 261-266) have suggested that the decrease in gradient is compensated by other changes in channel geometry such that continuity of sediment transport is provided. The decrease in channel slope across the treads of sieve lobes (Fig. 7 B and Plate 5) suggests similar compensating changes in channel morphology above the snout of the lobe.

Water flow across the tread of a sieve lobe may confine itself temporarily by deposition along its lateral edges where competence is reduced. Occasionally a mudless debris flow shoots out a few centimeters from the front or flank of the lobe and stops. This flow is produced by collapse of the over-steepened lobe-front. Collapse may be promoted by excess interstitial water, or by flow of water over the steep front or flanks of the lobe. In the latter instance lateral shifting of the flow, or a decrease in the infiltration rate as fine material is deposited upstream, may be responsible for the diversion or extension of the water flow. Backfilling behind the mudless debris flow proceeds until this part of the lobe has been built up to the elevation of the remainder. In this way remarkably complex multiple debris lobes are formed (Plate 7 A).

Sieve deposition also occurs at the toe of laboratory fans owing to the abrupt decrease in slope. The construction of the lobe proceeds as before except that mudless debris flows do not occur, perhaps because of the gentle slope of the model bed below the lobe. Instead the deposit is built and extended by grains that are pushed to the sides or edge of the lobe and then topple down the slope. The loss of flow in these lobes is only temporary; after infiltrating, the water encounters the impermeable bed of the model and emerges around the base of the lobe.

In the laboratory, sieve deposition generally occurred first at the toe of a fan. But each increment of material added to the fan increased its thickness and area, thus increasing the infiltration rate and the area over which infiltration occurred. Therefore, the locus of sieve deposition gradually moved up-fan resulting in a succession of sieve lobes (Plate 7 B). Laboratory fans A-4 through A-1 (Fig. 6) represent stages in this process, but in this example the up-fan migration of sieve deposition is caused by a controlled decrease in discharge with constant infiltration rate rather than by an increased infiltration rate at constant discharge.

From these observations the basic requirements for sieve deposition are:

1. A predominance of coarse material with insufficient fines to fill void space; and
2. A discontinuity in competence of the flow transporting this material.

The first condition is necessary because, once the lobe begins to form water must pass through it rather than over it. In the laboratory this requirement is satisfied by the grading of the material used (Fig. 4). The second condition may result from fulfillment of the first, as is the case for sieve deposition at midfan in the laboratory. Alternatively it may be satisfied by a break in slope, as at the toe of the laboratory fans, if the infiltration rate is not high enough to induce sieve deposition otherwise.

### Field Observations

In nature the above requirements may be satisfied in much the same way as in the laboratory. Debris calibre is primarily a function of source-area lithology. For sieve deposition, the bedrock must break down to cobble- and boulder-sized material and must be resistant to subsequent weathering. If significant amounts of sand- to clay-sized detritus are produced in the source area, this material will fill void space and prevent sieve deposition. Similarly the discontinuity in competence can be the result of a high infiltration rate or of an abrupt decrease in slope. These conditions are discussed in connection with the fans on which they occur.

## Natural Examples of Sieve Deposition

### Gorak Shep Fan

Before discussing the details of sieve deposition on this fan, it is convenient to consider certain other aspects of the fan's morphology.

Ages of material. During mapping of Gorak Shep Fan, six "ages" of alluvium were distinguished (Fig. 9 A, B). Both the recent channel deposits and the overflow channel deposits have a light-gray abrasion coating, but the overflow channels are topographically higher where the two diverge. The oldest channel deposits occur in terraces

Figure 9 A. Geomorphic map of Gorak Shep Fan constructed in the field on hazy, high-altitude air photographs. Age relationships are discussed in the text. Brackets indicate approximate area covered by Figure 9B. Small numbers indicate localities at which differential weathering counts (Figure 9 C) were made. Location of fan is given in the Appendix.

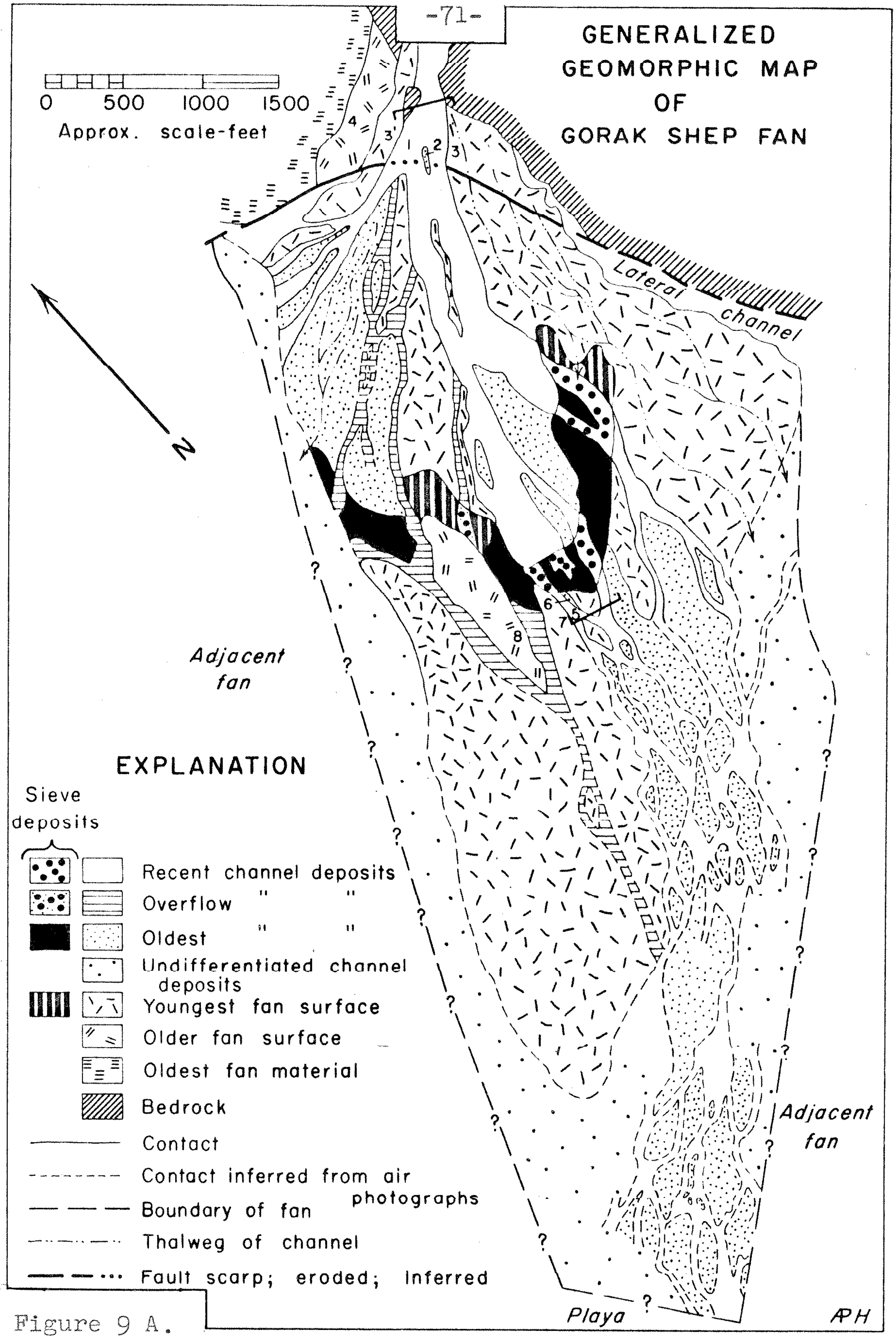

GENERALIZED GEOMORPHIC MAP OF GORAK SHEP FAN
0 500 1000 1500
Approx. scale-feet
N
1
2
3
3'
4
5
6
7
8
Lateral channel
Adjacent fan
Adjacent fan
Playa
EXPLANATION
Sieve deposits
Recent channel deposits
Overflow " "
Oldest " "
Undifferentiated channel deposits
Youngest fan surface
Older fan surface
Oldest fan material
Bedrock
Contact
Contact inferred from air photographs
Boundary of fan
Thalweg of channel
Fault scarp; eroded; inferred
?
APH

Figure 9 A.

Figure 9 B. Detailed Map of Middle Channel of Gorak Shep Fan.

Material ages were distinguished as described in the text. Cobble- and boulder-bars are concentrations of material of the same size as the material in the sieve deposits, but lacking the topographic form of sieve deposits. In general, the material is coarser in the bars nearer the fanhead.

Note the complexity of the sieve deposits when mapped in detail, and compare the map view with the photograph of the same area in Plate 6 B. The pebble-sized material in the recent channel apparently does not have a high enough infiltration rate to form sieve lobes under the conditions prevailing at this point on the fan.

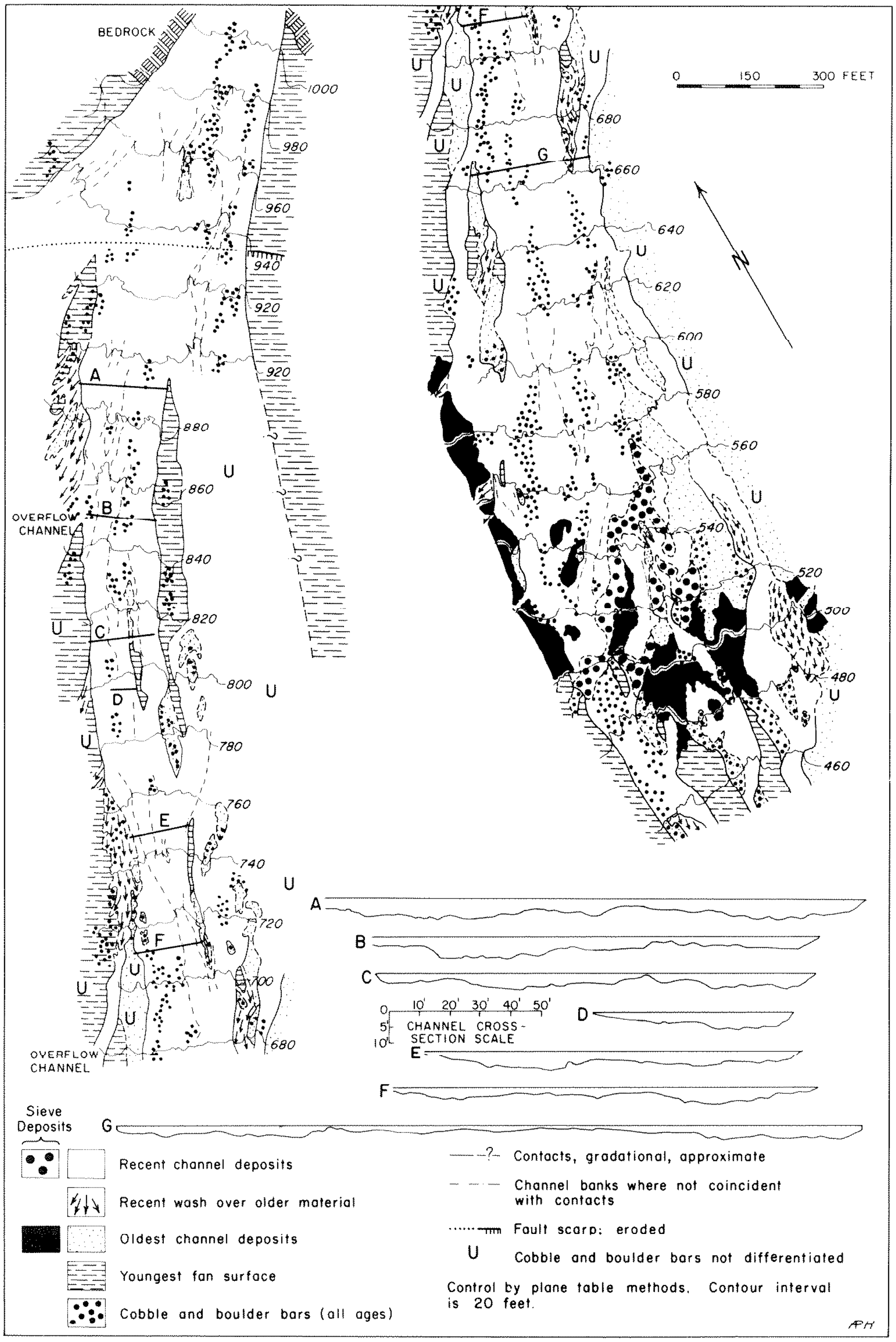

BEDROCK
1000
980
960
940
920
920
A
880
U
860
OVERFLOW CHANNEL
B
840
820
U
C
D
800
U
U
780
760
E
740
U
720
F
U
U
700
680
OVERFLOW CHANNEL
F
U
U
U
U
680
G
660
640
U
620
U
600
U
580
560
U
540
520
500
480
U
460
0
150
300 FEET
N
A
B
C
D
E
F
G
0
10'
20'
30'
40'
50'
5'
10'
CHANNEL CROSS-SECTION SCALE
Sieve Deposits
Recent channel deposits
Recent wash over older material
Oldest channel deposits
Youngest fan surface
Cobble and boulder bars (all ages)
?— Contacts, gradational, approximate
Channel banks where not coincident with contacts
Fault scarp: eroded
U Cobble and boulder bars not differentiated
Control by plane table methods. Contour interval is 20 feet.
APH

Figure 9 B.

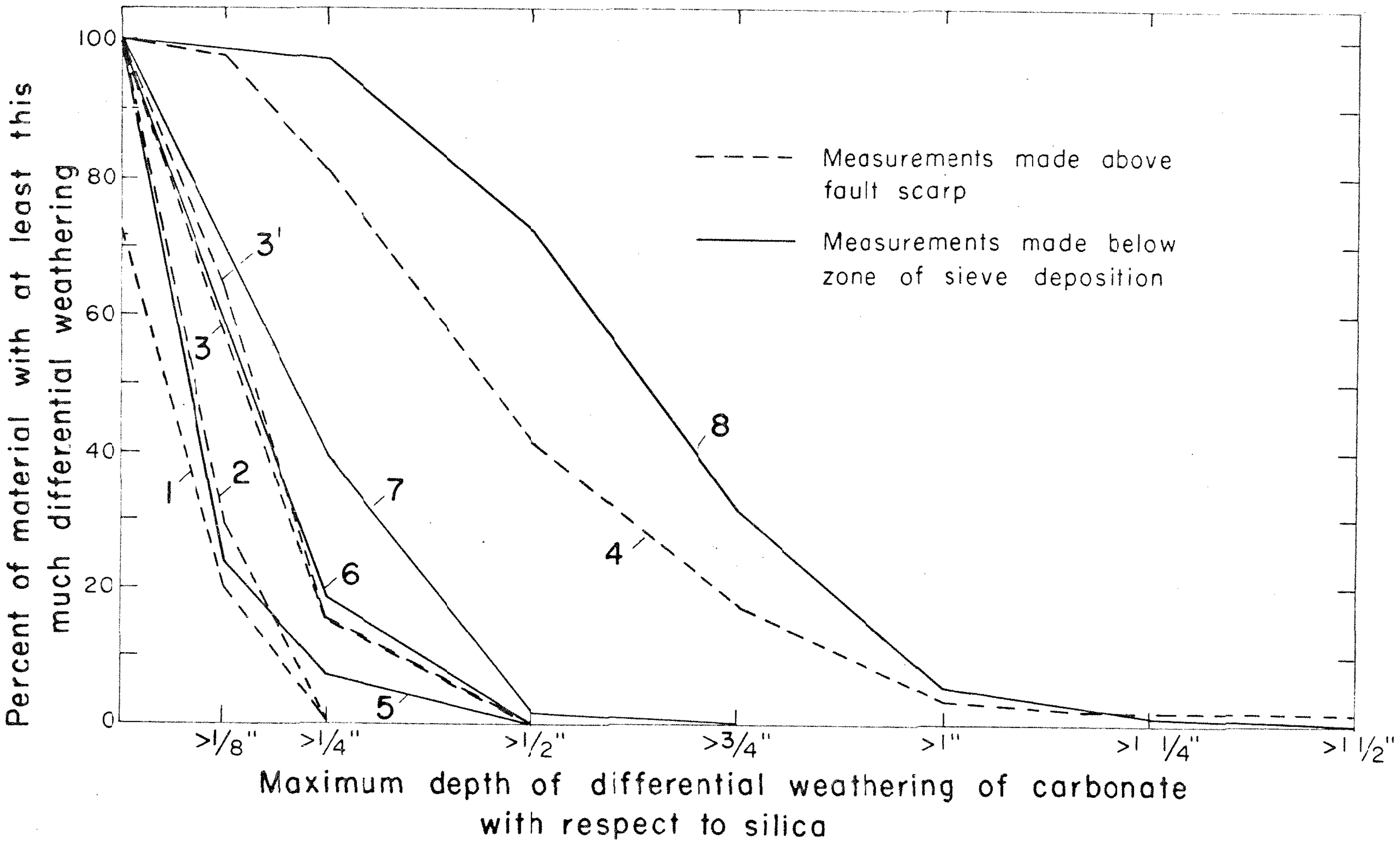


Figure 9 C. Age relationships on Gorak Shep Fan as determined by measuring the depth of differential weathering of carbonate with respect to silica in boulders containing both phases. Numbers refer to localities shown in Figure 9 A.

slightly above the recent channels and no longer have an abrasion coating; weathering has given it a brownish color. All channel deposits have open pore space at the surface.

The three older units are topographically higher than the channel deposits. Most pore space in these older deposits is filled with fines, resulting in generally smoother surfaces with areas of incipient desert pavement. These units are distinguished from each other by topographic position in terraces at the fanhead.

In order to verify and extend this chronology, a study of differential weathering on carbonate cobbles and boulders containing silica bands or knobs was made. Cobbles and boulders on the fan surface showing differential weathering were searched for, and the maximum depth of differential weathering on each was determined. The actual depth was not recorded; instead a tally sheet was constructed with columns headed by >1/8", >1/4", >1/2", >3/4", >1", etc. (The 1/8" division was not used on the first few measurements). A boulder with greater than 1/2" but less than 3/4" of differential weathering would rate a tally in each of the first three columns. In addition rocks with no visible differential weathering were recorded in a column marked ≡0, and the total number of rocks was recorded. In general only rocks greater than 6" in maximum diameter were counted; this requirement was relaxed in small areas, or relatively unweathered areas, where rocks containing silica bands or knobs were difficult to find. The results of the measurements are shown in Figure 9 C. The abscissa of Figure 9 C gives depths of weathering observed on rocks and the ordinate shows the percent of the total number of rocks selected for observation which had weathered to this depth or deeper. With the exception of locality 2 (Fig. 9 A) where only 10 rocks could be found, each of the lines in Figure 9 C represents between 70 and 77 (usually 75) measurements.

In areas near the fanhead (lines 1-4, Fig. 9 C) this method yielded results consistent with age relationships based on topographic position. Depths of differential weathering were consistently greater on older units. Note in particular the similarity of the two lines labeled 3 and 3' in Figure 9 C, which represent two series of measurements on opposing members of a paired terrace. The >1/8" division was not used at locality 3.

Two series of measurements, not shown on Figure 9 C, were made just below cross-section G, (Fig. 9 B) about halfway between the fanhead and the zone of sieve deposition. One series was in the recent channel deposits. It verified correlation of this material with that at locality 1. The second series was on the west bank of the channel on the "youngest fan surface." The debris at this locality, on the basis of these measurements, appears to be closer in age to the "oldest channel deposits" at the fanhead (locality 2) than to the terraces of younger fan-surface material (localities 3 and 3') with which it is correlated on the basis of topographic position and extent of pore-space filling. This reflects the arbitrary nature of such age distinctions on a surface of continuous but shifting deposition where graditional relationships are inevitable.

Several series of measurements were made below the zone of sieve deposition. These measurements suggest that gravels at localities 5, 6, and 7 are systematically older than those at localities 1, 2, and 3, respectively, with which they were correlated prior to the differential weathering study. This apparent discrepancy is attributed to the fact that Gorak Shep Fan is segmented (Bull, 1964). That is, tectonic disturbance of the fan-source system has resulted in a new steady-state slope of deposition. This slope is about $3^{\circ}$ steeper than the present slope of the previous fan surface. As a result a new fan has been built out over the upper part of the previous surface. The contact between the two segments is at the down-fan limit of the zone of sieve deposition. The break in slope at this point shows clearly on the profile in Plate 5. In a few places sieve deposits at the toe of the upper segment appear to be encroaching upon and overlapping the fan-surface material in the lower segment (Plate 6 B). With this type of segmentation, the older material in the lower segment is constantly reworked and abraded by flow that has crossed the upper segment. The slightly older ages indicated by measurements at localities 5-7 reflect this reworking of older material.

The small area of "older fan surface" below the zone of sieve deposition (locality 8, Fig. 9 A) is correlated with the fan surface at locality 4 on the basis of similarity of lines 4 and 8, in Figure 9 C. The material at locality 8 may be part of the pre-segmentation fan surface. Projection of the profile of the lower segment beneath the upper segment (Plate 5) suggests that the surface near the fanhead has risen 160 feet relatively. The fault along which this movement occurred is currently marked by a fifteen-foot high scarp (Plate 6 B).

From the above discussion one is led to conclude that the "age" of an area on a fan surface is not so much a measure of the time since deposition as it is a measure of the time since the material was last subjected to erosion and abrasion. In many instances the two intervals are essentially the same, but on Gorak Shep Fan and other fans with this type of segmentation, this is not the case.

Sources of fine material on Gorak Shep Fan. As noted above, channel deposits on Gorak Shep Fan are highly porous, but fan surface deposits have little open pore space, the voids being filled with sand- to clay-sized particles. Individual pebbles in such gravels appear to be in contact with their neighbors (Plate 8) and would not need to readjust and settle if the fines were removed. These relationships suggest that the fine material is of secondary origin.

Channel bank exposures of, and holes dug in the "youngest fan surface" revealed a few layers of coarse-pebble gravel with unfilled pore space (Plate 8 A). In at least three instances (Plate 8 A is one) such layers are overlain by granule-sized material in which the void space is filled. This relationship suggests that fines descending from the surface were trapped by the granule layer and constitutes further evidence that the filling process is secondary.

