

American Journal of Science

OCTOBER 1968

STEADY-STATE RELATIONSHIPS ON ARID-REGION ALLUVIAL FANS IN CLOSED BASINS*

ROGER LeB. HOOKE

Department of Geology and Geophysics,
University of Minnesota, Minneapolis, Minnesota 55455

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

$$A_f = cA_d^n$$

has been recognized previously (Bull, 1964a; Denny, 1965). The present study suggests that this relationship results from a tendency toward a steady state among coalescing fans in the same lithologic, tectonic, and geographic environment. The steady state exists when all fans are increasing in thickness at approximately the same rate. If rates differ, the areas of the fans change to approach a steady state. The exponent n is generally less than unity, apparently reflecting storage of debris in alluvial channels and on valley-side slopes in larger watersheds. The coefficient c may vary within a bolson due to lithologic or tectonic influences. It also varies among bolsons owing to differences in the ratio of erosional area in mountains surrounding the fans to depositional area occupied by fans.

Laboratory and field observations suggest that the steady-state slope of an alluvial fan is determined by debris size, depositional process, 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. Under otherwise equivalent conditions fans composed of coarse material are steeper than those composed of fine material, and fans built largely by debris flows or sieve deposition are steeper than fans on which fluvial processes dominated.

INTRODUCTION

Several workers (for example, Bull, 1964a; Denny, 1965) have recognized that with increasing drainage-basin area the area of an alluvial fan increases and fan slope decreases. This paper is concerned with the physical factors controlling fan area and fan slope. The boundaries of fans in several closed desert basins in California (fig. 1) were mapped in the field, and their areas and slopes were measured on U.S. Geological Survey 15-minute topographic maps. In addition, laboratory fans with radii up to 1.3 meters were built of silt and sand transported through a channel into a box under controlled conditions. The laboratory work influenced and confirmed many of the conclusions reached from field study.

AREA RELATIONSHIPS

Logarithmic plots of fan area, A_f , against drainage-basin area, A_d (fig. 2; Bull, 1964a, p. 95; Denny, 1965, p. 15), suggest a relationship of the form

$$A_f = cA_d^n \quad (1)$$

where c is the area of a fan with a drainage area of one square mile, and n is the slope of the regression line. If the lines in figure 2, along with

* California Institute of Technology Contribution Number 1352.

similar data from Bull (1964a, p. 95), are replotted on the same graph as in figure 3, n appears to be nearly constant, with a mean value of about 0.9. However c varies from one bolson to another and also varies with source-area lithology and tectonic history within a bolson. To understand these relationships it is first necessary to consider the process by which fan area is adjusted.

Uniform deposition.—On laboratory fans deposition during a single runoff event is generally localized. Thus one part of a fan may be built slightly higher than the surrounding conical fan surface. Such "highs" commonly develop below the intersection point or point where the main channel merges with the fan surface (pl. 1) (Hooke, 1967, p. 450). Braided flows crossing these intersection-point deposits tend to shift laterally into adjacent lower areas. Gradual migration of the intersection point in this