These fines could be: 1) transported by fluvial processes from the source area; 2) transported by eolian processes from elsewhere in the valley; 3) produced by post-depositional weathering. The source area for Gorak Shep Fan is underlain by a thick section of Lower Paleozoic carbonate rocks primarily dolomite. The source-area slopes are steep and have virtually no soil cover; local talus

Plate 8. Exposures of gravels on Gorak Shep Fan in the southeast bank of the main channel upstream from the fault scarp.

Figure A. Stratification is well defined. Void space in a lense of gravel (arrow) near the top of the bank has not yet been filled with secondary fines. No evidence of debris-flow action is seen in this bank.

Figure B. The high concentration of coarse material near the boulder is suggestive of a cobble bar like those mapped in Figure 9 B.

A.

Plate 8.

B.

piles of pebble- to boulder-sized material, in which the void space has been filled with fines, constitute the regolith. Despite the absence of an extensive soil cover, fines are undoubtedly transported to the fan from this source, but they must be incorporated into the youngest as well as the older gravels as a primary constituent. There is no obvious way in which fines from the drainage basin could be secondarily added solely to older deposits.

In order to evaluate possible contributions from other sources, the mineralogy of the fine fractions ($<0.117$ mm) from several sieve analyses (Table III), and a sample from the adjacent playa, were studied in the laboratory using X-ray techniques. The playa sample is assumed to represent the average mineralogic composition of the fine material contributed to the valley alluvium from all sources, and thus to be representative of wind-blown detritus in the valley. A few of these samples, and an 8.2 kilogram sample of pebble-sized material from the "recent channel deposits" were dissolved in HCl to determine the insoluble (non-carbonate) content. The playa contains roughly 25 percent by weight carbonate but the fine material on the fan is approximately 50 percent carbonate. These data are what one would expect if the playa sediments were derived from the fan by fluvial processes, with part of the carbonate going into solution en route to the playa. They do not suggest eolian transport in the reverse direction.

On the other hand, the fine fraction (<0.117 mm) from the sieve analyses is approximately six percent of the total (Table III). Of this, about half is carbonate and half is quartz and feldspar. Three percent of the 8.2 kg pebble sample was insoluble material in this same size range. Thus in order to produce a fan containing three percent insoluble residue in the <0.117 mm range from gravels consisting entirely of these pebbles, approximately 50 percent of the original gravels would have to be dissolved. It seems unlikely that this much solution has taken place. As previously noted (Fig. 9 C), the differential weathering of pebbles rarely exceeds a half-inch except on the very old parts of the fan. It was generally less than one-quarter inch. If one assumes that the rates of weathering are proportional to the absolute hardness, a quarter inch of differential weathering would imply a half inch of total weathering. This value is probably high as it does not take into account differences in solubility. Since most of the boulders measured were greater than 6 inches in diameter, a half inch of total weathering implies solution of less than 35 percent of the original rock. This value is a maximum for the following reasons: (1) the depth of differential weathering measured was the maximum observed on each rock; (2) the one-quarter inch value is higher than the average for the fan; (3) many of the rocks were larger than six inches in diameter; and (4) the solubility has been ignored. A more conservative estimate of the total loss due to solution would be about 20 percent.

These calculations suggest that about half (e.g. 20%/50%) of the fine material in the fan has been derived from abrasion and weathering of coarser material. The remainder is probably wind blown. Assuming that all material finer than 2.79 mm is secondary void space filling, Table III (p. 51) indicates that the $< 0.117$ mm fraction considered above is only about one-quarter of the total filling. Since the remaining three-quarters is predominantly carbonate, presumably produced by post-depositional weathering, eolian processes need be responsible for no more than about 12 percent (e.g., 1/2 x 6%/25%)of this filling.

Sieve deposition on Gorak Shep Fan. The causes of sieve deposition on Gorak Shep Fan are clear. Owing to the break in slope at the toe of the upper fan segment, most of the material in transport is deposited at this point. Furthermore, because of the resistance of the carbonate to arid-region weathering, and because of the steep slopes and hence short residence time of debris in the source area, the material deposited is predominantly pebble size and larger with a minimum of interstitial fines. Consequently these deposits have a high infiltration rate and sieve deposition occurs. Water percolating through the sieve deposits emerges below them and continues down-fan as surface runoff. In these respects, sieve deposition on Gorak Shep Fan resembles that on laboratory fans A-3 and A-4 (Fig. 6). Having lost its sediment load in the sieve deposits, the water is capable of erosion on the lower segment of the fan as demonstrated by extensive channel development (Fig. 9 A).

### Sieve deposition on Shadow Rock Fan

The drainage basin of Shadow Rock Fan is underlain predominantly by quartzite of the Lower Cambrian or Precambrian Campito Formation (Fig. 10) (Nelson, in press (b)). This rock is more resistant to weathering than the carbonate comprising Gorak Shep Fan, as evidenced by the dark desert-varnish coating on rocks on the older parts of Shadow Rock Fan and by the paucity of fine material, not only in the recent sieve deposits but over much of the fan surface (Fig. 11 A). This paucity of fines results in

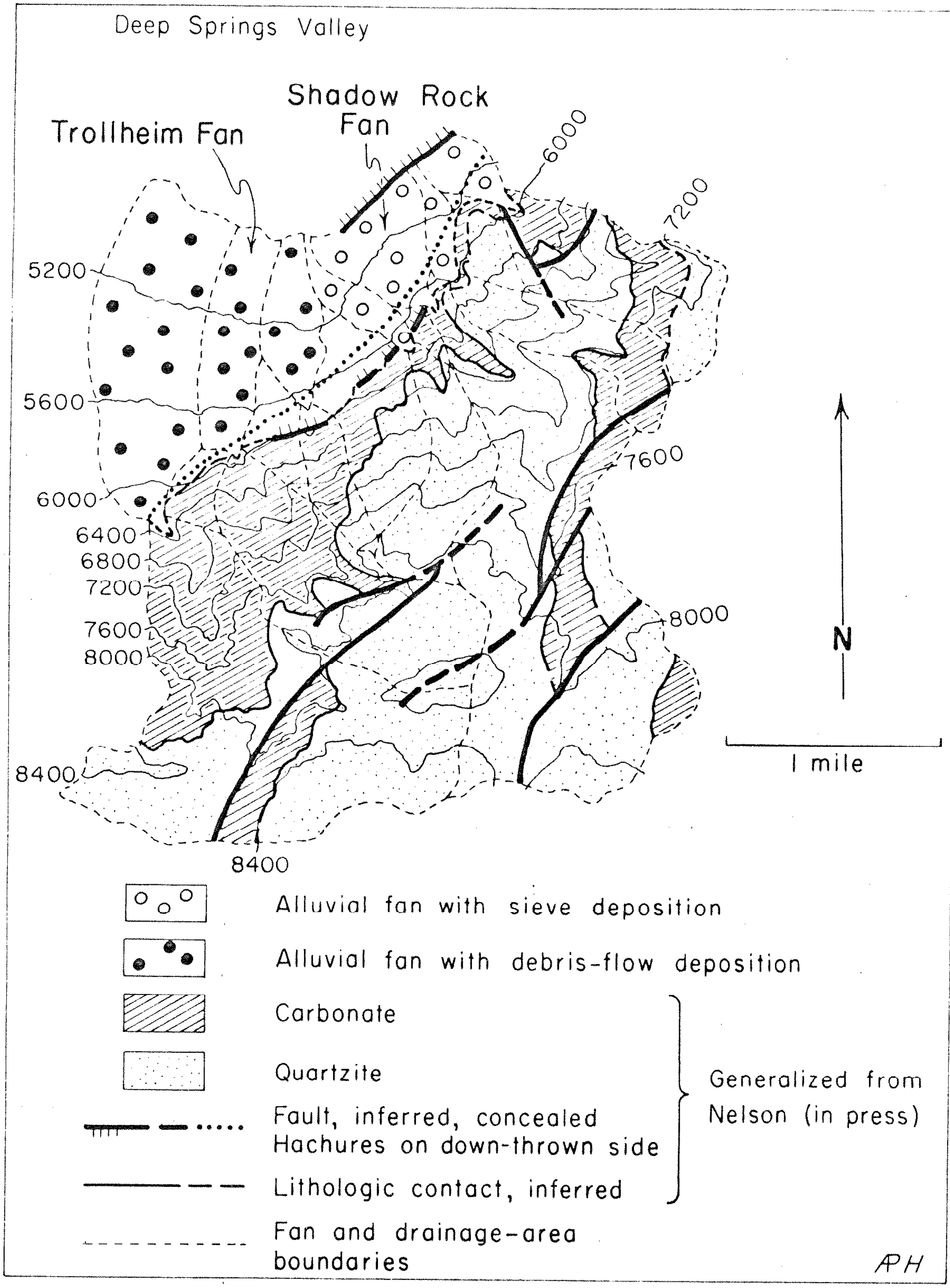


Figure 10. Fans and drainage-basin lithology in southeastern Deep Springs Valley. Geology generalized from Nelson (in press, (a) and (b)).

a high infiltration rate in the older deposits as well as in recent sieve lobes. Thus sieve deposition can and does occur almost anywhere on the fan. The location of a given sieve lobe is determined, not by a break in slope as on Gorak Shep Fan, but rather by the size of discharge. Larger discharges should continue further down-fan before loss of water by infiltration is sufficient to cause sieve deposition. Once the flow has infiltrated, it apparently does not return to the fan surface. Hence freshly abraded gravel does not extend to the toe of the fan (Fig. 11 A) as it does below the sieve deposits on Gorak Shep Fan.

Modification of sieve deposits on Shadow Rock Fan. Sieve deposits on Shadow Rock Fan are modified by two processes. The first involves erosion by subsequent higher-water flows. The succession of sieve deposits in the main channel (Fig. 11 B) provides evidence for this process. The first deposit (No. 1 in Fig. 11 B) is a well-formed lobe and is continuous across the channel. Deposits 2, 3, and 4 are also well formed, but 2 and 3 are small and do not extend completely across the channel (Fig. 11 A). The fifth and sixth deposits are poorly developed. The fifth consists of several separate lobes (Fig. 11 B) and its overall slope is only slightly steeper than the slope of the channel (Plate 5). The sixth also has a low slope. In contrast, the seventh is a single steep lobe extending all

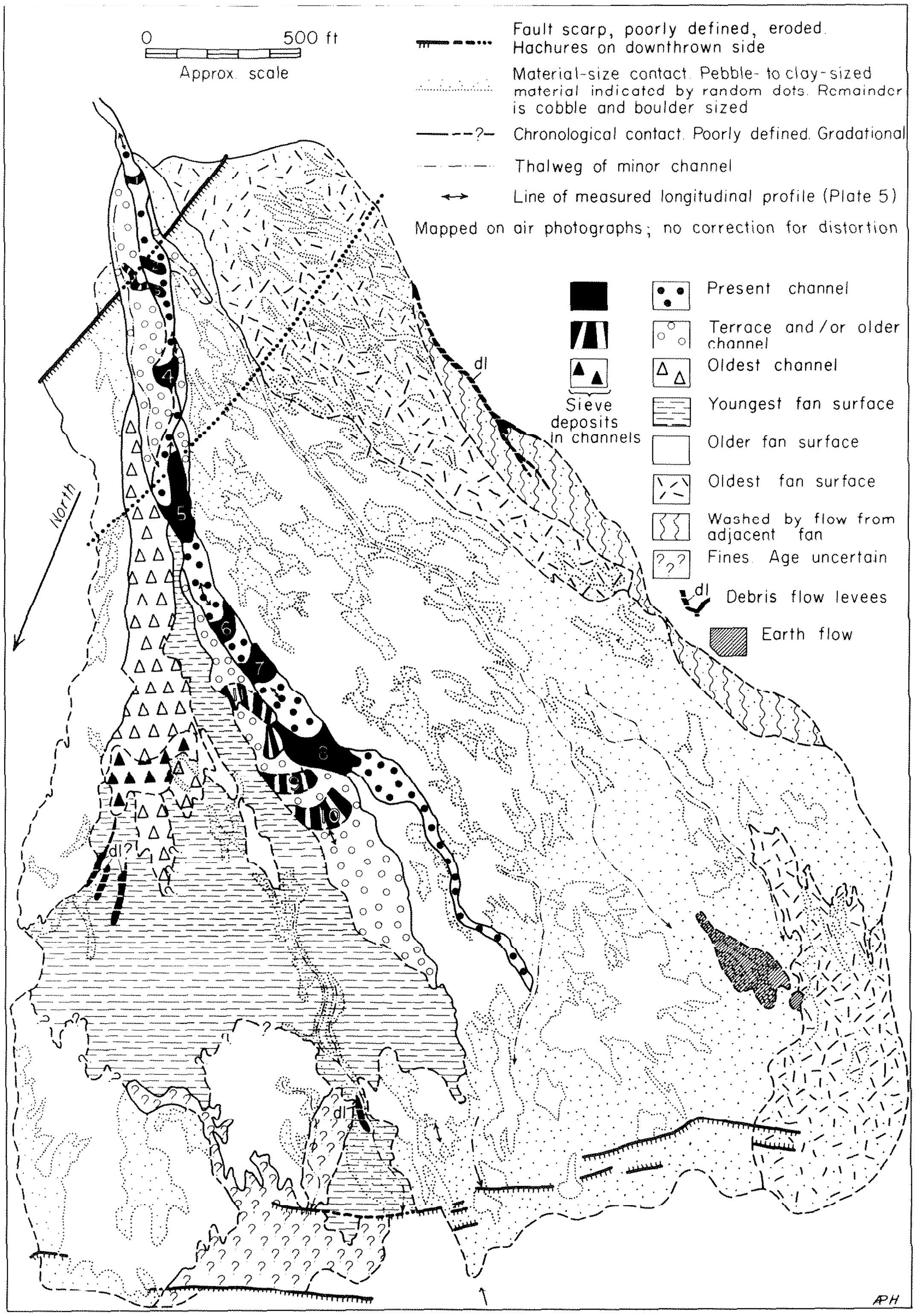


Figure 11 A. Geomorphic map of Shadow Rock Fan. See Appendix for location of fan and detailed explanation of age relationships.

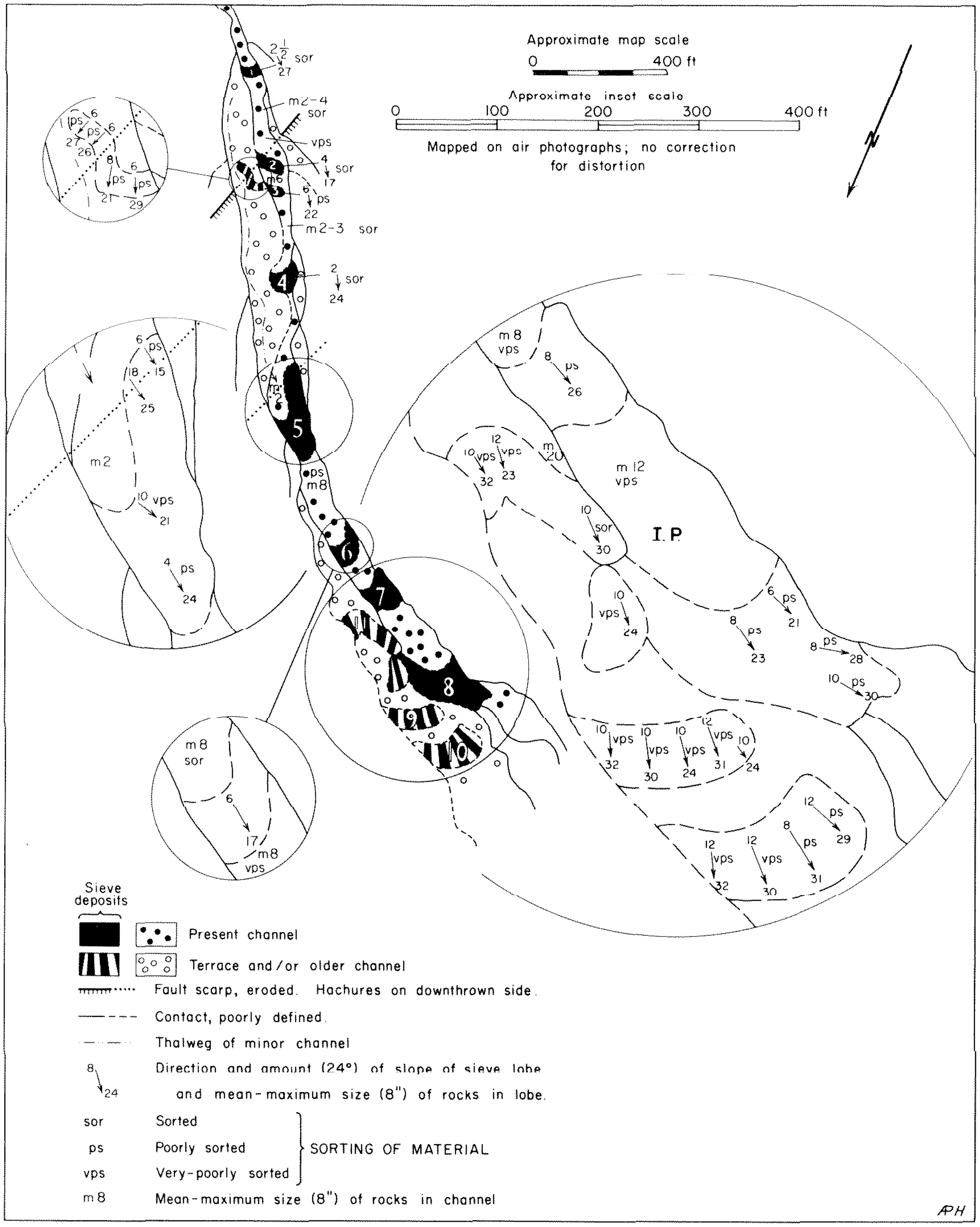
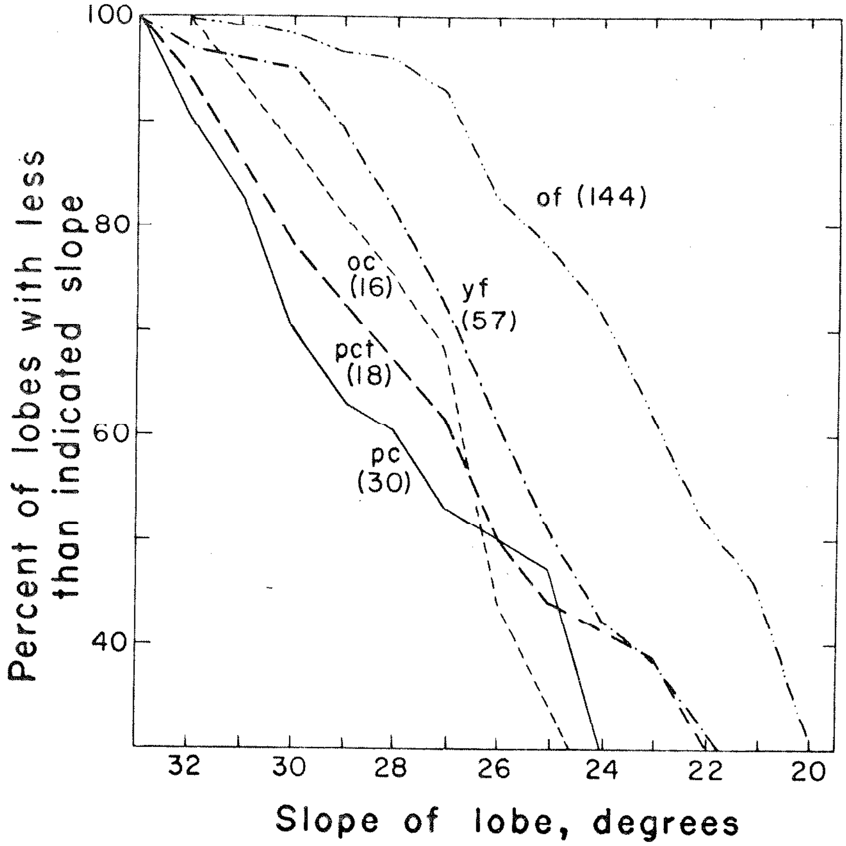


Figure 11 B. Size and sorting of material and slopes of sieve lobes in the present channel of Shadow Rock Fan. The mean-maximum size is the mean size of the coarsest 60 to 80 percent of the local debris based on field estimates.



Explanation

| | |
|---|---|
| pc | present channel |
| pct | terrace above present channel and older channel |
| oc | oldest channel |
| yf | youngest fan surface |
| of | older fan surface |

Numbers in parentheses indicate number of measurements made in each map unit.

Figure 11 C. Age relationships on Shadow Rock Fan as determined by measuring slopes of lobe-fronts of different ages. Slopes of lobe-fronts are decreased by creep. Thus there are fewer lobes with high slopes in the older units. All measured slopes, greater than $12^o$, are included in calculating the percentages on the ordinate, but below the 30 percent level there is no systematic trend in the position of the lines.

the way across the channel; it is the best-developed sieve deposit on the fan. The eighth deposit, just below the main intersection point, consists of several lobes.

These relationships are attributed to the fact that larger discharges should continue farther down-fan before losing enough water to cause sieve deposition. In passing over sieve lobes formed by smaller earlier flows, these larger discharges will modify the earlier deposits. This was observed frequently on laboratory fans. Sieve deposit number 1 on Shadow Rock Fan is the most recent deposit and was formed by a low flow. The small size of deposits 2 and 3 suggest that they are younger than deposit 4, but subsequent slightly larger discharges appear to have eroded them a bit and added material to the fourth. This fourth deposit, well formed and relatively unmodified, is younger than the seventh deposit, formation of which probably required a discharge large enough to modify any older deposits upstream. In this category are deposits 5 and 6 which have several small lobes, unlike the lobes observed in the laboratory each of which was wide as the channel that formed it. The multiple-lobe character suggests modification.

This interpretation is appealing in that it explains the presence of modified sieve lobes in older material elsewhere on the fan. Deposits 9 and 10 are instructive in this regard. These slightly dissected features consist of several lobes (Fig. 11 B) with roughly concordant treads and with fronts falling along an arcuate line across the channel. Like deposits 5 and 6, they represent an intermediate stage between well-formed lobes such as 7, and the hummocky topography that characterizes the rest of the fan (Plate 6 A).

Creep is a second process by which sieve deposits on Shadow Rock Fan are modified. The slopes of many lobe-fronts were measured, and these data are summarized in Figure 11 C. Lobe-fronts in the older units generally have lower slopes. The age relationships upon which this interpretation depends are based upon the darkness of desert-varnish coating and upon the amount of fine material exposed on the fan surface (Fig. 11 A). Thus, the data in Figure 11 C may be interpreted as evidence for creep, or if the existence of creep is accepted, the data justify the age relationships shown in Figure 11 A. Since independent evidence exists both for creep and for the age relationships, the data in Figure 11 C support both conclusions.

## Distinguishing between Debris-flow and Sieve Deposits

In the field, fresh debris-flow deposits are readily distinguished from recent sieve deposits. However, as the detailed map of Trollheim Fan (Fig. 12 B) indicates, separation of these deposits after modification by erosion

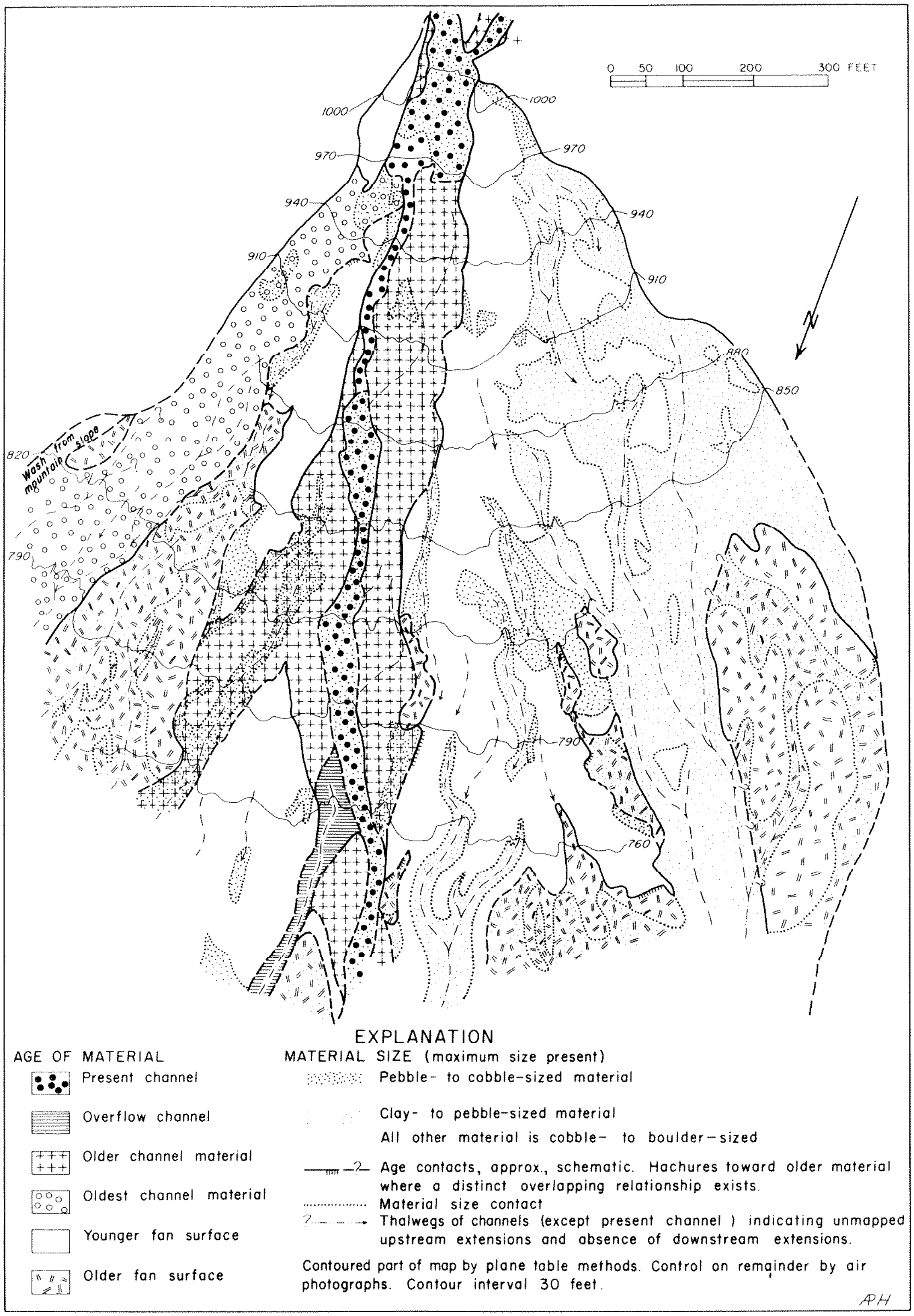


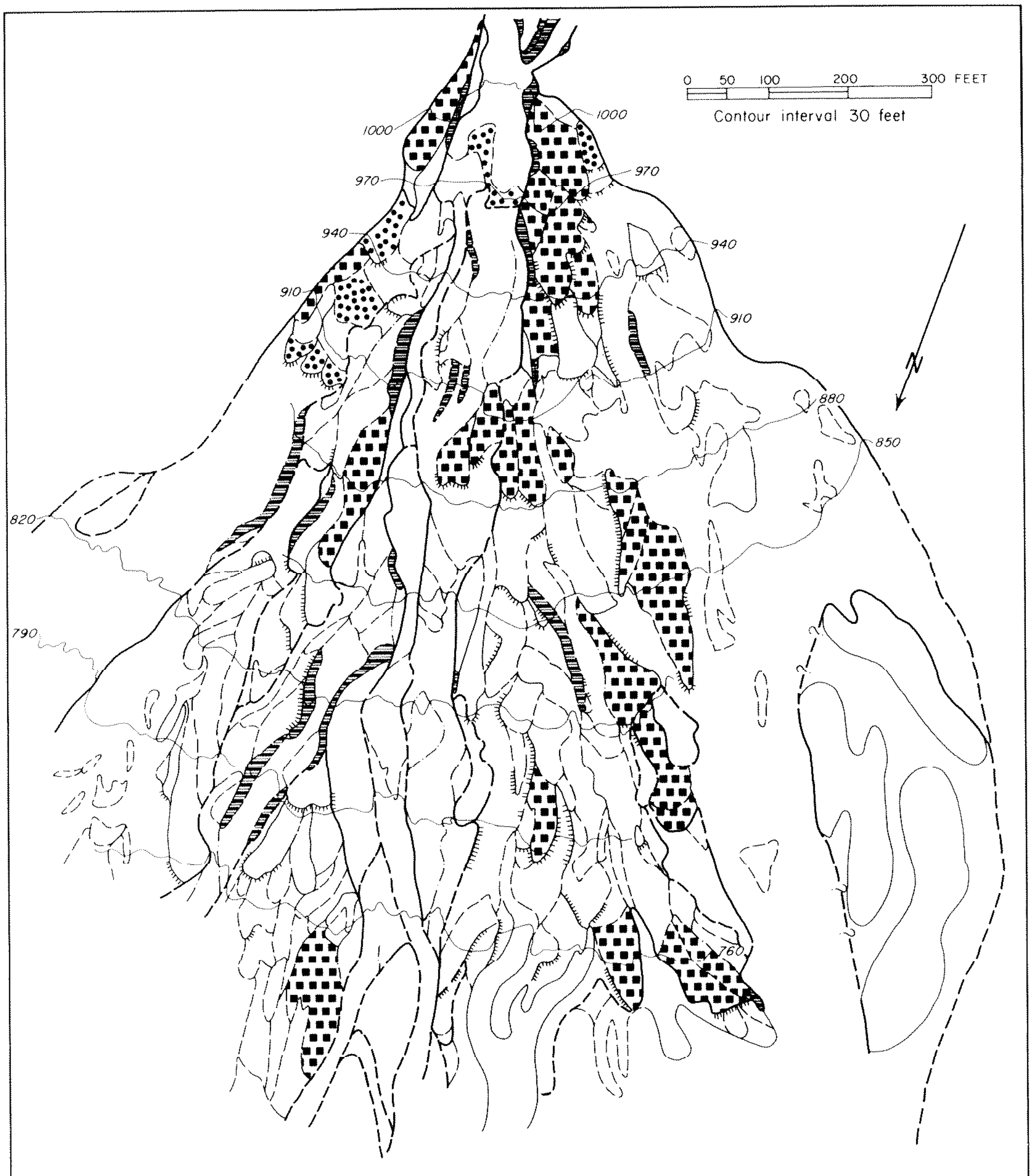
Figure 12 A. Geomorphic map of the upper segment of Trollheim Fan. The distribution of younger fan surface material reflects segmentation (Plate 5). See Appendix for location of fan and detailed explanation of age relationships.

Figure 12 B. Geomorphic map of the upper segment of Trollheim Fan showing units distinguished on the basis of material size and topographic (frequently lobate) form.

Units interpreted as debris flows are flat-topped lobes with steep edges. They have sharp contacts with surrounding material. These lobes are one to three or four feet thick. Debris-flow levees are linear ridges of coarse material, normally bordering channels.

Units interpreted as sieve lobes are generally thicker than debris-flow lobes and they lack the flat top. Some of these, particularly the lobe at the head of the present channel, may be gradually advancing gravel bars. Identification of these lobes is much more tenuous than identification of the debris-flow lobes.

The overlapping relationships indicated by hachures often provide evidence for sequence of deposition. This is particularly true of the debris flow lobes SW of the main channel at the fanhead.



EXPLANATION

▦ Probable debris-flow lobes

▥ Debris-flow levees

⁘ Possible sieve deposits

——?— Age contacts, approximate, schematic. (See fig. 12A)

— — — Contact between units distinguished by topography or material size, approximate

Hachures toward older material where a distinct overlapping relationship exists

— — — — Erosional banks

Contoured part of map by plane table methods. Control on remainder by air photographs

APH

Figure 12 B.

and down-slope movements is not as easy. Only a few of the units mapped could be identified with any confidence. Much of the remaining material, particularly that in the channel bottoms, may be attributed to normal fluvial processes, which are likely to be important regardless of the presence of debris-flow or sieve deposits.

Yet, sieve deposition and debris-flow deposition are not mutually incompatible on the same fan. Shadow Rock Fan is predominantly composed of sieve deposits, but four linear ridges, shown in Figure 11 A, are probably debris-flow levees built by flows originating on the fan or in its source area. A fifth feature, the long branched ridge on the south side of the fan, is undoubtedly a levee, apparently built by a debris flow originating in the dolomitic terrane between Shadow Rock Fan and the fan to the southwest (Fig. 10).

Similarly there are lobes of material among the debris flows of Trollheim Fan that have been mapped as possible sieve deposits (Fig. 12 B). For formation and preservation of such deposits on a debris-flow fan, the water flow must originate in a part of the drainage basin that has little fine detritus. Then, once the sieve deposit is formed, the channel must be diverted to another part of the fan before the void space can be filled with fine material. Otherwise water will flow over, rather than through the deposit, and will destroy it.

The criteria used to distinguish these deposits on Trollheim Fan were developed through comparison of the deposits with each other and with those on Shadow Rock Fan. These criteria are:

1) Recent sieve deposits are composed of pebble- to boulder-sized material without fines, and thus, have a high infiltration rate. In contrast, recent debris-flow deposits have a matrix of fine material in which the coarser debris is embedded.

2) On fans where the evidence for sieve deposition is especially good, the reason for the discontinuity in competence that initiated sieve deposit is usually apparent.

3) Although most sieve deposits would be described qualitatively as very poorly sorted (Fig. 11 B), they contain neither the especially large boulders ( $>$ 3 ft. diameter), nor the granule-sized and smaller material, characteristic of many debris flows.

4) Relatively unmodified debris flows on Trollheim Fan are 2 to 10 feet thick and several times as wide. The sides and snout are steep and appear to overlap the underlying material. In contrast, the fronts of sieve deposits on Shadow Rock Fan are commonly 15 to 30 feet high but, owing to dissection of all but the most recent lobes, their treads are

usually narrow and rounded in cross section and are V-shaped in plan, pointing up-fan. Contacts between sieve deposits and the underlying material are usually gradational and the lobes rarely give the impression of having overlapped the underlying material.

5) Debris-flow deposits can generally be traced some distance up-fan and have a slope approximately equal to the fan-surface slope, whereas sieve lobes typically have short treads with slopes less than the fan slope (Fig. 8 and Plate 5).

6) Dissection of sieve deposits usually takes the form of short gullies leaving the rounded V-shaped treads mentioned above, whereas dissection of debris-flow deposits involves long channels or channel networks.

7) Debris-flow levees are distinctive and are indicative of debris-flow action.

8) Fresh sieve deposits are clearly related to a channel from the fanhead, but fresh debris-flow deposits may not be related to any visible channel.

In addition to these criteria it should be noted that conditions are generally marginal for one type of deposition. Thus, once sieve deposition has been positively identified as an important process on a given fan, it may be assumed that debris-flow deposition on that fan is substantially less important, and that most other lobes on the fan are of sieve origin, even though they have been modified or their origin is less readily determined. Similarly if debris-flow deposition is identified as an important process on a fan, sieve deposition on that fan is probably much less important.

## Channels Narrowing Down-Fan

Experience in the laboratory suggested that down-fan narrowing of channels and convex channel profiles should occur if infiltration losses are significant.

Natural channels that narrow down-fan have been observed on Little Cowhorn Fan (Fig. 3 B) and on Sand Fan (Fig. 13). However sieve deposition has not been observed on either fan, and in the region in which narrowing occurs neither of them show a marked convexity in longitudinal profile (Fig. 3 B and Plate 5). The channel of Little Cowhorn Fan above the main intersection point consists of a series of steps where the channel drops over boulders, connected by straight reaches graded to the level of the top of the step (Fig. 3 B). The channel of Sand Fan is straight or concave, the only convexity being in the vicinity of the intersection point. Conversely, fans on which sieve deposits demonstrate the importance of infiltration do not have channels which narrow <u>uniformly</u> down-

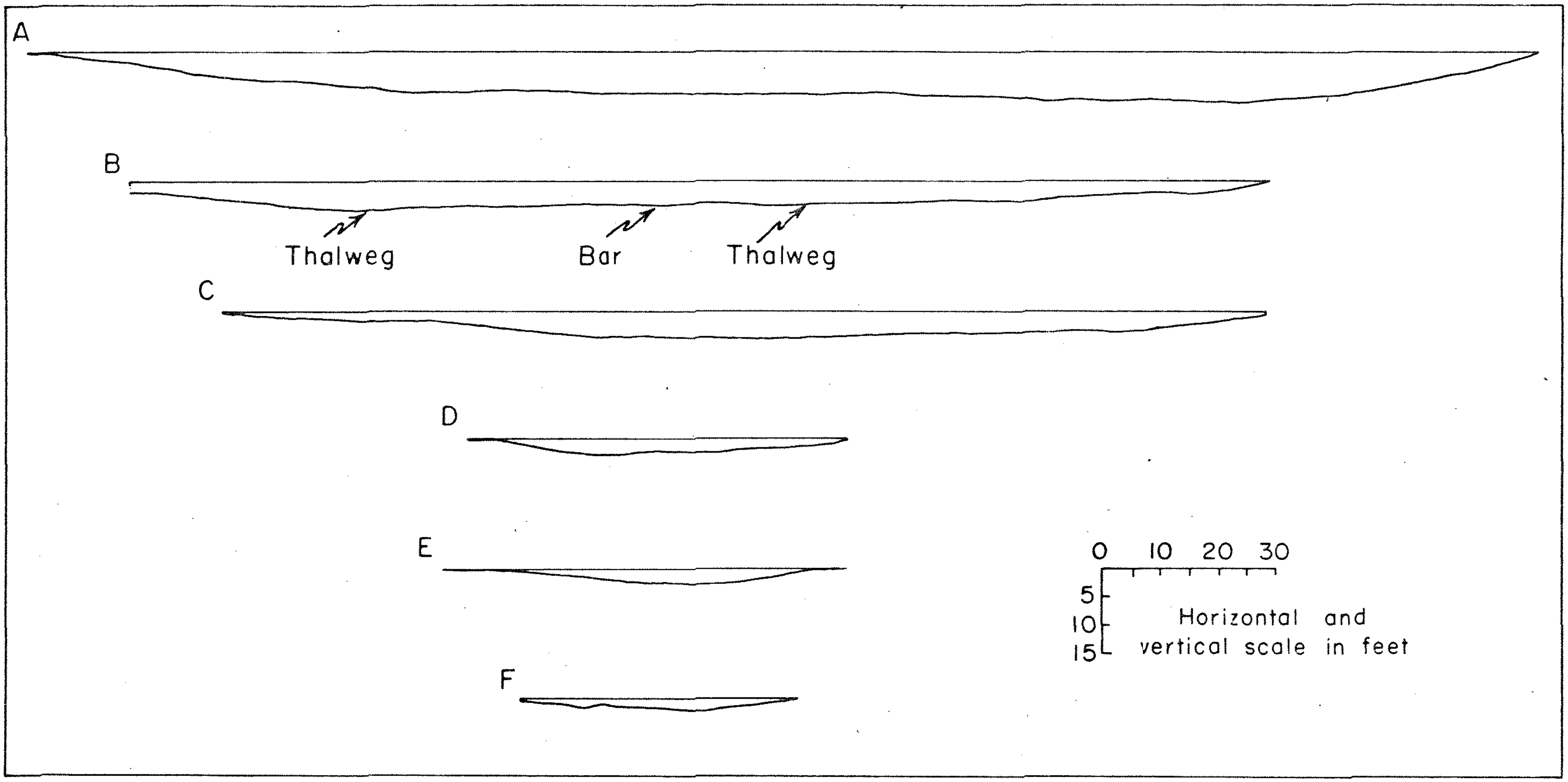


Figure 13. Cross sections of channel on Sand Fan. For locations of sections see profile in Plate 5.

fan and which have uniformly convex profiles above the zone of sieve deposition as observed on laboratory fans (Compare Fig. 6, Runs A-3 and A-7, and Fig. 7 B with Figs 9 B, 11 A, and Plate 5). This appears to be the result of the variability of natural discharges and of the fact that natural channels are formed by several flow events, rather than by one event as in the laboratory. These observations suggest that infiltration is not the cause of the narrowing reported above.

The channels near the head of Gorak Shep Fan are an exception. These channels are uniformly convex (Plate 5) but in this case the convexity is attributed to division of the flow between the three branches of the main channel at the fanhead (Fig. 9 A). The hydraulic radius of each of the smaller channels will normally be greater than that of the parent channel and hence a steeper slope may be required to maintain velocity. This hypothesis assumes that some flow events are large enough to flood all three channels simultaneously. The most recent flows have not been this large; they have cut narrow sub-channels within the main channel (Fig. 9 B). The straight profile of these channels between this upper convexity and the sieve deposits farther down-fan suggests that infiltration is not the cause of the convexity.

Field observations suggest two alternative explanations for channels that narrow down-fan. Consider a debris flow that extends only part way down a V-shaped channel, but does not fill the channel. The section of the channel above the nose of the flow will be regraded at a higher level in the original V-shaped cut. If the regraded channel is flat-bottomed, its bottom width will be greater than the bottom width of the unfilled channel downstream below the debris-flow nose. This could explain the down-fan narrowing of the main channel on Little Cowhorn Fan, the two steps in the channel profile being remnants of debris-flow lobes that caused regrading.

The second explanation involves a process of channel widening at the fanhead. This widening is caused by deposition within the channel forming a bar that divides the flow and forces it against the banks causing erosion. This process has been observed on laboratory fans. The wide part of the channel on Little Cowhorn Fan between sections A and B is probably due to division of the flow around a boulder bar. The broad channel at the head of Sand Fan is due to deposition caused by a sharp decrease in channel slope at the fanhead (Plate 5). The resulting debris accumulation forms a slight convexity in the cross-sectional profile of the channel at section B (Fig. 13). If this is to represent a stable or equilibrium condition, the deposited material must subsequently be transported down-fan. This can be accomplished by underloaded flows or by small flows that occupy only a part of the total width of the channel.

# AREA RELATIONSHIPS ON ALLUVIAL FANS

The area of an alluvial fan is a function of the area of the drainage basin subtended by the fan. This relationship has been recognized previously by Denny (1965, p. 38) and Bull (1964). It may be expressed by the equation

$$A_f = c\ A_d^n \tag{1}$$

where $A_f$ and $A_d$ are the areas of the fan and its drainage basin respectively, and c and n are constants for a given group of fans.