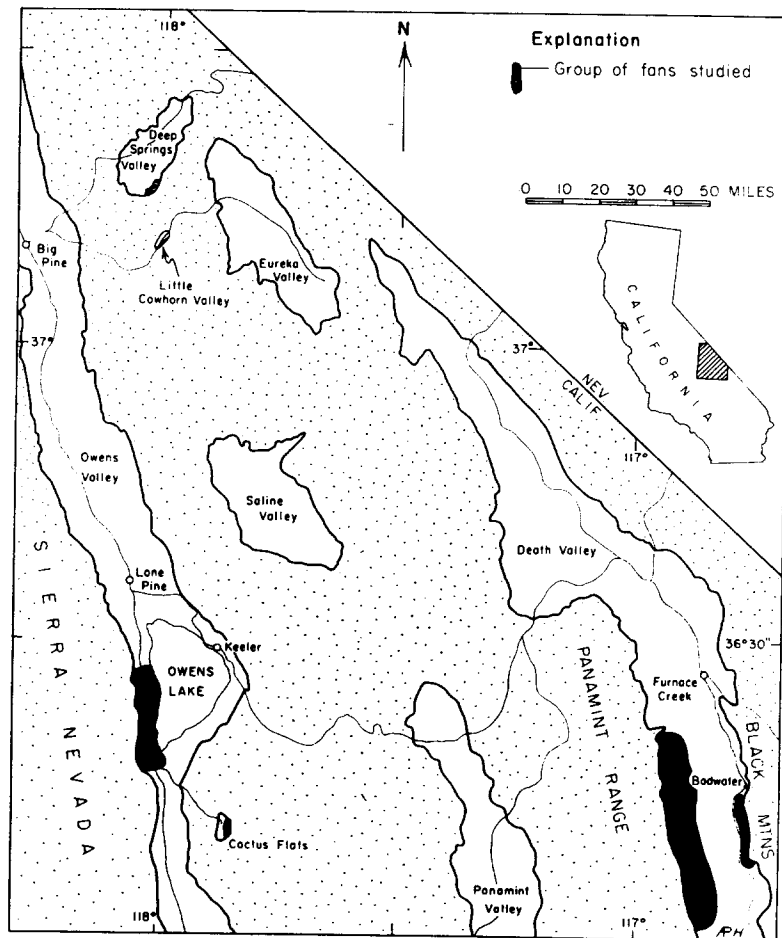


Fig. 1. Index map for groups of fans discussed in this paper.

way in addition to more catastrophic diversions of the main channel nearer the fanhead are responsible for shifting the locus of deposition. When observed over a period of several runoff events, such shifting results in deposition of a relatively uniform layer of sediment over the entire fan surface.

On a natural fan, deposition is uniform if all parts of the fan increase in thickness at the same rate. Thus charcoal buried at a depth of x meters near the apex would yield essentially the same radiocarbon age as charcoal buried x meters beneath the toe or beneath either flank. Because deposition during any one storm is localized, one charcoal deposit might be buried several hundred years later than another, but if x is large, the difference in age between the two samples should be a small percentage of the total age.

The situation in nature is complicated by the fact that natural fans commonly are segmented (Bull, 1964a), and current deposition is concentrated on the active segment. On segmented fans deposition is considered to be uniform only on the active segment. The ensuing discussion is written in terms of *unsegmented* fans.

Evidence for uniform deposition in nature is similar to, but not as complete as, the evidence in the laboratory. Gradual shifting of the locus of deposition during floods has been described by Eckis (1928, p. 234-235) and Bull (1964b, p. A27) and is a common phenomenon as indicated by braiding of large parts of the fan surface below the intersection point. Abandoned channels above the intersection point testify to abrupt changes in the zone of deposition. The patterns of deposits of different ages as shown on geomorphic maps of Denny (1965, pls. 1-5) and Hooke (1967, figs. 2, 3, and 4) also suggest such changes. Units commonly radi-

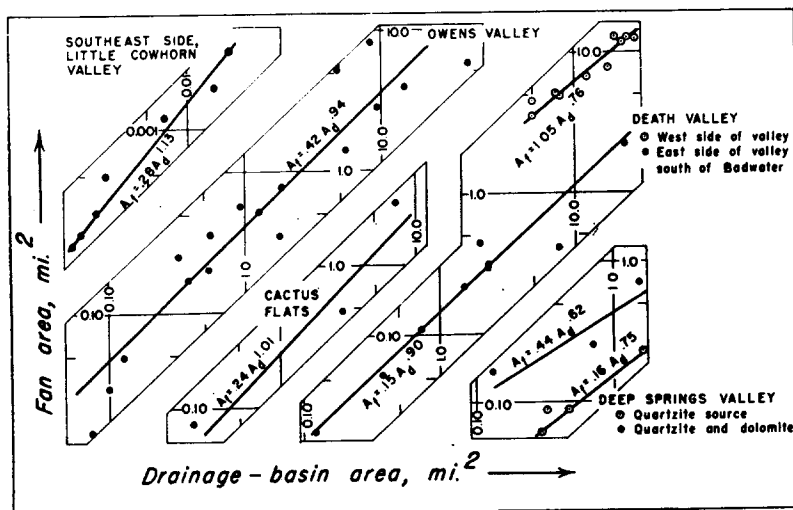


Fig. 2. Relationship between fan area and drainage-basin area. Regression lines fitted by eye.