## Quasi Steady-state of Alluvial Fans

Fans in the same lithologic, tectonic and geographic environment can be treated as a group, distinct from fans in a different environment. The value of c is different for each group of fans thus defined (Fig. 14 A). In effect a group of adjacent fans are competing for the available space in a depositional basin. As a result there is a tendency for each fan to reach and maintain a steady-state area. If the area of one fan is too small with respect to the volume of material being added to it, it will increase in thickness faster than the adjacent fans, and will thus expand its area by encroaching upon the adjacent fans as shown in Figure 15, until the steady-state area is

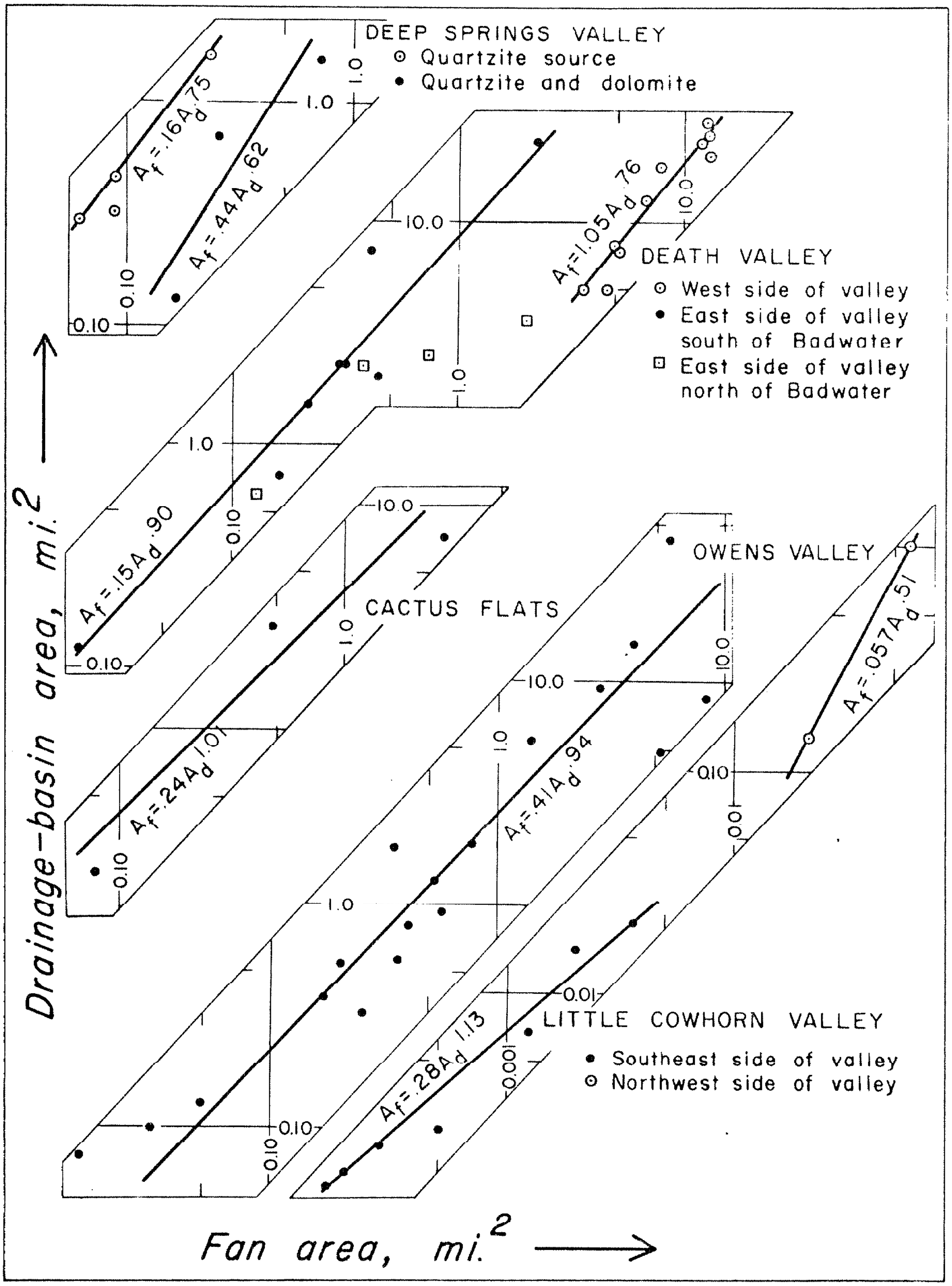
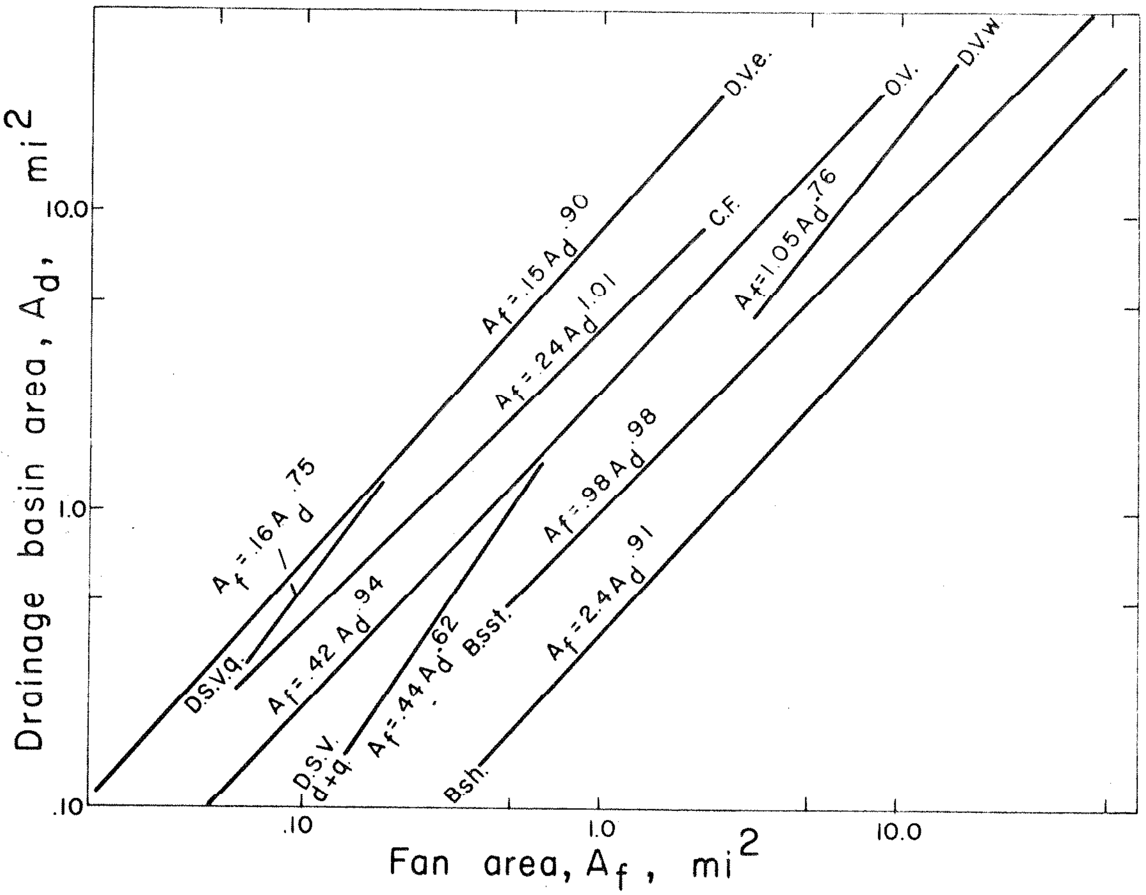


Figure 14 A. Relationship between fan area and drainage-basin area. Regression lines were fitted by eye.



| Explanation | |
|---|---|
| B. sh. | Bull (1964), shale source |
| B. sst. | Bull (1964), sandstone source |
| C. F. | Cactus Flats |
| D.S.V. q. | Deep Springs Valley, quartzite source |
| D.S.V. d.&q. | Deep Springs Valley, quartzite & dolomite source |
| D. V. e. | Death Valley, east side |
| D. V. w. | Death Valley, west side |
| O. V. | Owens Valley |

Figure 14 B. Effect of geomorphic environment on the relationship between fan area and drainage-basin area. The data on which the lines are based are presented in Figure 14 A and in Bull (1964, p. 95). Lines through Bull's data have been redrawn to fit the points more closely.

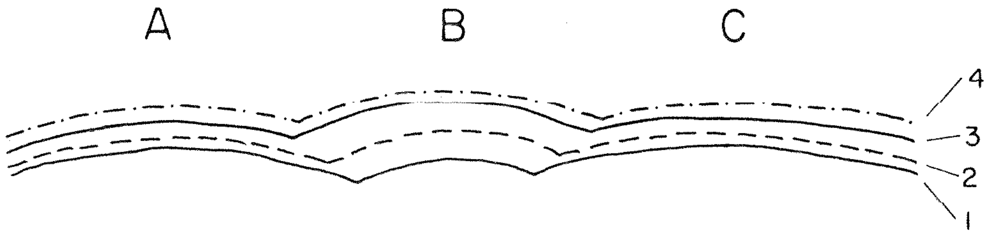


Figure 15. Hypothetical transverse cross section through three adjacent coalescing fans. Line 1 shows the fan surfaces prior to attainment of a quasi steady-state. Fan B is increasing in thickness faster than A or C as shown by lines 2 and 3. Finally (line 4) a steady-state condition is re-established with a bigger fan B and smaller fans A and C. The net rate of increase in thickness has increased for all fans.

established. Theoretically, the increase in rate of deposition experienced by fans A and C in Figure 15 should be propagated to neighboring fans to the left and right respectively until the entire bolson has readjusted itself. In practice the time lag between the initial perturbation and the final readjustment is so long that fans in different parts of the bolson behave independently. This behavior accounts for much of the scatter of points in Figure 14 A. The rest of the scatter is attributed to unidentified lithologic, tectonic and climatic variations and to the difficulty in determining the position of fan boundaries.

In a closed basin containing a playa surrounded by fans, the quasi steady-state concept can be extended to include the playa. Over a sufficiently long time period (probably a few centuries) the ratio of playa-area to fan-area in a given bolson should be constant once the steady-state condition has been established. That is the net change in thickness of the playa should equal the net change in thickness of the fan during any time interval sufficiently long to cancel out the effect of short term climatic and tectonic fluctuations but not so long that net denudation becomes significant. The ratio of these areas should reflect strongly the weathering characteristics of rocks in the drainage basin, since lithology controls the amount of fine material produced by weathering.

The significance of this quasi steady-state condition will be more fully appreciated by considering some perturbations of the playa-fan system. Suppose the volume of material deposited on the playa in a given time interval increases markedly while the volume deposited on the fan remains constant. The playa will increase in thickness more rapidly than the fan, and will begin to encroach upon the fan. The playa area increases and the fan areas decrease until both are again increasing in thickness at the same rate. Alternatively, suppose the entire bolson is tilted. The fans on the down-dropped side will become segmented and will no longer deposit material near the toe. The fans on the upthrown side will also become segmented

(Bull, 1964, p.105), but in this case the locus of deposition will move toward the toe rather than toward the head. The fans will encroach upon the playa from one direction, but the playa will be free to shift toward the down-dropped side of the basin, thus maintaining its size.

Finally, consider the effects of a shift from net aggradation to net degradation by deflation on the playa. If other conditions remain constant, the fans will encroach upon the playa. If net deflation persists as the fans advance, the playa must eventually be completely overlapped and eliminated. It is more likely that the volume of material deflated from the playa surface will decrease as the area of the playa decreases and that the rate of deposition will eventually exceed the rate of deflation. A steady-state condition will then be re-established before the playa is buried. Thus if playas are presently undergoing deflation as some authors have suggested (Ekblaw, 1927; Blackwelder, 1931, 1946), the present situation probably represents no more than a perturbation from the normal steady-state condition. This perturbation in no way invalidates the quasi steady-state concept or the applicability of this concept in explaining the area relationships in Figure 14.

The extension of the quasi steady-state concept to the playa is critical to an understanding of the relationships in Figure 14 A, as coalescing fans must be restricted not only along their lateral margins but also at the playa-fan margin. Furthermore, some fans on the east side of Death Valley do not coalesce, nor do those on the southeast side of Little Cowhorn Valley. The mountain front in these two areas is nearly linear and fans approximate 180 degree conical segments bounded solely by the mountain front and playa. In the area between fans playa material extends to the mountain front. Consequently adjustment of the areas of these fans is accomplished by variation of the playa-fan contact alone. Incidently, this reduces the time lag between the initial perturbation of a fan and the final adjustment of the system. Thus fans in these two areas would be ideal for studies of lithologic and topographic influences.

The steady-state condition requires that the area of each fan be proportional to the volume of debris contributed to it in a given time interval. This volume is presumably a function of the discharge reaching the fan, which in turn, is a function of the amount of precipitation in the drainage area above the fan. The relationship between precipitation and the volume of material reaching the fan is influenced by the lithologic and topographic character of the drainage basin, the rainfall-runoff relationship, the conditions required to generate debris flows, and many other factors. The remainder of this discussion will be devoted to qualitative evaluation of these influences and their effect upon the exponent, n, and coefficient, c, in equation (1).

## Factors Influencing n

The weighted mean value of n, determined by assigning to each fan in a group the value of n for that group, and averaging over all fans represented by the lines on Figures 14 A and B, is 0.90. Observed values range from 0.62 to 1.13 (Fig. 14 A, ignoring the northwest side of Little Cowhorn Valley where only two fans were measured). The weighted mean value appears to be determined by a relationship between storm size and drainage-basin size, and the variability of n apparently results from systematic variations of factors such as lithology with drainage-basin area. Hence equation (1) may be written

$$A_f = cA_d^{n'+y} \qquad (1')$$

where y represents the systematic variations with drainage-basin area, and n' is the mean value, 0.90.

These conclusions are based on consideration of the following empirical relationships: First, it is well-known that the discharge of a given frequency from a drainage basin increases less rapidly than the area of the basin thus

$$Q_r = z(r)\ A_d^k \qquad k < 1 \qquad (2)$$

where $Q_r$ is the annual flood with a recurrence interval of r years. The value of z(r) depends upon recurrence interval and upon topography, lithology, and climate in the basin. Secondly, it has been found that the sediment discharge, L, may be expressed in terms of the water discharge, Q, by an equation of the form

$$L = pQ^j \qquad (3)$$

(Leopold and Maddock, 1953, p. 21) where p is a function of the source-area lithology and topography and of climatic factors affecting the rate of weathering. Discussion of j and k is deferred for the moment.

Combining equations (2) and (3) yields

$$L_r = pz(r)^j \; A_d^{jk} \qquad (4)$$

where $L_r$ is the sediment discharge during the peak runoff of a storm of recurrence interval r. Since equation (1') reflects the fact that the fan area is proportional to the volume of material reaching it per unit time, comparison of equations (1') and (4) suggests that

$$n' = jk. \qquad (5)$$

More rigorous mathematical techniques indicate that this is the case if j and k are independent of recurrence interval. The author is indebted to Professor Norman H. Brooks for many details of this more rigorous treatment.

Equation (5) suggests that detailed consideration of j and k should provide some insight into the physical significance of n. The exponent k is found empirically to be less than unity. This is apparently because a storm of a given recurrence interval is likely to cover a larger fraction of a small drainage basin than of a large basin, and because smaller basins generally have steeper slopes and hence higher runoff (Langbein and Schumm, 1958, p. 1079). Observed values of k for the mean annual flood, which has a recurrence interval of 2.3 years, range between 0.7 and 0.8 (Leopold and Miller, 1956, p. 23). The value of k at a higher recurrence interval can be estimated from data plotted by Craeger et. al. (1945, p. 126) for "unusual floods," and independently from an empirical curve used by the California Division of Highways to estimate flood discharges in the desert (R. A. Hayler, written communication to J. M. Cowgill, 6/26/53). The recurrence interval is not stated in either instance, but both references are concerned with observed maximum flood discharges and the period of observation is probably about 40 years, suggesting that the appropriate recurrence interval is in this neighborhood. For drainage-basin areas between 1 and 5 square miles, both references indicate a value for k of 0.84. Furthermore, both indicate that k decreases with increasing drainage-basin area. Since most fans considered in this report have drainage basins of less than 5 square miles, the values cited by Leopold and Miller (1956, p. 23) are likely to be too low for the present application. The 0.84 value may be more nearly correct. Thus observed values of k do not seem to vary systematically with recurrence interval, and the physical factors, storm size and drainage-basin slope, offered to explain these values of k give no reason to expect such variation. Hence in this case the assumption leading to equation (5) seems justified.

Consideration of the exponent, j, is hampered by less adequate knowledge of the physical significance of this quantity. Leopold and Maddock (1953, p. 22, 26) have suggested that suspended sediment concentration should decrease with increasing discharge in the downstream direction (increasing drainage area), and that j should thus be less than unity, but Leopold and Miller (1956, p. 13) report measurements of sediment concentration in arroyos which indicate a value of j of about 1.3. A value of j less than unity can be explained in terms of the lower average slope of larger drainages and the lower rainfall intensities responsible for the discharge of a given frequency in these drainages. Leopold and Miller (1956, p. 13-15) explain their higher value in terms of percolation into the stream bed and continued entrainment of sediment along the channel. They feel that the first factor is more important. None of these explanations, with the possible exception of percolation, give any reason to expect j to vary with recurrence interval. In the case of percolation, small flows should lose a greater proportion of their water than larger flows and thus would have higher sediment concentration downstream. However this effect might be offset by deposition. Hence in this case available information does not contradict the assumption that j is independent of recurrence interval.

Brune (1948, Figs. 3 and 4) presents perennial stream data from which jk can be calculated to be between 0.80 and 0.85. In view of the observed values of k, this suggests that j is nearly unity in this instance.

It was suggested above that k was less than unity in part because larger drainages have lower slopes. In the drainages represented by Figure 14 this is not the case. Statistical measurements of slopes, using a grid sampling pattern, indicate that the mean drainage-basin slope is nearly constant and is essentially independent of area, if drainage basins in the same part of the same bolson are compared. Therefore, on alluvial fans, k should probably be higher than 0.84. These observations suggest that the mean value for n of 0.90 for alluvial fans can be explained in terms of the relationship between storm area and drainage-basin area. The factors, such as percolation, suggested by Leopold and Miller (1956, p. 13) are apparently not as important on fans as on ephemeral streams.

## Variability of n

Fans and source areas on the southeast side of Little Cowhorn Valley are more than an order of magnitude smaller than most others in Figure 14. Hence the influence of storm size on n should be negligible, since k increases with decreasing drainage-basin area (see p. 112), and a value for n of 1.0 might be expected. The higher observed value (1.13) suggests that:

1. The larger drainage basins are supplying systematically more material per unit area than the smaller basins; or
2. The system is not in quasi steady-state and, owing to some fortuitous circumstance in the geometry or history of the bolson, the smaller fans are increasing in thickness faster than the larger fans. When the steady-state condition is re-established the large fans will be relatively smaller and the small fans relatively larger; or
3. The exponent j is greater than unity.

Study of the bedrock geology suggests that the first explanation is correct. Bedrock structure in the source areas parallels the bedrock-alluvium contact (Nelson, in press (a)). Consequently a greater proportion of the smaller drainages is underlain by the topographically lower unit, in this case the quartzitic Hines Tongue member of the Reed Formation (Table IV). The Hines Tongue should be more resistant than the dolomite of the upper member of the Reed Formation which becomes increasingly important in the larger drainages. The dominating influence of the Hines Tongue in the smaller drainages probably results in a lower sediment yield per unit area from these basins and hence in the abnormally high value of n. There is no apparent reason to expect variation in the rate of increase in thickness with drainage-basin size, and no reason to expect a high value of j. The lithologic explanation offered can be visualized as a systematic variation in c (equation (1)) with drainage basin area, or, what is the same thing, as a non-zero value of y in equation (1').

Table IV

Variation in Lithology with Drainage-basin Area
on Southeast Side of Little Cowhorn Valley

| Drainage-basin area, thousandths of a square mile | Approximate percent of drainage area underlain by Hines Tongue |
|---|---|
| 1.4 | 96 |
| 1.6 | 79 |
| 2.1 | 69 |
| 2.5 | 77 |
| 6.9 | 67 |
| 16 | 62 |
| 21 | 49 |

Abnormally low values of n in Figure 14 A are associated with fans on the northwest side of Little Cowhorn

Valley ($n = 0.51$) and with fans draining quartzite and dolomite source areas in Deep Springs Valley ($n = 0.62$). In these areas the expected value of n, based on the variation of k with drainage-basin area, is again 0.90 or slightly higher. In Deep Springs Valley variations in the ratio of dolomite to quartzite in the source areas of the three westernmost fans (Fig. 10) appear to be in the wrong direction to account for the observed low value of n; a greater percentage of the larger basins is underlain by less resistant dolomite. On the other hand, higher mean slopes in the smaller drainages (Table V), or recent capture by the intermediate-sized basin of about half of the area of the smallest basin, are possible explanations.

The second of these explanations is based on topographic-map study and requires that the time since capture be insufficient to re-establish a quasi steady-state condition. Thus the intermediate-sized fan would be increasing in thickness faster, and the smaller fan slower, than the mean for the bolson. Assuming that the smaller drainage was twice as large before capture, and adjusting the points on Figure 14 A accordingly, results in a much better fit of data to the line and increases n to about 0.83. Since this explanation accounts for both the low value of n and for the scatter of points in Figure 14 A, it is favored over that involving variation in mean slope. Topographic

Table V

Variation of lithology and slope in three drainage basins in Deep Springs Valley. For these drainage basins n = 0.62.

| Drainage basin area, $mi^2$ | Percent of basin underlain by dolomite | Statistical Slope Analysis<br>Mean slope | Mean of highest 50 percent of measured slopes | Mean of highest 25 percent of measured slopes |
|---|---|---|---|---|
| .13 | 26 | .625 | .697 | .738 |
| .69 | 50 | .469 | .645 | .693 |
| 1.53 | 60 | .410 | .538 | .603 |

relationships suggest that enlargement of the larger drainage on the northwest side of Little Cowhorn Valley may also be responsible for the low observed value of n there.

## The Coefficient, c

The primary factor influencing c is the ratio of depositional area to erosional area in a bolson. In a mature region, such as the Mojave Desert of southern California, the residual mountain areas are small and the alluvial basins large. Consequently c is relatively large. A similar situation exists in the San Joaquin Valley of

California (Bull, 1964) where coefficients range from 0.98 to 2.4 (Fig. 14 B). In contrast, the coefficients in the more youthful valleys with which this study deals range from 0.15 to 1.05 (excluding the anomalous northwest side of Little Cowhorn Valley).

In addition to variations in c from valley to valley, there are three explanations for variations within a single valley. The first is geographic: some fans may be so far removed from the others that they are essentially independent. The second is tectonic, as well exemplified in southern Death Valley where geologic evidence for recent eastward tilting of the Panamint Range - Death Valley block is good (Maxson, 1950, p. 113; Denny, 1965, p. 38). As a result, fans on the west side of the valley have been extended, while those on the east have been buried by the playa. This is nicely illustrated by the separation of drainage area to fan area lines for the west and east sides of the valley (Fig. 14 A), a relationship recognized independently by Denny (1965, p. 38). The values of c are 1.05 and 0.15, respectively. The third explanation for variation of c within a valley is lithologic. In San Joaquin Valley, California, Bull (1964, p. 94) found that drainage areas underlain predominantly by mudstone and shale produced fans about twice as big as drainage areas of comparable size underlain predominantly by sandstone (Fig.

14 B). Bull attributed this to greater erodibility of shale. The effect of lithology is also apparent on fans in the southeast corner of Deep Springs Valley. Fans with quartzite source areas are smaller than fans with source areas of comparable size underlain by dolomite and quartzite (Figs. 10 and 14 A). If fans from both types of source area are increasing in thickness at the same rate, this size difference must reflect a lower sediment yield, per square mile of drainage-basin area, from the quartzite source areas. In view of the coarseness of the material in the sieve deposits on the quartzite fans and the absence of extensive debris-flow action on these fans, a lower sediment yield from the quartzite drainages is reasonable.

## FAN SLOPES AND PROFILES

Bull (1964) noticed that radial profiles of many fans are composed essentially of straight-line segments. Each segment presumably represents a period of tectonic stability in the fan's history. Implicit in Bull's discussion of segmented fans is the assumption that the depositional slope of a fan is uniquely determined by conditions in the source area. Thus the fan and its source area appear to constitute a steady-state system with respect to fan slope as well as fan area. If the steady-state system is disrupted by tectonic movements, a new segment reflecting the altered conditions is built. For instance, if the slope of the fan is decreased by tilting without altering conditions in the source area, a new fan will be built out over the head of the old fan.

Data collected during the present study suggest that the steady-state slope of a fan is controlled by the calibre of debris supplied to the fan and by the nature and magnitude of the debris transporting processes. These influences were observed on laboratory fans as follows:

1) Fans built with lower discharges generally had steeper slopes (Fig. 6). During the Series B experiments an increase in discharge generally resulted in regrading of the fan to a lower slope.

2) Fans composed partly of debris-flow material

were generally steeper than those built by fluvial processes alone (Runs B-1 and B-3, Plates 3 and 4). Similarly, the initiation of sieve deposition on a laboratory fan was generally accompanied by a four- to five-degree increase in fan slope. (Sec page 25)

3) On laboratory fans B-3 and B-4 there was an abrupt decrease in slope associated with a change from coarse sand and granules just below the intersection point to sand and silt farther down-fan (Plates 2 H and 3 C and D; note especially break in slope along bulkhead in 3 C and D). This break in slope was independent of the influence of debris-flow action as it occurred in the absence of debris flows during run B-3.

The remainder of this section will be devoted to discussion of evidence for the importance of these influences in controlling slopes of natural fans.

## Dependence of Fan Slope on Lithology

Source-area lithology is a major factor in determining the dominant debris size on natural fans. On the east side of Death Valley three fans with source areas underlain by Oligocene to Recent sedimentary and volcanic rocks (Jennings, 1958) have distinctly lower overall slopes than fans with drainage basins of the same size underlain by Precambrian metamorphic rocks (Fig. 16). The dominant

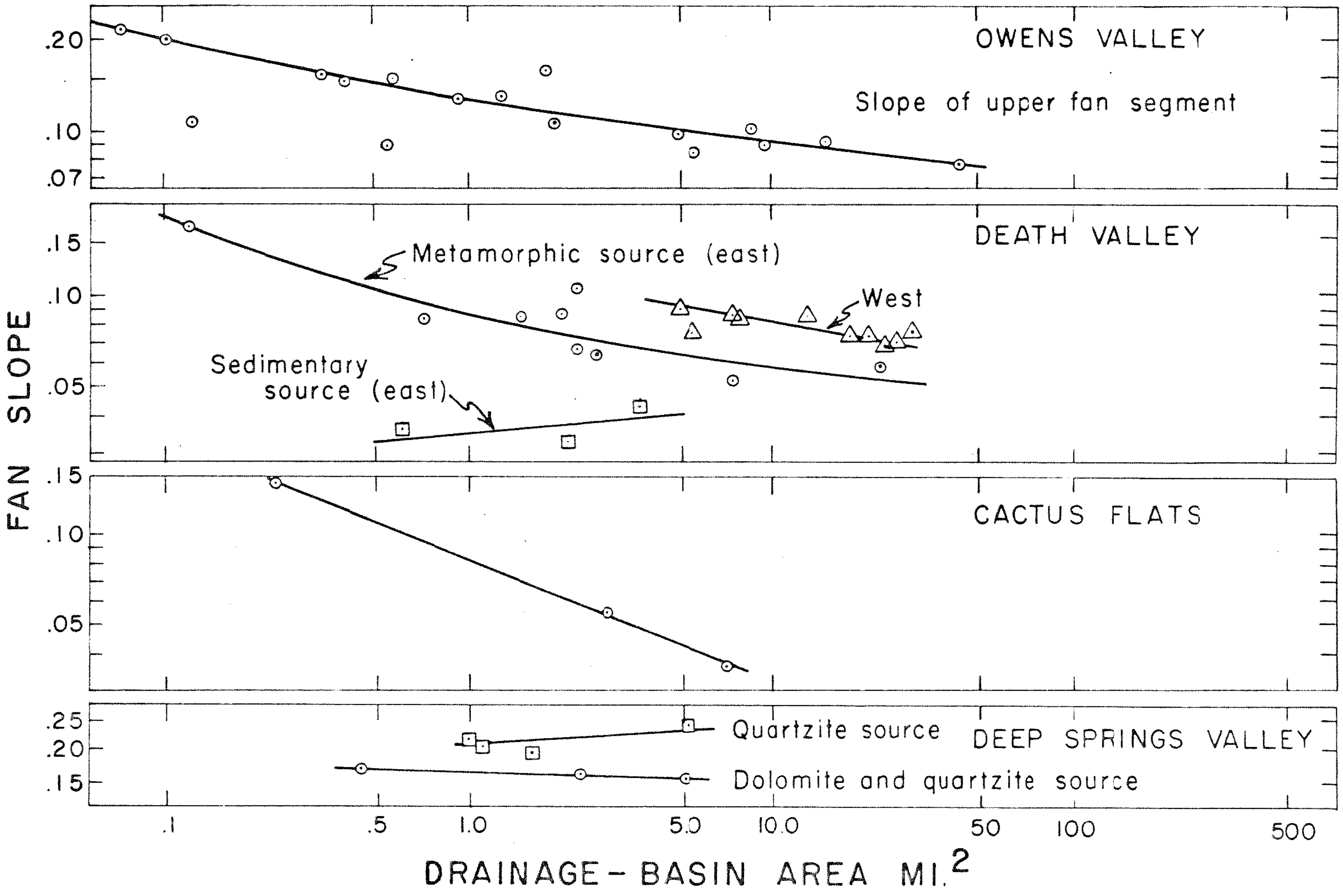


Figure 16. Relationship between fan slope and fan area. Regression lines were fitted by eye.

size on the three fans with low slopes, based on field estimates, is in the sand to granule range, and on the steeper fans it is pebble or larger. Similarly the dominant size on the two larger fans in Cactus Flats is in the fine sand to granule range. These two fans have slopes that are low in comparison with the slopes of most other fans with drainage basins of similar area plotted on Figure 16.

Source-area lithology may also influence fan slope by controlling depositional processes. In Deep Springs Valley (Fig. 16) fans draining quartzite terrane are steeper than those with the same size drainage basins underlain by quartzite and dolomite. Sieve deposition predominates on fans with quartzitic source areas and debris-flow deposition on fans with source areas partly underlain by dolomite. The differences in fan slopes are judged to be due not to a difference in dominant size but rather to this difference in depositional process.

Fans in San Joaquin Valley with source areas underlain by mudstone and shale are generally steeper than those with comparable source areas underlain predominantly by sandstone (Bull, 1964, p. 95). Bull (1964, p. 94) apparently attributes this to greater erodibility of the mudstone and shale. In this paper it has been argued that erodibility affects fan area, as Bull realized, but no relationship between erodibility and fan slope has been recognized. On the basis of field discussions with Bull (4/65) I believe that a greater activity of debris flows on fans with mudstone and shale source areas is responsible for the steeper slopes observed. This is in accord with the laboratory experiments.

## Dependence of Fan Slope on Discharge

Eckis (1928, p. 234) and Melton (1965, p. 24) noted that overall fan slope decreases with increasing fan area. In view of the relationship between fan area and drainage-basin area, overall fan slope should also decrease with the increasing drainage-basin area as reported by Bull (1964, p. 95). Similar relationships are apparent for several groups of fans in Figure 16. This decrease in fan slope with increasing drainage-basin area could be attributed to a systematic variation in debris calibre or depositional process, or to an increase in discharge, with drainage-basin area.

Field examination did not reveal systematic variations in either debris calibre or depositional process with drainage-basin area. The smallest fans sometimes do appear to be composed of coarser debris, but this variation is apparent only on the smallest fans present. Furthermore, qualitative field observations detected a variation in dominant size judged to be responsible for a 30- to 40-percent difference in fan slope on the east side of Death

Valley (Fig. 16). If debris calibre were the only factor influencing the trend of the lines in Figure 16, one might also expect an observable variation in dominant size with increasing drainage-basin area in places such as Owens Valley, but none is detected.

With these qualitative arguments it is impossible at present to dismiss the possibility that debris calibre or depositional process may be responsible for the prevailing negative slope of lines in Figure 16. The argument for the dominating importance of discharge is based on the known increase in discharge with drainage-basin size, and on laboratory observations indicating that an increase in discharge does result in a decrease in fan slope, other factors remaining constant. It is reasonable that larger discharges, with potentially higher flow velocities and higher bed shear stresses, will transport on a lower slope the same material transported by smaller discharges on a higher slope.

Since natural fans are subjected to a range of discharges, the hypothesized relationship between fan slope and discharge suggests that discharges of a certain size may be more important than either larger or smaller discharges in determining fan slope. Hence slope may be related to both a dominant discharge and a dominant debris size.

## Dependence of Fan Slope on Drainage-basin Slope

In order to investigate the influence of mean drainage-basin slope on fan slope, a statistical mean slope was determined from topographic maps using a grid sampling pattern with between 5 and 150 points, depending on the drainage-basin area. To study contributions to the mean slope by relatively flat areas which probably contribute small amounts of debris, the means of the highest 25 and 50 percent of the slopes were calculated in addition to the mean slope. The 25 percent figure is based on the premise that the dominant size is approximately $d_{75}$. Plots of each of these mean slopes against fan slope indicated that fan slope was essentially independent of all of them.

On the other hand a fairly good relationship between overall drainage-basin slope and overall fan slope exists for some groups of fans studied. Melton (1965, p. 23-24) reports a similar relationship between fan slope and relative relief ratio, $H/\sqrt{A_d}$, where H is the maximum relief in the drainage basin and $A_d$ is the basin area. In view of the absence of any relationship between the various mean drainage-basin slopes and fan slope, neither $H/\sqrt{A_d}$ nor the overall drainage-basin slope can be interpreted as a statistical measure of the drainage-basin steepness. Instead, owing to the natural concavity of most stream profiles, both of these quantities must be interpreted as crude measures of the stream gradient as Melton (1965, p. 26-29) has unwittingly demonstrated. To test this hypothesis a statistical mean channel slope was determined by measuring the slope at 5 or 6 evenly spaced points in the downstream half of the main channel (or channels) in the source area. This slope is plotted against fan slope, for the two valleys thus studied (Fig. 17). The data from Owens Valley are not good, but the data from Death Valley are reasonably satisfactory. Since the slope of an alluvial channel in a drainage basin is probably adjusted to transport the load supplied with the available discharge, as is the slope of a perennial river, the relationships in Figure 17 further confirm the hypothesis that the fan slope is also a slope of transportation controlled by debris calibre and discharge.

## Fan Profiles

The fan profiles in Plate 5 all are uniformly concave near the toe. The term "uniformly concave" is used herein to describe a smooth curvature uninterrupted by straight segments. The up-fan extent of this toe concavity varies. Cactus Flats Fan is uniformly concave from the toe to the intersection point but Sand, Trollheim, and Shadow Rock fans have short toe concavities which die out in a distance roughly equivalent to one quarter of the fan length. Up-fan from the toe concavity these profiles consist of one or more straight segments.

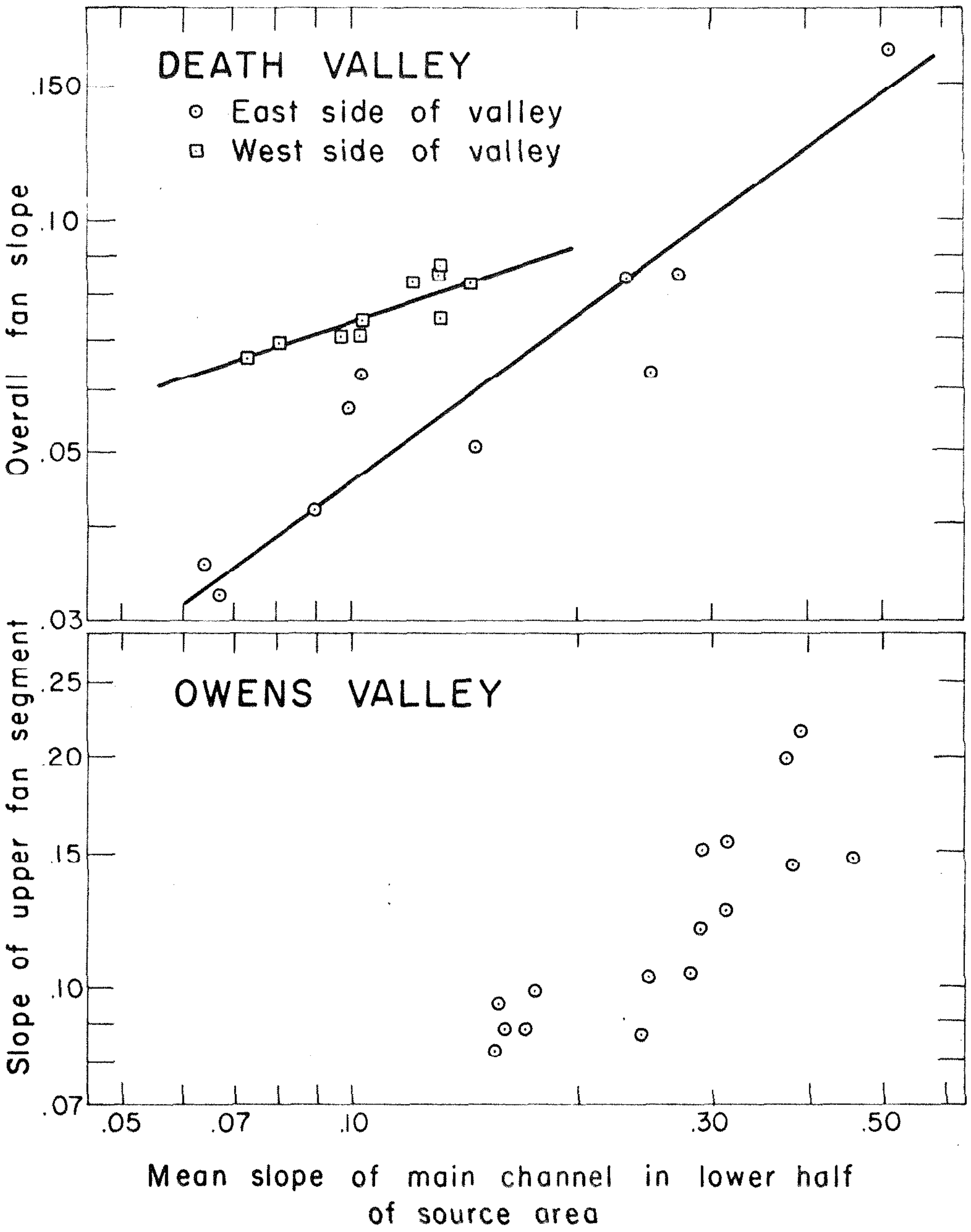


Figure 17. Relationship between fan slope and mean slope of the main channel in the lower half of the source area.

Qualitative estimates of the material-size distribution on these fans suggests that this may be a factor in determining the up-fan extent of the toe concavity. The material on Sand and Shadow Rock fans is more uniform than that on Cactus Flats Fan, in terms of estimated geometric standard deviation. Sand Fan is composed predominantly of coarse sand, and Shadow Rock Fan, predominantly of boulders. On the other hand, Cactus Flats Fan appears to have a much wider size distribution with coarser debris concentrated at the fanhead.

One possible interpretation of these observations, from the point of view of process, is that a dominant debris size controls the slope and smaller material simply fills in the void space. After all void space is filled, any excess small debris is transported to the toe of the fan where it is deposited, at a lower slope, in the concavity. The straight segments are not bounded by as pronounced or extensive a concavity apparently because much of the excess small material transported to the toe of the segment continues on across the lower segments to the toe of the fan.

# CHANNELS AND DEPOSITION ON ALLUVIAL FANS

## Introductory Statement

The concept of a quasi steady-state fan area requires, on a geologic time scale, that deposition occur on all parts of the fan surface. But deposition over short periods is usually localized (Figs. 3, 9, 11, 12). Thus, at times, debris must be transported across upper parts of the fan to be deposited at points more distant from the source area. Such transportation is accomplished primarily by flows in channels. This conceptual picture of the function of channels not only explains the apparent contradiction of a depositional fan whose most obvious surficial features are channels, but also provides a framework within which to discuss deposition.

On laboratory fans debris flows which overtop channel banks are responsible for most deposition above the intersection point and the locus of such deposition is controlled in part by the location of the main channel. Below the intersection point both debris-flow and fluvial deposition are significant, and the locus of deposition is largely controlled by the position of the intersection point. These observations are inferred to hold for natural fans with significant debris-flow deposition.

However laboratory observations suggest that it is impossible to define precisely the conditions under which channel diversion and shifting of the intersection point take place because the physical factors involved are too numerous and complex. Thus the position of the main channel or intersection point should probably be viewed as varying randomly with time, in much the same way that the result of a coin toss is random. The requirements that deposition occur over the entire fan surface, and that deposition from a single source area be restricted to one fan, provide certain limits on the position of the channel and intersection point in the same way that the two sides of a coin limit the possible results of a toss.

## Position of the Intersection Point

To understand the limits on the position of the intersection point, it first must be realized that the preceding discussion is idealized. Should tectonic movements, climatic change, or other changes in the system, result in segmentation, deposition will not occur on certain parts of the fan surface for a geologically long period of time. The position of the intersection point must then be considered relative to the active segment. This situation is illustrated by fans in eastward-tilting Death Valley. The most recent segment on the west is at the toe of the fans, and on the east it is at the head (Fig. 20 A). Consequently, relative to the entire fan profile, intersection points are unusually near the toe on the west and unusually near the head on the east, but relative to the active segments the intersection points appear to be reasonably located.

Radially, the intersection point is commonly near the middle of an active segment, or near midfan on unsegmented fans. From laboratory observations, this appears to be because debris-flow deposition predominates above the intersection point, and because deposition near the toe can occur without down-fan migration of the intersection point. Thus, if deposition occurs uniformly over all parts of a fan surface, the average radial position of the intersection point should be related to the relative importance of debris flows and fluvial processes in transporting material to the fan. This was observed to be the case on laboratory fan B-3. At the end of each episode of this run the distance of the intersection point from the fanhead was measured. The average distance during the first 34 episodes, during which water flows alone were used, was 19 cm, and the average for the remaining 32 episodes, each of which began with a debris flow, was 41 cm. This effect is also apparent in Figures D and H of Plate 3.

Within the area defined by these limits gradual shifting of the intersection point greatly facilitates distribution of material. On laboratory fans such shifting generally resulted from deposition at the intersection point by either debris flows or fluvial flows. This deposition involved, or was accompanied by backfilling and up-fan migration of the intersection point as low banks of the main channel were buried. This process has been described by Eckis (1928, p. 234-235) from observations during a water flood on a natural fan. On laboratory fans a subsequent flow would then erode a new channel. Such channels usually took a course down the flank of the intersection-point deposit and thus were offset laterally from the previous course.

## Diversion

Diversion of the main channel near the fanhead facilitates distribution of debris-flow material over parts of the fan surface above the intersection point. In addition diversion is a relatively catastrophic way in which shifting of the intersection point may occur. Remnants of older channels from which the flow has been diverted (Figs. 3 A, 11 A, and 12 A) testify to the importance of this process.

The most obvious cause of diversion in the field is debris-flow action. One common process is blocking or filling of the main channel by a flow too viscous to move farther, or occasionally, according to Beaty (1963, p. 527), by a single boulder carried by the flow. Water flows or debris flows, which may or may not be part of the same runoff event, are subsequently diverted at this point.

Evidence for this type of diversion usually consists of an abandoned channel ending upstream in a pile of boulders. In some instances the pile of boulders does not appear large enough to have caused diversion. Beaty (1963, p. 528) attributes diversion in these instances to temporary dams, subsequently broken by larger surges, but not before a significant diversion channel was cut. Alternatively, the original dam may have been modified by creep or by lateral erosion of flows in the new channel. For instance, the accumulation of boulders separating Channel 3 from Channels 1 and 2 on Little Cowhorn Fan (Fig. 3 A) is interpreted as a modified debris-flow dam.

A debris flow may also build a levee across the old channel and proceed down-fan in a new direction. Sharp (1942) mentions levees showing this relationship to earlier channels, although not on alluvial fans. Channel 2 on Little Cowhorn Fan (Fig. 3 A) may have been abandoned when a debris flow left the channel at a low point in the bank, and built a levee across the thus abandoned channel.

If aggradation by fluvial flows occurs in a channel well above the intersection point, either because of backfilling behind a bar or low debris-flow dam, or because of a change in flow regime, the channel may become too shallow and overflow may occur at a low point in the bank. Since most of the sediment load remains in the master channel in the initial stages of such a diversion, the overflow channel can experience rapid erosion. However laboratory observations suggest that the overflow channel must have a steeper gradient than the main channel in order to capture the flow and cause diversion. A small channel heading near the main channel and diverging from it can facilitate diversion, but headward erosion (Rich, 1935; Denny, in press) need not be involved. Overflow during previous events, but without diversion, may indeed be responsible for the smaller channel as is probably the case with the small channel diverging from Channel 1 on Little Cowhorn Fan (Fig. 3 A, B) at Section C.

Sieve deposition is another form of fluvial aggradation producing diversion. For instance, on Shadow Rock Fan (Fig. 11 A) sieve deposits 8 and 11 appear to be responsible for diversion from the older channel, containing sieve deposits 9 and 10, to the present course. Likewise the dissected sieve deposit just east of deposits 2 and 3, plus other lobes not shown, seem to be responsible for confining the flow against the west bank of the channel. The thalweg shown near the east bank is much lower topographically than the main channel, and is separated from it by these deposits.

## Channel Patterns Below the Intersection Point

At the intersection point, flow in the main channel spreads out and much of the coarser material in transport is deposited. The flow then becomes concentrated in several secondary channels heading in the intersection-point deposit. Farther down-fan these secondary channels form either a tributary drainage network (Fig. 3 A) or a braided channel pattern (Plates 2 F and H, and 3 H).

A typical characteristic of the tributary pattern is a marked increase in channel depth and decrease in channel slope immediately below the junction of two tributaries (Fig. 3 A, B just above cross section N). The resulting channel shallows down-fan and often ends in a secondary intersection point (Fig. 3 A, B). These relationships suggest that tributary patterns develop through erosion and redistribution of material by underloaded water-flows that deposited most of their original coarser sediment-load at the main intersection point. This further suggests that a significant fraction of the material on such fans cannot be transported past the intersection point by fluvial processes. The abundance of cobble- and boulder-sized material below the intersection point on Little Cowhorn Fan support the obvious conclusion that debris flows are probably more important than fluvial processes on this and perhaps other fans with tributary secondary-channel patterns.

In contrast a braided pattern suggests a predominance of fluvial activity below the intersection point. This is not to say that debris-flow deposition is unimportant, but rather that fluvial processes are capable of transporting coarse detritus past the main intersection point and of eroding and redistributing material deposited below the intersection point by debris flows.

On laboratory fans such braiding was not restricted to individual secondary channels; instead the entire fan surface had the characteristic morphology of a braided stream (Plate 2 H and 3 C, D, and H). This type of braiding appeared to be the result of deposition in response to a rising baselevel. Thus unlike the perennial stream which may be braided and yet not aggrading (Leopold, Wolman, and Miller, 1964, p. 295), braided surfaces on laboratory fans, and probably also on natural fans does reflect aggradation.

## Fanhead Incision

Most geologists have assumed that material at the fanhead was deposited before fanhead incision occurred and that some fundamental change in regime was responsible for incision. Observations on laboratory fans suggest that incision can be the natural result of an alternation of debris flows and water flows (Plate 2 E, F, G and H; Plate 3 F, G, H) and that fanheads are, so to speak, "born incised."* Owing to the high viscosity and finite yield

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*This idea was first suggested by David Schliecher in 1961 in a proposition submitted for his Ph. D. oral qualifying examination in Geology at the California Institute of Technology.

strength of debris-flow material, the hydraulic gradient required for debris-flow movement is greater than that required by water for transport of much of the finer material in debris flows. Consequently water flows tend to erode channels in debris-flow deposits. This has been observed in nature by Pack (1923, p. 355) and Blackwelder (1928, p. 460) on a debris flow in Utah. Pack (1923, p. 355) reports that

> "In places the debris deposited by the preceding mud-flows was incised sufficiently to permit the water to flow through them in fairly well-defined channels. Well-washed and well-sorted boulders and gravels were strewn along the water channels, forming a bold contrast with the heterogeneous masses deposited by the mudflows."

Even though a fanhead is incised, debris flows may overflow the channel and deposit material on the fan surface near the fanhead. This occurred repeatedly on laboratory fans. The debris flow need not plug the channel permanently, as once the peak discharge has passed the level of flow commonly recedes and subsequent water flows tend to follow the original course (Plate 2 G and H).

Fanhead incision also occurs on laboratory fans when the locus of deposition shifts to a place that has not received sediment for several episodes. The slope toward such topographic lows is greater than the steady-state slope of the fan under the prevailing discharge and sediment calibre conditions. Incision due to this process alone is temporary and lasts only until the low area is built to the level of the rest of the fan. The depth of incision produced in these ways, and uninfluenced by any other factors, is herein called the depth of normal fanhead incision.

In many instances fanhead incision is so great that overbank deposition on the adjoining fan surface is impossible. It is inferred that in these instances the fan-source system has been disturbed and deposition is no longer occurring over the entire fan surface. Climatic change and tectonic movement are two common causes of such disturbance. Abnormally deep fanhead incision is not as widespread as would be expected if climatic change were the principal factor, so tectonic movement is probably the more common cause. Fans on the west side of southern Death Valley, for example, have been deeply incised as a result of eastward tilting of the valley.

Eckis (1928, p. 237-238) has suggested that fanhead incision is a normal phase of a fan's evolution. A stream in the mountains constructs a fan, but since the stream continues to cut down within the mountains, it ultimately dissects the fan that it has built. This explanation can not be applied to many fans. For instance, in a closed basin, an aggrading playa provides a constantly rising base level, and Eckis' type of fanhead incision would imply flattening of the graded profile. This in turn requires either a decrease in calibre of material or some other change in regime. Flattening of the profile should produce segmentation (Bull, 1964), but fanhead incision is by no means restricted to segmented fans. If the profile is not flattened the result should be drowning of the canyon mouth and formation of a fan-bay, not fanhead incision. Eckis' explanation appears applicable only in special cases.

Lustig (in press) has suggested that climatic change has resulted in an increase in debris-flow action and that fanhead incision is due to debris-flow erosion. As discussed earlier, laboratory data suggest that most debris flows do not accomplish significant erosion. The tractive force approximation and other assumptions on which Lustig's conclusions are based are open to question.

## Depth of Normal Fanhead Incision

Laboratory run B-3 was designed to study factors affecting the depth of normal fanhead incision. It was already clear from the results of run B-1 (Plate 4) that no incision occurs on laboratory fans built entirely by debris flows with no intervening or subsequent water flows. During the first half of run B-3 (Table I) only water flows were used. The main channel was incised (i.e., deeper than bankfull flow) at the end of only six out of the first 26 episodes (Fig. 18; Plate 3 A-D). In five of these episodes (17, 18, 20-22) the flow had just shifted to a part of the fan that had not received debris for several episodes, and incision was due to the steeper slope toward these areas as described above. The same explanation probably holds for incision following episode 26, but the cause was not as clear in this instance.

The duration of water flow was increased three times during these first 26 episodes, but simultaneous changes in the depth of the channel were not observed. Thus the absence of incision cannot be attributed to lack of sufficient time for erosion. Furthermore, the flow at the end of episodes 19 and 25 was clear, rather than muddy, and sediment transport was small. This suggests that the absence of incision during these episodes cannot be attributed to inability of the flow to transport more sediment than it was transporting, but must instead be attributed to the inability of the flow to transport any sediment.

Following the 26th episode the discharge was doubled. As a result the slope of transportation was decreased and the fan regraded. This accounts for the incision observed at the end of episodes 27-29, 32 and 33 (Fig. 18), and for the relatively constant elevation of the fanhead during these episodes. During episodes 30, 31, and 34 the fan was already regraded in the direction of the flow and the channel was no longer incised. Shifting of

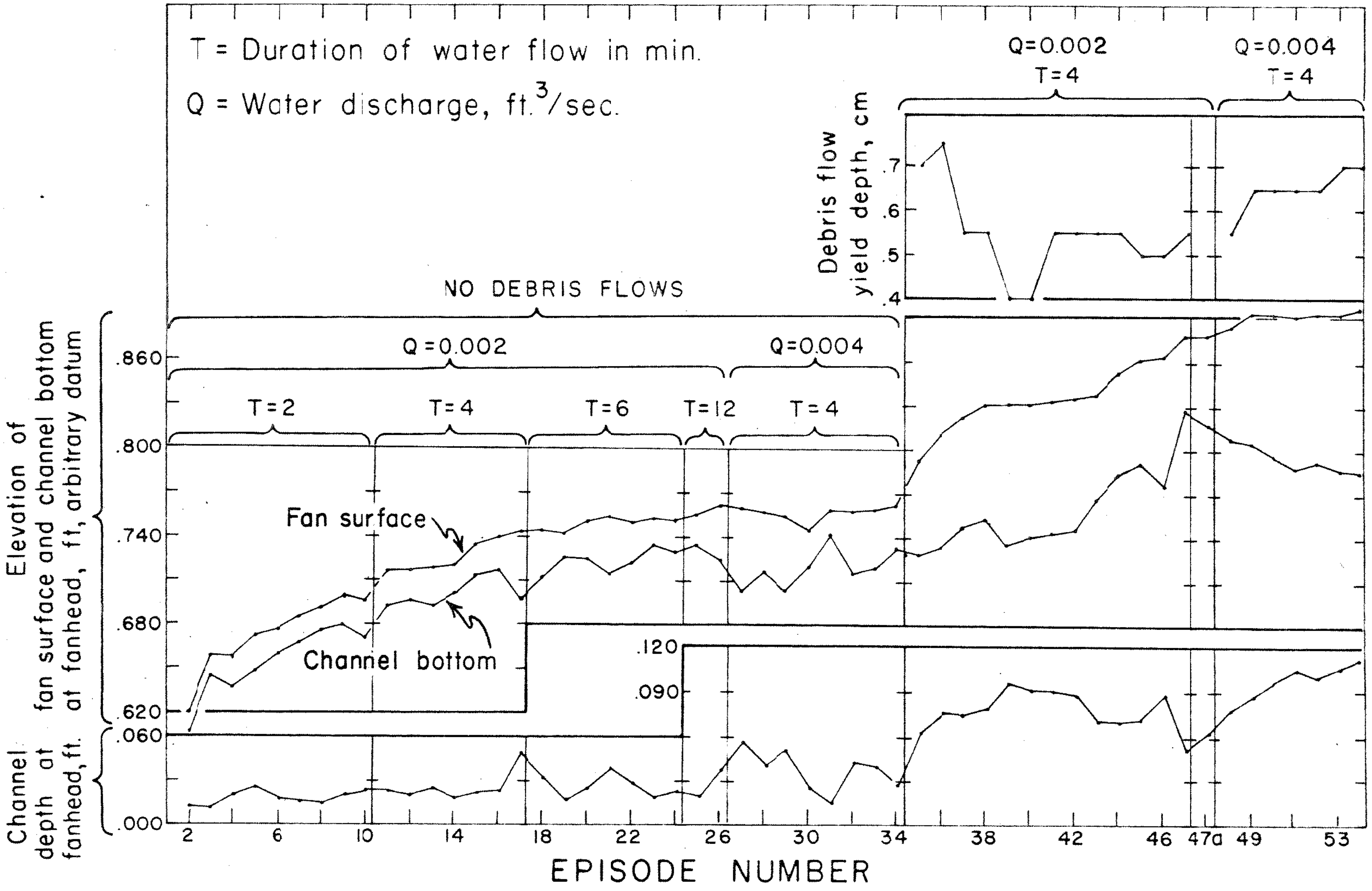


Figure 18. Changes in fanhead elevation and depth of incision during laboratory run B-3. There was no debris flow during episode 47a.

the flow to a steeper part of the fan accounts for the incision following episodes 32 and 33.

Starting with 35, each episode began with a debris flow and was followed by a water flow carrying sediment. The rapid increase in depth of incision and in the elevation of the fanhead are clearly shown in Figure 18. During episodes 35-47 the steady-state depth of incision was approximately 0.090 feet. When, owing to backfilling above the intersection point or to deposition in the channel, the depth of incision dropped below this value, overbank deposition by debris flows, near the fanhead, resulted in an increase in the fan-surface elevation (Episodes 35-38 and 43-45, Fig. 18).

The water discharge was doubled following episode 47a. As a result the elevation of the fanhead again remained relatively constant while the channel was eroded and the rest of the fan regraded. During episodes 51-54 a new steady-state depth of incision was attained. The increased depth of incision in these episodes relative to episodes 39-42, is attributed to the higher yield strength of the debris flows (Fig. 18) and to the lower fan slope, both of which tend to increase the depth required for movement of the flows.

As a result of this laboratory study, it is inferred that two factors affect the depth of normal incision on natural fans with a significant amount of debris-flow deposition. First, for uniform deposition over the entire fan surface, it appears that debris flows must occasionally exceed the channel depth and deposit material near the fanhead. If the depth of incision is so deep that overbank deposition does not occur for a geologically long period of time, deposition farther down-fan will eventually result in backfilling in the channel above the intersection point. The depth of incision will thus be decreased until overbank deposition near the fanhead again proceeds at the same rate as deposition elsewhere on the fan. Alternatively if overbank deposition at the fanhead occurs frequently and the rate of deposition is faster here than elsewhere on the fan, the depth of incision will increase until depositional rates are again equal.

The maximum depth of a debris flow is a function of its viscosity and peak discharge, other factors remaining constant. Owing to variations in viscosity and in the magnitude and frequency of debris flows and water flows, the depth of incision will vary with time. However it probably fluctuates about a mean value, and this mean may be related to a dominant debris-flow discharge. This is not to say that the dominant flow deposits material at the fanhead; consideration of the area over which debris-flow deposition occurs suggests that the dominant flow may exceed the channel depth at a point farther down-fan, leaving deposition at the fanhead to still larger flows.

Second, to the extent that the intersection-point deposit acts as a temporary baselevel to which the main channel is graded, the depth of incision at the fanhead will be a function of the radial position of the intersection point. Shifting of the intersection point occurs during nearly every runoff event, but overbank deposition at the fanhead occurs much more rarely. Over a sufficiently long time the intersection point will have an average radial position in a steady-state situation. Depth of normal incision should then be determined by the characteristics of debris flows.

## Fanhead Incision on Gorak Shep Fan

Application of these principles to Gorak Shep Fan, which contains no apparent debris-flow material, is instructive. The depth of incision below the fault scarp is only 4 or 5 feet (Fig. 9 B) and this depth decreases slowly down-fan. In the absence of evidence for debris-flow deposition, it is inferred that overloaded fluvial flows which aggrade the channel rapidly are responsible for deposition on the fan surface below the fault scarp. This type of deposition was common on laboratory fans of Series A. Owing to the similarity of transport processes, and to the relatively uniform grading of debris, water flows which erode the channel require almost as high a slope for debris transport as flows which deposited the debris. As a result fanhead incision takes the form of a wide, shallow channel rather than a narrow, deep one.

# RATES OF DEPOSITION

## Theory

The many factors affecting the rate of deposition on fans may be grouped into three independent categories, climate, lithology, and stage. The qualitative effects of stage are twofold: First the steeper the terrain the more rapid the erosion. This is true as long as the weathering rate, a function of climate and lithology, is rapid enough to provide material for erosion. Second, as the fans become thicker they will gradually bury the base of the mountain front and will grow in area at the expense of the drainage basin. Less material will be supplied from the smaller source area and deposition will occur over a larger area so the rate of increase in thickness of the fan will decrease.

The lithology of the source area influences the rate of production of material. A rock that readily produces a wide range of debris sizes will result in rapid fan growth, for every runoff event will be loaded to capacity. If very fine material is the only product of weathering, the competence of debris flows and the bedload potential of fluvial processes will not be used.

On the other hand if coarse debris is the primary product, small runoff events will be ineffective and debris flows may never form. The rate of production of material is also important, for if floods of moderate size and recurrence interval are capable of removing all of the debris produced by weathering within that recurrence interval, much of the additional energy of a flood of greater recurrence interval will be wasted.

The third variable, climate, is defined quantitatively by several interdependent factors, of which precipitation, runoff, temperature, and frequency distribution of rainfall are most important here. Of these runoff dominates for it transports material to the fan. Runoff increases with increasing precipitation and decreases with increasing temperature. In the small desert drainages of concern in this report, runoff is completed within a few hours or a few days of the storm. Thus temperature may not be as significant as in humid regions. On the other hand, soil and bedrock porosity and permeability will affect runoff, as they determine the infiltration rate and the capacity of the terrain to retain water. The frequency-distribution of rainfall can also have a significant effect on erosion (Leopold, 1951); many small storms may yield as much precipitation as one large storm without producing any runoff. Climatic factors are also largely responsible for the type and amount of erosion-inhibiting vegetation in the source area.

In addition climate and lithology combined largely control the relative volumetric importance of debris flows and fluvial processes in transporting material to a fan. Since the sediment to water ratio is much higher in debris flows than in streams, rates of deposition on fans containing substantial debris-flow material are likely to be higher than on fans composed entirely of stream-laid detritus under otherwise equivalent conditions.

In order to obtain a quantitative estimate of depositional rates on fans it is convenient to start with a relationship obtained by Langbein and Schumm (1958) for annual sediment yield as a function of effective mean-annual precipitation. The effective precipitation is obtained by measuring the mean-annual runoff and using a graph relating runoff to precipitation at a mean temperature of $50^{\circ}$ F. The relationship thus defined is of the form

$$s = a(A_d)\ f(p) \qquad (6)$$

where p is the effective mean-annual precipitation in inches, and s is the mean-annual sediment yield in tons per square mile. The form of the functions $a(A_d)$ and $f(p)$ are empirically determined. For values of p less than about 12 inches, this relationship indicates that the sediment yield increases with increasing precipitation. However, sediment yield decreases at higher values of p, because of increasing vegetation.

Langbein and Schumm's (1958) reservoir sedimentation data are more appropriate for present purposes than their data from river gaging stations, because many of the desert reservoirs are in steep terrain, similar to the topography in which many alluvial fans are found, and because most of the desert reservoir data are from drainage areas of less than 10 square miles. Since the coefficient, a, in equation (6) decreases with increasing drainage area, reflecting the gentler slopes characteristic of larger drainages and the lower probability of an intense storm covering the entire drainage, Langbein and Schumm adjusted the reservoir sedimentation rates downward to obtain equivalent values for drainage areas of 30 square miles. The adjustment was based on empirical data indicating that the sediment yield per square mile was inversely proportional to the 0.15

power of the drainage area. For reasons to become obvious later, it is convenient to replace Langbein and Schumm's mean value for $a(A_d)$ of 20, with an expression reflecting the variability of $a(A_d)$ with drainage-basin area, thus:

$$a' = 20\ (30/1)^{0.15} = 33$$

and equation (6) becomes

$$s' = 33\ \frac{1}{{A_d}^m}\ f(p) \qquad (7)$$

where $s'$ is the annual sediment yield in tons per square mile from a drainage basin of area $A_d$, and the empirical exponent 0.15 has been replaced by m.

Assume that equation (7) adequately accounts for the effect of climate on rates of fan deposition. This is true only to the extent that the effects of temperature, vegetation, runoff, and frequency of rainfall on sediment yield from topographically and lithologically similar drainage basins, vary in a consistent manner with precipitation, and that this variation is accounted for by the empirical function f(p). In order to use equation (7) it is assumed that the effective-annual precipitation equals the mean-annual precipitation as the latter is more readily estimated from existing records.

The data from desert regions on which equation (7) is based show "highly variable rates of sedimentation" for drainage areas of less than 5 square miles (Langbein and Schumm, 1958, p. 1078). In view of the assumptions in the last paragraph, it must be assumed that this variability is entirely related to topographic and lithologic differences between drainage basins. Considering the great variability of these two factors, this assumption is not unwarranted. On the other hand, empirical data which could be used to evaluate the effects of lithology and topography are not readily available. Consequently this assumption does not appear explicitly in the derivation to follow.

Realizing that the effects of lithology and topography must be ignored for the present, it is possible to write an approximate equation for depositional rates on fans, using the previously discussed relation

$$A_f = cA_d^n \tag{1}$$

First, the total sediment yield is obtained by multiplying equation (7) by the drainage-basin area, $A_d$, thus

$$s'A_d = 33\, A_d^{1-m}\, f(p). \tag{8}$$

Dividing equation (8) by the fan area, $A_f$, and substituting equation (1) yields

$$s'' = 33\, \frac{1}{c}\, A_d^{1-m-n}\, f(p) \tag{9}$$

where s" is the annual sediment-deposition on the fan in tons per square mile. This may be converted into feet of deposition over the entire fan surface per 1000 years, x, by assuming a mean specific gravity of 2.3 (Dr. Thane McCulloh, written communication, 12/8/64). The resulting relationship is

$$x = 0.017\, \frac{1}{c}\, A_d^{1-m-n}\, f(p) \tag{9'}$$

If the exponent 1-m-n is not zero, this equation states that the rate of deposition is a function of drainage-basin size, or in view of equation (1), of fan size. Thus small fans would be increasing in thickness at a different rate than larger fans. This would not only violate the quasi steady-state fan-area concept but would also make the relationships in Figure 14 fortuitous. Therefore n must be equal to 1-m and equation (9') becomes

$$x = 0.017 \frac{1}{c} f(p). \tag{10}$$

The reasons advanced to explain the fact that n is less than unity are identical to the reasons advanced by Langbein and Schumm (1958, p. 1079) to explain the variation of $a(A_d)$ with drainage-basin area. Therefore setting 1-m equal to n does not violate explanations of the physical significance of m and n.

Equation (10) is plotted in Figure 19 for various values of c. The form of the function f(p) is taken from Langbein and Schumm (1958, p. 1078) except that in the region $0 \leqslant p \leqslant 8$ their curve has been replaced by a straight line. The S-shaped curve presented by Langbein and Schumm (1958) is not warranted by their data; it is simply a consequence of their attempt to find a single simple equation that would fit the rest of the data. In fact, 47-year precipitation records at two stations in New Mexico (Leopold, 1951, p. 352-353) and 7-year records at three stations in the desert regions of California, indicate that larger storms account for a greater fraction of the total precipitation at the stations with lower mean-annual rainfall. This suggests that runoff in desert areas may be a greater fraction of the total precipitation in dryer parts of the desert, and that dx/dP should be greatest at the origin.

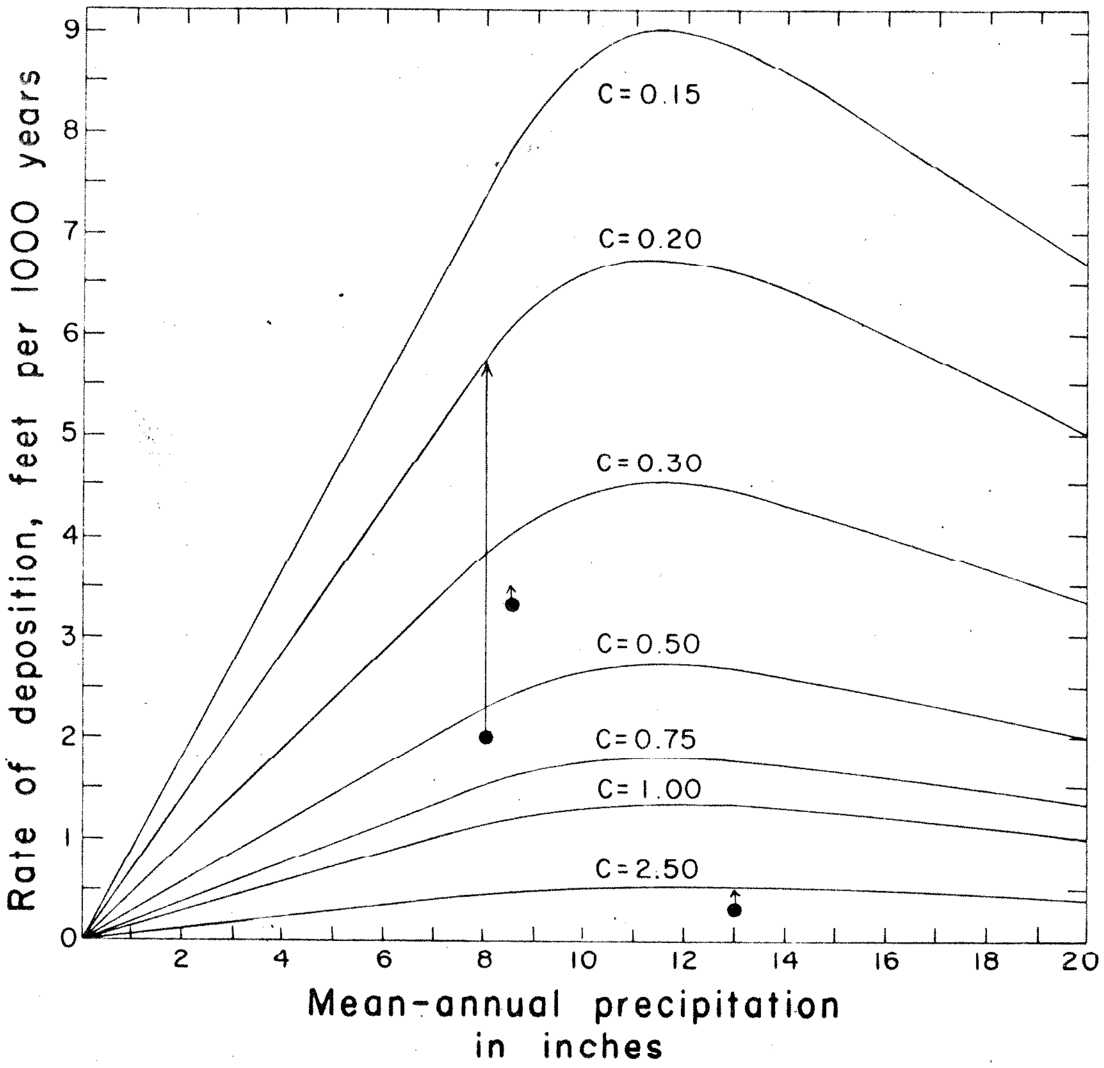


Figure 19. Relationship between precipitation, the coefficient c, and rates of deposition determined from equation (10). Dots indicate rates calculated from field evidence. Arrow indicates corresponding rate determined from this graph.

To use Figure 19 the mean-annual precipitation in the fan's source area must be estimated from available precipitation records, and the value of c must be determined. For any given fan c is a function of the exponent n in equation (1). The value of n in graphs such as Figure 14 A may be influenced by systematic variations with drainage area of factors such as lithology, topography and climate. Hence the weighted-mean value of n, 0.9, should be used, as this value seems to account adequately for the effects of drainage-basin slope and storm size on the sediment yield from basins of varying size. Using this value of n, the appropriate value of c may be calculated from equation (1). However the value of $A_f$ substituted into equation (1) should allow for sediment from the source area that is deposited in the playa. The most convenient procedure is to measure the fan area, $A_f$, the playa area, $A_p$, and the total depositional area in the bolson, $A_{db}$. Then $A_{db} - A_p$ is the total area of fans in the bolson and

$$c = A_d^{-0.9}\left(A_f + \frac{A_f}{A_{db} - A_p} A_p\right). \qquad (11)$$

Alternatively the value of c determined from a graph such as Figure 14 A could be used, again taking into account deposition on the playa. To the extent that the resulting value of c represents an average for a large part of the bolson, and that the source-area conditions are thus more likely to correspond to conditions in the average source-area studied by Langbein and Schumm (1958), this procedure is better. However, it might involve the use of a very unsatisfactory value of n. A third possibility is to use equation (1), substituting the entire depositional area (fans plus playa) for $A_f$ and the entire erosional area for $A_d$. This is undesirable in view of the possible influence of tectonic movements (see Death Valley, Fig. 14 A) or climatic variations on the rates of deposition. The procedure to be used in any given circumstance must be governed by the nature of the problem under investigation and by careful consideration of the geomorphic and tectonic history of the fan.

## Field Estimates of Rates

Figure 19 may be checked by considering a few instances in which rates are known or can be inferred. Data from Little Cowhorn Fan (Fig. 3 B) may be used for this purpose. A minimum age for the present channel on this fan was obtained through a study of the "annual rings in big sagebrush" (Artemesia Tridentata) (Ferguson, 1964). Two plants collected from the bottom of channel 1 near Section D (Fig. 3 B) yielded ages of 77 and 80+ years. The latter had approximately half a dozen rings missing from the center and was collected a few inches above and about 4 feet south of the thalweg. The former was from the bouldery step in the channel just above section D. The channel at this point is confined by debris-flow levees, and its bottom is only slightly below the level of the fan surface outside the levees. It is unlikely that the levees could have been built while the plants were living. Thus it seems safe to conclude that this part of the channel is more than 85 years old.

A plant collected from the bouldery step just above the 190 foot contour in channel 1 (Fig. 3 B) yielded an age of 95 years, the pith ring being 1870. This plant could have been alive while channel 2 or possibly channel 3 was active, as it is topographically above these channels. However, it is again unlikely that the debris flow or flows which formed the levees of the lower part of channel 1 and the lobes below the main intersection point, could have passed over this plant without destroying it. Consequently these flows probably occurred prior to 1870.

Immediately below the main intersection point on channel 1 is a mound of recent material deposited by flows that spread out and lost competence at the intersection point. From the profile in Figure 3 B it is estimated that this mound reaches a maximum thickness slightly in excess of one foot. This is the most recent material deposited at this point. In order to estimate the amount of material deposited during the life of the present main channel a line (A in Fig. 3 A) was drawn around material which appears to be relatively fresh, and to have issued from channel 1. The area enclosed by this line is $4.3 \times 10^4$ $ft^2$ or 6.8 percent of the fan area. The mean thickness of the deposit was assumed to be two feet. It was further assumed that two-thirds of the material transported through the channel during its lifetime was deposited beyond the limits of the circled area, either nearer the toe of the fan or in the playa. This assumption is not unreasonable as the playa occupies 38 percent of the depositional area of the bolson and much of the material is fine enough to have been washed beyond the limits of area A. If the channel has been in existence for 200 years, this gives a rate of deposition on the fan of 2 feet/1000 years. The assumptions made have been in the direction of maximizing the rate of deposition, but any one of them, except the last, could be in error by a factor of 2 or more in either direction.

The corresponding rate, determined from Figure 19, is 5.8 feet/1000 years. To obtain this rate the mean-annual precipitation was estimated by determining the mean precipitation at three nearby rainfall stations for the period 1955-63 (U. S. Weather Bureau), plotting this precipitation against the altitude of the respective stations, and interpolating the data to get a value for the precipitation on Little Cowhorn Fan at an intermediate elevation. The mean-annual precipitation estimated in this way was 8 inches.

The constant c was evaluated by means of equation (11) and is 0.20. In view of the uncertainties in both methods the agreement of the rates is satisfactory.

The rate of deposition on Arroyo Hondo Fan can be estimated from a radiocarbon date of 1040 ± 200 years on charcoal buried in the upper segment (Bull, 1964, p. 99). Using Bull's data (1964, Fig. 58 and Plate 7) it is possible to estimate that this segment has a radius of 0.55 miles and covers $120^{\circ}$ of an arc in plan view. The depth to the sample is 10.5 feet. From U. S. Geological Survey $7\frac{1}{2}$-minute topographic maps it was found that the upper fan segment has a slope of 0.020 compared to 0.011 for the next lower segment. Assuming that the surface of the upper segment at the time of deposition of the charcoal was parallel to the present surface, the volume of material deposited in this segment since burial of the charcoal is calculated to be $6.0 \times 10^{7}$ ft.$^{3}$ In addition to the material deposited in the upper segment, substantial amounts of debris have probably been deposited farther down-fan (Bull, 1964, p. 110) and some backfilling and deposition may have occurred above the fanhead. In view of the fine calibre of debris on fans in this area (Bull, 1963, p. 248) (dominant size probably less than 1 mm), and the resulting ease with which such material may be transported farther down-fan, it seems reasonable to assume that the material in the upper segment represents only 10 to 20 percent of the total volume deposited since burial of the charcoal. By dividing this total volume by the fan area, the average rate of deposition is estimated to be in the neighborhood of 0.2-0.4 ft/1000 years.

The rate from Figure 19 was determined as follows: First a value of 2.9 for c was calculated from equation (11), using Bull's (1964, p. 92) measurements of fan and drainage-basin areas. Since there was no reason to prefer this value of c over that given in Figure 14 B, the average of the two, 2.65, was used. The mean-annual precipitation was estimated by interpolating linearly between the New Idria and Mendotta Dam rainfall gaging stations (Bull, 1964, p. 123, Fig. 82) to obtain an approximate mean-annual precipitation of 13 inches over the Arroyo Hondo drainage basin. Figure 19 then yields a rate of 0.5 feet/1000 years, in good agreement with the value estimated on the basis of the radiocarbon date. In view of the relatively subdued topography in this drainage basin, a rate lower than 0.5 feet/1000 years might be expected.

A third field estimate can be made using a radiocarbon date of 1380 ± 250 years from charcoal in a fire hearth buried at a depth of 6 feet in the lower segment of Antelope Springs Fan in Deep Springs Valley (Lustig, in press). The position of the toe of the upper fan-segment was located by plotting the fan profile from the U. S. Geological Survey Blanco Mountain 15-minute topographic map, and extrapolating the upper and lower straight-line segments beneath the convexity at the base of the upper segment (Bull, 1964, Fig. 55). Areas of the fan, the lower segment, the playa (below 4940 contour), and the drainage-basin were determined from the topographic map. The total depositional area, $A_{db}$, is given by Lustig (in press). To estimate the total volume of debris deposited on the fan since the hearth was built, it is first assumed that no deposition has occurred on the upper segment, and that deposition resulting in the convex profile between the two segments is compensated by thinning of the lower segment as it overlaps the toe of the upper segment. It is further assumed that the stratigraphic section in which the fire hearth was found is not a scour-and-fill deposit in the present channel. In other words, the hearth is assumed to have been built on the fan surface rather than in a shallow channel, and the depth of burial of the charcoal is thus the average depth of deposition over the lower segment and playa in the last 1380 years. The volume of debris thus estimated is then adjusted, using the principles involved in equation (11), to account for material deposited on the playa. Had the fan not been segmented, this volume of material would have been spread over the entire fan surface as well as the playa. Under these conditions the mean rate of deposition over the entire fan surface would have been 3.5 ± 0.6 feet/1000 years.

The corresponding rate from Figure 19 was obtained by using equation (11) to evaluate c and by using the method outlined for nearby Little Cowhorn Fan (p. 160) to estimate the mean-annual precipitation. The resulting values, $c = 0.46$ and $p = 8.5$ inches, give a rate of deposition of 3.3 feet/1000 years. The agreement with the figure from the radiocarbon date is exceptionally good. Inasmuch as this field estimate involved fewer major assumptions than the other two, this agreement is particularly significant.

# APPLICATIONS OF ALLUVIAL FAN MORPHOLOGY TO OTHER ASPECTS OF EARTH SCIENCE

Alluvial fan morphology is not completely random, nor are the systematic relationships so complicated as to defy identification. Several of these relationships have been identified during this study. A thorough understanding of them will enable scientists to use fan morphology in solving other earth-science problems. For instance it may some time be possible to use debris-size analyses and slope measurements to determine the dominant fluvial-discharge. Similarly the depth of fanhead incision may eventually be related quantitatively to the dominant debris-flow discharge. Either or both of these discharges might then be used to estimate hydrologic characteristics of the source area and of the region in general, and perhaps for deciphering climatic variations in the past.

Fan morphology can be extremely useful in recognizing and interpreting recent local drainage changes resulting from stream capture and basin integration. An example of this application was given in the discussion of the variability of the exponent, n.

The most obvious application of alluvial fan morphology at the present time is to Pleistocene and Recent tectonic problems of the basin and range province. Bull (1964) has shown that segmentation of a fan can be related to tectonic disturbance of the fan-source system. Other features such as channel orientation with respect to the fan axis may reflect longitudinal tilting of a bolson about an axis perpendicular to the mountain front along which the fans are situated.

An intriguing possibility is the use of depositional rates on alluvial fans to estimate rates of tectonic processes. Two examples illustrate this application. Evidence from Gorak Shep Fan (p. 78) suggests approximately 160 feet of vertical displacement of the source area relative to the fan during deposition of the upper segment. The area of the upper segment below the fault scarp (Fig. 9 A) is about 0.17 $mi^2$. Projection of the profile of the lower segment beneath the upper segment indicates a thickness of the upper segment near the fanhead of about 130 feet. Since the segment subtends an angle at the fanhead of about $125^o$, the volume of the segment may be approximated by the volume of a $125^o$ segment of a right-circular cone with an altitude of 130 feet and with radius chosen such that the surface area of the conical segment is 0.17 $mi^2$. Dividing this volume by the area of the segment gives a mean thickness of 45 feet. Not all debris carried from the source area since the beginning of this period of uplift has been deposited in the upper segment, but in view of the coarseness of debris and the lack of evidence for extensive deposition below the zone of sieve deposition, it is not unreasonable to assume that the material in the upper segment represents about 60 percent of the total.

To obtain the rate of deposition on the upper segment from Figure 19, a value of c (=0.17) is obtained by means of equation (1) using the area of the upper segment as $A_f$ and n = 0.9. The mean-annual precipitation is estimated to be about 3 inches on the basis of precipitation records at nearby Death and Deep Springs valleys (Fig. 1). The absence of vegetation in the source area of Gorak Shep Fan suggests that climatic conditions here are more like those in Death Valley than in Deep Springs Valley. From Figure 19, these values give a rate of deposition of about 2.5 feet/1000 years. Decreasing this by 40 percent to account for debris not deposited in the upper segment, gives a figure of about 1.5 feet/1000 years. It would thus require about 30,000 years to deposit the debris in the upper segment.

The 160 feet of vertical displacement has probably been episodic; the elastic rebound theory suggests periods of gradual deformation followed by more rapid displacement on faults. However, the above calculation permits an estimate of the mean rate of uplift during deposition of the upper segment. The mean rate so calculated is 5 feet/1000 years and is probably in error by less than an order of magnitude.

The second example involves the age of segmentation and rate of eastward tilting of southern Death Valley. To study the age of segmentation, two topographic profiles across the valley were constructed (Fig. 20 A). These profiles show that the Panamint fans on the west have three segments and the Black Mountain fans on the east, only two. Field observations indicate that the most recent segment on the east side is at the fanhead, and on the west it is at the toe. To determine the volume of material in these latest segments the next older surface was projected beneath the segment in question (Fig. 20 A). These volumes were then divided by the present fan areas to obtain the equivalent thickness deposited over the entire fan surface. Additions of material to the playa, additions to the fan below the upper segment of east-side fans, and erosion of the upper segment of west-side fans were all taken into consideration in obtaining the equivalent thicknesses.

To obtain rates of deposition for these fans from Figure 19, and thus an estimate of the time since segmentation, a value of n of 0.9 was assumed, and c was calculated from equation (1), $A_f = cA_d^n$, using the measured fan and drainage-basin areas and taking deposition on the playa into consideration. The values are given in the first column of Table VI. The mean-annual precipitation in each drainage basin was estimated by means of a linear

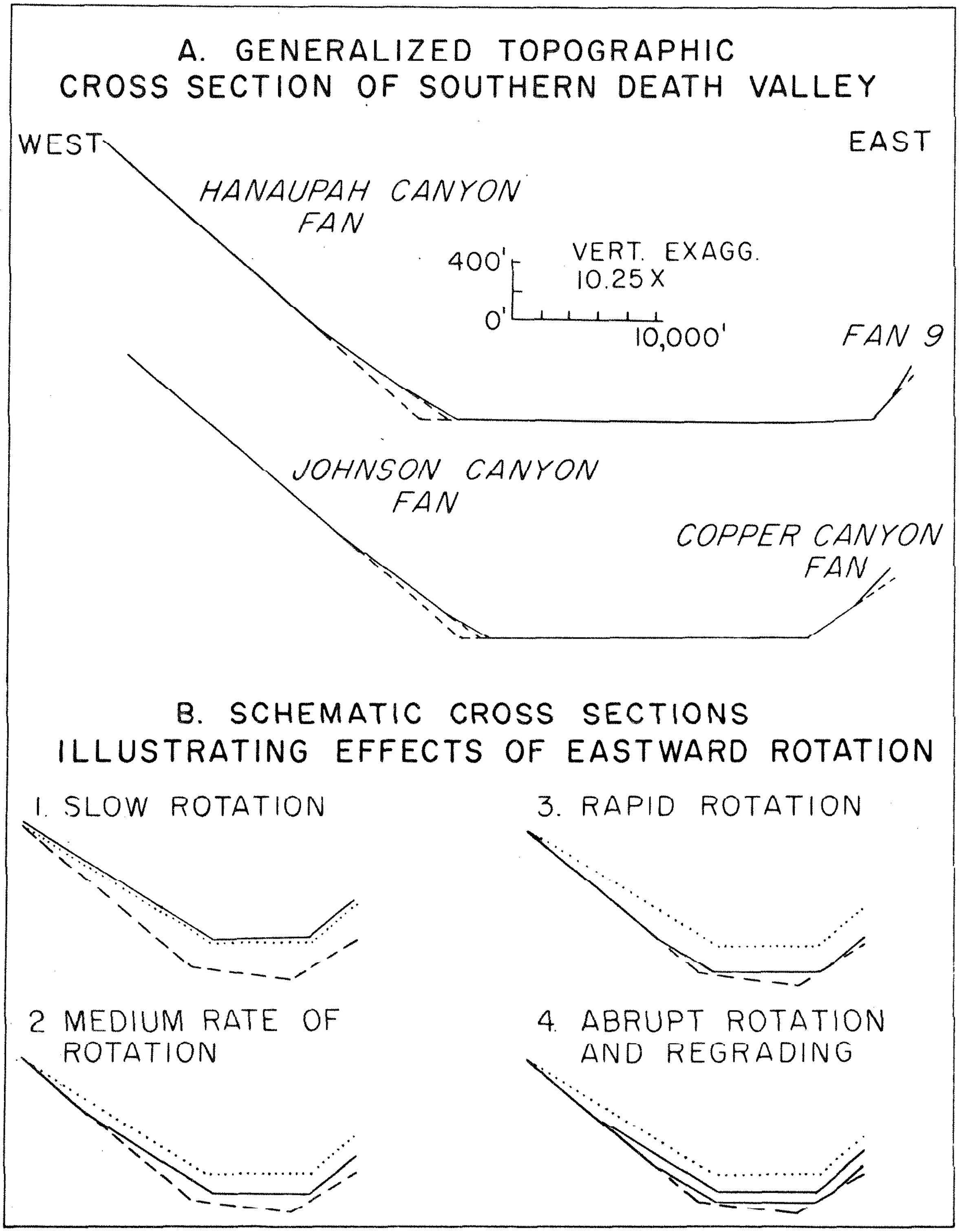
Figure 20. Effects of tectonic rotation on alluvial fans in southern Death Valley.

A. Dashed lines show projections of fan surface beneath younger segments.

B. Diagrams show the ground surface prior to rotation (dotted line), the same surface after rotation (dashed line), and the new surface resulting from deposition upon the old surface during rotation (solid line(s)). Deposition is assumed to occur at the slope of the pre-rotation surface (dotted line). Each diagram shows the same amount of rotation, but since the rate of rotation varies, the time interval represented by each diagram, and hence the amount of deposition during rotation, varies from one diagram to the next.

In diagram B 1 the rate of rotation is so slow that deposition slightly exceeds the net change in elevation by rotation.

Note that the fans on the east in diagrams B 3 and B 4 consist of a new upper segment and a lower segment which is part of the pre-rotation surface.



A. GENERALIZED TOPOGRAPHIC CROSS SECTION OF SOUTHERN DEATH VALLEY

B. SCHEMATIC CROSS SECTIONS ILLUSTRATING EFFECTS OF EASTWARD ROTATION

Figure 20.

extrapolation of precipitation with altitude. This extrapolation was based on a measured mean-annual precipitation of 2 inches on the floor of Death Valley (U. S. Weather Bureau), and estimated values of 13 inches on Telescope Peak on the west side, and 5 inches at Dantes View on the east. These last two values are based on known precipitation at similar altitudes in the White Mountains and on the author's knowledge of vegetation at the two localities. The resulting figures and the rates of deposition determined from Figure 19 are given in the second and third columns of Table VI. It is realized that precipitation may not have been constant throughout the time represented by these fan segments. However, there is at present no way of estimating the variation. The error involved by assuming constant rates of deposition is probably much less than other uncertainties.

The length of time required for deposition of the respective segments is obtained by dividing the equivalent thickness by the rate of deposition (Table VI, column 4). The resulting figures suggest that the most recent segments on opposite sides of the valley are correlative and that they began to form about 2500 years ago. This date falls within the estimated limits of error (± 65%) of all but one of the calculated ages. Similarly the middle segments on west-side fans required approximately 14,500 years to

## TABLE VI

### Age of Segmentation in Southern Death Valley

| Fan | (1) Coefficient c | (2) Estimated Mean Annual Precipitation, inches | (3) Rate of Deposition, ft/1000 years | (4) Time Required for Deposition, years | (5) $\Delta\theta$ Degrees |
|---|---|---|---|---|---|
| Most Recent Segment | | | | | |
| East side valley | | | | | |
| Fan 9 | .23 | 3.5 | 2.2 | 4,100 | 4.0 |
| Copper Canyon Fan | .13 | 4 | 4.4 | 1,300 | 2.1 |
| West side valley | | | | | |
| Johnson Canyon Fan | .94 | 7 | 1.1 | 2,900 | 0.75 |
| Hanaupah Canyon Fan | .69 | 8 | 1.7 | 1,900 | 0.62 |
| Middle Segment | | | | | |
| Johnson Canyon Fan | .94 | 7 | 1.1 | 17,000 | 0.49 |
| Hanaupah Canyon Fan | .69 | 8 | 1.7 | 12,000 | 1.13 |

develop, and deposition in these segments began about 17,000 years ago.

Segmentation of fans in southern Death Valley is almost certainly the result of eastward tilting of the Panamint Range-Death Valley block. It is unlikely that climatic change alone could be responsible, as the most recent segment on the east is at the fanhead, and on the west it is at the toe. This would require climatic changes in opposite directions on opposite sides of the valley, or climatic changes in the same direction which produced opposite effects. Steepening of the drainage basin of Black Mountain fans by uplift of the Black Mountains without tilting of Death Valley would produce segmentation of fans on the east side only. Tilting of the Panamint Range-Death Valley block is an adequate explanation, and the most logical one in view of independent physiographic evidence for such tilting (Maxson, 1950; Denny, 1965; Greene and Hunt, 1960; Drewes, 1963, p. 66). This tilting appears to be the result of displacement on faults in Death Valley at the base of the Black Mountains and in Panamint Valley at the base of the Panamint Range.

It is pertinent to consider the nature of the tilting that produced segmentation. First, consider the consequences of gradual and continuous rotation of the Death Valley-Panamint Range block without faulting. If such deformation is slow enough, deposition will occur over the entire fan surface and the steady-state slope will be maintained by greater deposition on parts of the fan that experience a relatively greater downward displacement (Fig. 20 B 1). If rotation is somewhat more rapid deposition may not keep pace and segmentation may occur on the Panamint fans (Fig. 20 B 2). With a still higher rate of rotation, segmentation will occur nearer the toe of the Panamint fans and may also occur on Black Mountain fans (Fig. 20 B 3).

Continuous rotation is not the only way to develop segmented profiles. Episodic rotation followed by long periods of quiescence may have the same effect (Fig. 20 B 4). If a long enough time elapses between such episodic movements, the fan profile may become completely regraded, thus obscuring evidence for rotation.

From this discussion three possible explanations emerge for the present pattern of fan-segmentation in southern Death Valley (Fig. 20 A). These are: (1) continuous deformation with abrupt increases in the rate of rotation; (2) abrupt tilting followed by periods of stability; and (3) continuous deformation with interspersed periods of more rapid or abrupt rotation. If episodes of abrupt rotation are associated with displacement on faults, the third explanation is consistent with the elastic rebound theory of faulting in which gradual deformation precedes rupture. The absence of a middle segment on east-side fans is consistent with any of these explanations.

To investigate these possibilities further, two types of calculation were made. The first is based on the hypothesis of continuous deformation, and involves the difference in the average rates of deposition on east-side and west-side fans, respectively. Since deposition produces a wedge under such conditions, a point can be found along the fan radius at which the rate of deposition equals the mean rate for the entire fan, and the distance across the valley floor from the point of mean deposition on east-side fans to the corresponding point on west-side fans can be measured. If the position of the fan or segment margins is not changing with time and if the playa surface is maintained horizontal by non-uniform deposition, the mean rates of deposition in feet/1000 years on the fans will be steady-state rates and the rate of tilting in radians/1000 years will equal the difference in rates of deposition on opposite sides of the valley divided by the distance across the valley as defined above. For instance, consider the fan surfaces prior to segmentation. The rates of deposition on opposite sides of the valley are determined from Figure 19, using values of c which reflect a contribution of sediment to the playa and which, on the Panamint fans, include only the depositional area prior to extension of the toe during segmentation. The difference in rates so determined is 1.7 feet/1000 years (Table VII). Thus, under steady-state conditions, the surface of Black Mountain fans at the beginning of any 1000 year time interval must, by the end of that time interval, have dropped 1.7 feet relative to the same surface on the Panamint fans. The mean horizontal distance, across the valley floor over which this relative vertical movement takes place is 42,000 feet. The rate of tilting is thus $\mathrm{Tan}^{-1}\ 1.7/42{,}000 = 0.0023^{\circ}/1000$ years. A rough estimate indicates that approximately 130,000 years would be required, after the beginning of rotation, to reach a new steady-state with this rate of tilting. The same procedure can be used to estimate rates of tilting during deposition on the more recent fan segments. These rates are given in Table VII.

Since these calculations are based on the assumption that rotation was continuous and that a steady-state morphology was attained with a constant rate of rotation, the calculations cannot in themselves prove continuous deformation. However, independent evidence to be discussed subsequently suggests that part of the deformation was of this nature.

In the second calculation the angles between the surfaces of each segment and the surface of the next older segment were determined from Figure 20 A.(Table IV, column 5). As the fans on the east side of the valley were

## TABLE VII

### Rates of Tilting in Southern Death Valley

| | Mean Rate of Deposition on Segment, ft/1000 yrs. | Estimated Rate of Gradual Rotation, degrees/ 1000 yrs. | Estimated Net Rotation, degrees |
|---|---|---|---|
| Most Recent Segment | | | |
| East side of valley | 12.5 | 0.018 | 0.7 |
| West side of valley | 3.4 | | |
| Middle Segment | | | |
| East side | 3.0 | 0.0011 | 0.8 |
| West side | 2.4 | | |
| Pre-segmentation | | | |
| East side | 3.0 | 0.0023 | |
| West side | 1.3 | | |
| Other estimates of tilting rates | | | |
| Gordon Greene (written communication, 4/5/65, Tiltmeter studies. Extrapolated from 2.1 years of record) | | | |
| Dantes View | | 0.13 | |
| Trail Canyon Fan | | 0.11 | |
| Greene and Hunt (1960) Archeological evidence and shorelines | | 0.018 | 0.072 |

dropped, relative to their source areas in the Black Mountains by displacement on the fault at the base of the mountains, the source areas steepened. As a result the calibre of debris deposited on these fans probably increased following segmentation, and the resulting steady-state slopes were probably steeper than the fan slopes prior to tectonic disturbance. This should accentuate the angular difference, $\Delta\theta$, between segments, and thus angular differences on east-side fans are probably not equivalent to the angular rotation of the Panamint Range-Death Valley block.

Eastward tilting of the Panamint Range results in slight steepening of the source areas of Panamint fans. However this effect is likely to be much less than the steepening of source areas in the Black Mountains. Furthermore alluvial terraces several feet above the present stream channel and 4 or 5 miles above the head of Johnson Canyon Fan suggest that readjustment of slopes in the Panamint source areas may be relatively rapid. The slope of new segments may not be appreciably different from the slope of older segments prior to tilting, and the angular difference, $\Delta\theta$, should approximate the net rotation. The estimated net rotations in Table VII were obtained by averaging the $\Delta\theta$ values for west-side fans given in column 5 of Table VI.

Interpretation of these results is aided by additional data. First, tiltmeter observations over a 2.1 year period prior to 1961 (Gordon Greene, written communication, 4/5/65) in the southern Death Valley region indicate rates of tilting that are highly variable in both magnitude and direction. At the two stations closest to the area considered in the present calculations, Trail Canyon Fan and Dantes View, net rates of eastward tilting on the order of $0.1^{\circ}/1000$ years, in addition to larger north-south components were observed. Other stations farther north and west all had a net westward component at the end of the 2.1 year period, but two of these had large eastward components after the first year of observation. These data suggest that deformation is continuous and thus support the assumption that gradual deformation has occurred and hence may be responsible for the observed segmentation. This assumption is implicit in the calculation of rates of gradual rotation.

On the other hand, the rates of tilting are one to two orders of magnitude too small to account for the corresponding total angular displacements (Table VI). Such large differences do not seem attributable to errors in the assumptions involved in either calculation. Thus episodes of abrupt rotation, in addition to the gradual deformation, are implied.

Greene and Hunt (1960, p. 275) found that the "eastern shoreline of a shallow lake, which flooded the floor [of Death Valley] just prior to introduction of the bow and arrow, is now 20 feet lower than the western shoreline." The two shorelines are about 3 miles apart and the bow and arrow was introduced approximately 2,000 years ago (Greene and Hunt, 1960). Half of this difference in shoreline elevations "can be explained by the presence of a recent fault scarp" at the foot of the Black Mountains (Greene and Hunt, 1960, p. 275). These observations suggest a rate of gradual eastward tilting of 0.018 degrees/1000 years, plus 0.036 degrees of more rapid tilting associated with faulting, or a total rotation of 0.072 degrees over a 2,000 year period. This amount of rotation is too small to be observable in segmentation of fans. Furthermore if the faulting occurred within the past few hundred years, the effect of the faulting on the average rate of gradual rotation would not be observable in the estimated rates determined from fan morphology (Table VII). Under these conditions the rate of gradual deformation determined from Greene and Hunt's data (0.018 degrees/1000 years) should agree with the corresponding rate determined from consideration of depositional rates on the most recent fan segments (also 0.018 degrees/1000 years). The observed agreement is astonishing in view of the assumptions involved and is undoubtedly fortuitous. Agreement within a factor of 2 or 3 would have been considered good.

Average rates determined over substantially longer time intervals (since mid-Tertiary) from data of Drewes (1963) and Hunt (written communication, 4/26/65) are an order of magnitude less than the more recent rates determined from alluvial fan morphology.

These lines of reasoning suggest that tilting of Death Valley consists of gradual deformation interspersed with episodes of much more rapid rotation. By analogy with the elastic rebound theory of faulting, it seems likely that major fault displacements were associated with the rapid rotation. Minor faulting may occur during the periods of gradual deformation, but the accompanying tilting of the structural block is too slight to result in fan segmentation. Such tilting is included in the average rate of gradual deformation. On the basis of this model and the above calculations, the recent tectonic history of Death Valley may be summarized as follows: Estimates of the rates of deposition on the pre-segmentation surfaces on opposite sides of the valley suggest that the pre-segmentation surface on west-side fans may have been built during a long period of slow but continuous deformation. Evidence for major episodes of faulting or abrupt increases in the rate of rotation during this period is lacking. At the end of this period the rate of tilting was about 0.0023 degrees/

1000 years. About 17,000 years ago an episode of much more rapid rotation resulted in segmentation of west-side fans. Segmentation of the Black Mountain fans may have occurred also, but owing to the higher rates of deposition on these fans, the new segment has now completely buried the pre-segmentation surface. There is no direct evidence for major faulting during this episode, but the elastic rebound model suggests that such faulting probably occurred. By approximately 2,500 years ago the rate of rotation had decreased to about 0.0011 degrees/1000 years. The net rotation of the block between 17,000 and 2,500 B.P. was about 0.8 degrees. About 2,500 years ago another episode of rapid rotation, again probably associated with faulting, resulted in segmentation of fans on both sides of the valley. Then for about 2,000 years deformation occurred gradually at an average rate of 0.018 degrees/1000 years. Net rotation since 2,500 B.P. has been about 0.7 degrees. The most recent event is the faulting which resulted in the scarp reported by Greene and Hunt (1960).

This interpretation suggests an increase in the net rate of rotation with time which is consistent with other geologic (Drewes, 1963, p. 66) and physiographic (Maxson, 1950, p. 108) evidence. In the period under consideration this increase seems to be primarily the result of an increase in the frequency of major fault displacements, rather than the result of an increase in the rate of gradual deformation. However the length of the alluvial-fan record is much too short to warrant placing much significance in this observation.

# CLOSING STATEMENT

This study has treated the principal depositional processes on alluvial fans and their consequences in terms of fan morphology. In many instances morphologic characteristics such as slope, fan area, and depth of fanhead incision are systematically related to the depositional processes. As a result these characteristics tend to assume and maintain a quasi steady-state form.

One of the most exciting products of one of these quasi steady-state conditions, the fan-area relationship, is a procedure for estimating rates of deposition on fans. This procedure needs and deserves refinement, especially with respect to evaluation of the effect of source-area topography and lithology on rates of deposition. An accurate method for determining depositional rates on fans will have many applications, only one of which, the determination of rates of tectonic movement, has been discussed here.

Two other quasi steady-state relationships, involving fan slope and depth of fanhead incision, respectively, have not been developed to the extent that their possible importance in evaluating climatic conditions and depositional processes warrant. A better understanding of them should increase knowledge of the relative role of debris flows and fluvial processes in fan morphology.

Quasi steady-state relationships are reflections of the dependence of certain physical variables on others. For instance, large fans do not have lower slopes simply because they are large. Slope is a function of discharge and sediment grading, and large fans, because of their large drainage areas, usually have higher discharges than small fans. Thus these relationships are expressions of basic physical laws of geomorphology.

Some features on fans appear to vary randomly with time. Among these is the position of the intersection point and the trend of the main channel. There are definite physical reasons for changes in these features but the combinations of significant variables are so numerous as to defy analysis, in much the same way that a throw of a pair of dice appears to be random. Thus, as with the dice, these alluvial fan features must be treated in terms of probability. Even here the concept of a steady-state fan area is involved, for the analysis depends upon the concept that deposition must, over a long enough period of time, occur uniformly over the entire fan surface.

# APPENDIX

## Location of Fans Studied in Detail and Further Explanation of Age Relationships

### Little Cowhorn Fan

Little Cowhorn Fan is located in the N 1/2 of NE 1/4 of SE 1/4 of Sec. 16, T. 9 S., R. 36 E. on the Waucoba Mountain 15-minute Quadrangle, California, and is in Little Cowhorn Valley.

### Gorak Shep Fan

Gorak Shep Fan is located in the vicinity of 37° 07' 45" N, 117° 38' 27" W. in southern Eureka Valley, California, and is on the Last Chance Range 15-minute Quadrangle.

### Shadow Rock Fan

Shadow Rock Fan is located in the NW 1/4 of Sec. 16, T. 8 S., R. 36 E. on the Blanco Mountain 15-minute Quadrangle, California, and is in southeastern Deep Springs Valley.

The ages of the three channels on this fan are based on topographic relationships, particularly at the point where the oldest channel diverges from the present channel. Successively older channel deposits are at successively higher elevations at this point.

The three ages of fan-surface material are based on the darkness of the desert-varnish coating. Topographic position and texture of surface material on air photographs were used to distinguish the "oldest" surface from the adjacent "older" surface.

These relationships are confirmed by the data on creep-smoothing of the fan surface (Fig. 11 C) and by the areal ratio of patches of fine detritus to deposits of coarse detritus in the three ages of fan-surface material. The fines are secondary; thus the more fine material the older the unit.

## Trollheim Fan

Trollheim Fan is located in the E 1/2 of NW 1/4 of Sec. 20, T. 8 S., R. 36 E. on the Blanco Mountain 15-minute Quadrangle, California, and is in southeastern Deep Springs Valley.

The two youngest channels on this fan are the same age and are separated only by a low bank parallel to the SW branch. The older channel material exists as a terrace above the present channel but below the adjacent fan surface. The material in these channels has an abrasion coating, giving it a lighter color than that on the adjacent fan surface.

The oldest channel was identified on the basis of its continuity with the fanhead and its topographic position with respect to the adjacent higher fan surfaces. The topography in this channel is also much more irregular than the creep-smoothed topography on the adjacent fan surface.

Weathering characteristics were used to distinguish the two ages of surface material. Blocks of quartzite in the older fan-surface material have a deep-brown desert-varnish coating, quite distinct from the light-brown coating of the younger fan-surface material. Furthermore many of the carbonate boulders in the former material have been reduced to crumbly fragments while those in the latter material retain their original form.

### Sand Fan

Sand Fan is located in the NE 1/4 of Sec. 33, T. 25 S., R. 38 E., on the Inyokern 15-minute Quadrangle, California.

### Cactus Flats Fan

Cactus Flats Fan is located in parts of Sections 17, 18, 19 and 20, T. 20 S., R. 38 E. on the Haiwee Reservoir 15-minute Quadrangle, California, and is in Cactus Flats.

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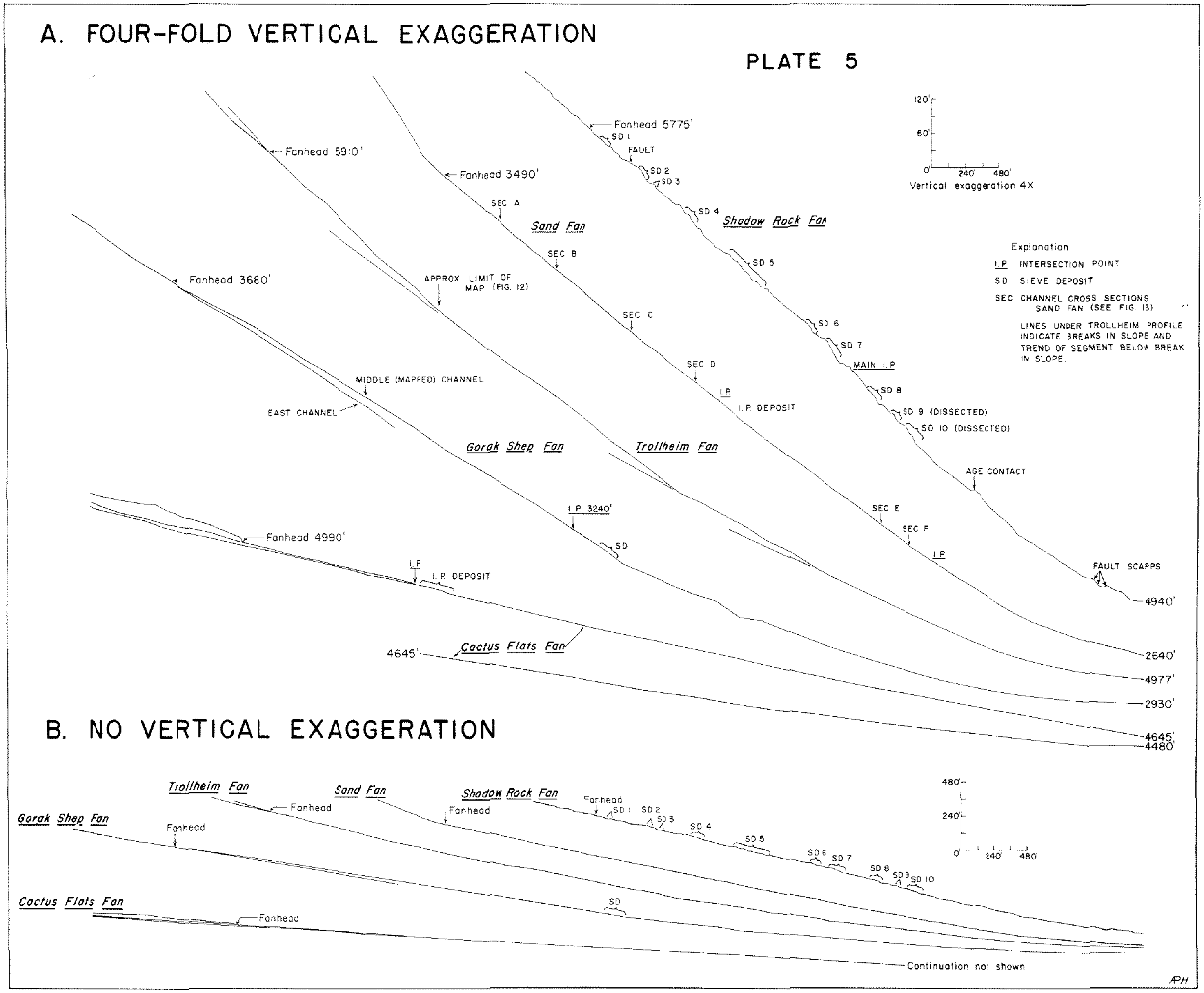
PLATE 5


A. FOUR-FOLD VERTICAL EXAGGERATION
120'
60'
0'
240'
480'
Vertical exaggeration 4X
Explanation
I.P INTERSECTION POINT
SD SIEVE DEPOSIT
SEC CHANNEL CROSS SECTIONS SAND FAN (SEE FIG. 13)
LINES UNDER TROLLHEIM PROFILE INDICATE BREAKS IN SLOPE AND TREND OF SEGMENT BELOW BREAK IN SLOPE.
Shadow Rock Fan
Fanhead 5775'
SD 1
FAULT
SD 2
SD 3
SD 4
SD 5
SD 6
SD 7
MAIN I.P
SD 8
SD 9 (DISSECTED)
SD 10 (DISSECTED)
AGE CONTACT
FAULT SCARPS
4940'
Sand Fan
Fanhead 3490'
SEC A
SEC B
SEC C
SEC D
I.P
I.P DEPOSIT
SEC E
SEC F
I.P
2640'
Trollheim Fan
Fanhead 5910'
APPROX. LIMIT OF MAP (FIG. 12)
4977'
Gorak Shep Fan
Fanhead 3660'
MIDDLE (MAPPED) CHANNEL
EAST CHANNEL
I.P 3240'
SD
2930'
Cactus Flats Fan
Fanhead 4990'
I.P
I.P DEPOSIT
4645'
4645'
4480'
B. NO VERTICAL EXAGGERATION
Trollheim Fan
Fanhead
Sand Fan
Fanhead
Shadow Rock Fan
Fanhead
SD 1
SD 2
SD 3
SD 4
SD 5
SD 6
SD 7
SD 8
SD 9
SD 10
Gorak Shep Fan
Fanhead
SD
Cactus Flats Fan
Fanhead
Continuation not shown
480'
240'
0'
240'
480'
PH