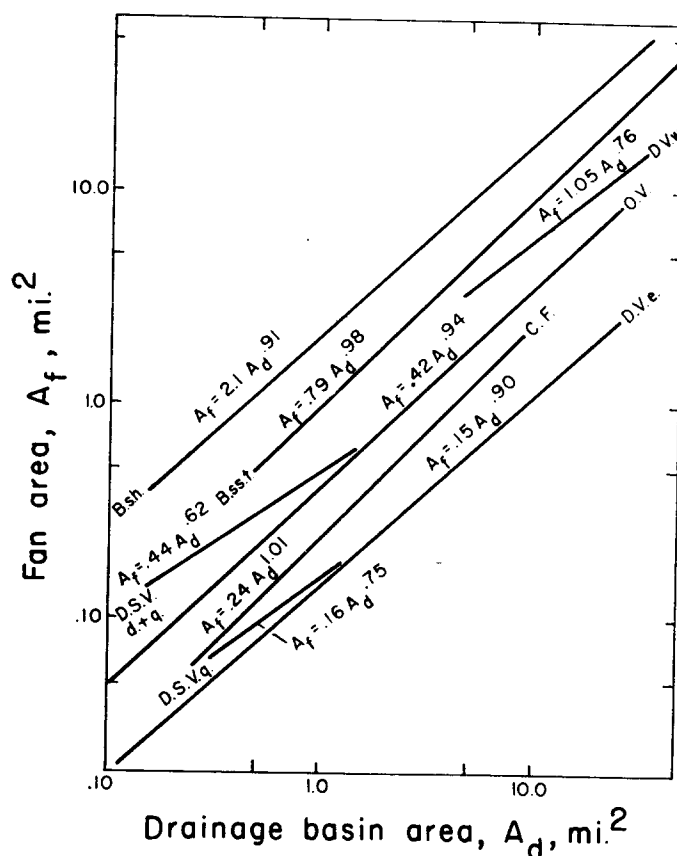


Fig. 3. Effect of geographic location on relationship between fan area and drainage-basin area. Data on which the lines are based are presented in figure 2 and in Bull (1964a, p. 95). Lines through Bull's data redrawn on the basis of least-squares fits (Bull, written commun., July 1965).

Explanation:

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

ate from the fanhead, indicating that diversions have occurred and that the zone of deposition shifts up- and down-fan more rapidly than it migrates laterally. Such shifting of the locus of deposition results in uniform deposition.

The best evidence for uniform deposition on natural fans is their relatively smooth conical surfaces. Most surface relief is associated with channels, and channels are the relatively short lived paths along which

PLATE 1



Laboratory fan composed of fluvially deposited debris. Scale below the number "21" is graduated in centimeters and is ten centimeters long. Note break in slope (arrow) associated with a change from granule-sized material near the fanhead to silt toward the toe. Water is flowing in a slightly incised channel at the fanhead and spreads out in a braided pattern below the intersection point, I.P.

debris is transported across higher areas to be deposited in lower areas (Hooke, 1967, p. 456-457). When these lower areas have been raised to or slightly above the general level of the rest of the conical surface, the channels will be backfilled, and flow diverted to another low area. (A process by which uniform deposition can occur on unsegmented fans with incised fanheads has been described previously [Hooke, 1967, p. 457-459].)

Adjustment of fan and playa areas.—If deposition is uniform there will be a tendency for each fan in a closed basin to reach and maintain a steady-state area. If the area of one fan were too small for the volume of material being added to it, it would be increasing in thickness faster than adjacent fans. Thus the area of this fan would increase, as shown in figure 4A, until the steady-state area was reestablished. Because the volume of material supplied increases with drainage area, this tendency toward a steady-state fan area is responsible for the observed increase in fan area with increasing drainage-basin area.

Theoretically, the increase in rate of deposition experienced by fans A and C in figure 4A would be propagated to neighboring fans to the left and right respectively until the entire bolson had readjusted itself. However, because deposition is slow and at any one time is localized,

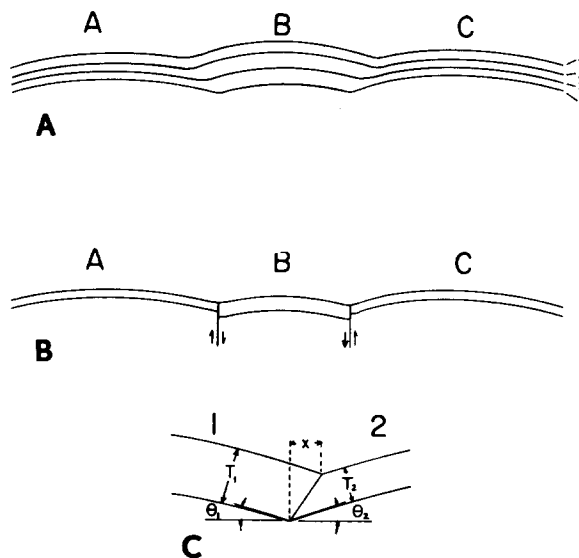


Fig. 4. A. Hypothetical transverse cross section through three adjacent coalescing fans. Line 1 shows the fan surfaces prior to attainment of a steady state. Fan B is increasing in thickness faster than A or C, as shown by lines 2 and 3. Finally (line 4) a steady-state condition is reestablished with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

B. Hypothetical cross section through three adjacent coalescing fans showing higher rate of deposition on fan B as a result of tectonic down warping or faulting of basement beneath B.

C. Cross section of boundary between two fans showing symbols used in text.

there will be a time lag between the initial perturbation causing the increase in rate of deposition on fan B and the final readjustment. This time lag probably is so long that fans in different parts of a bolson behave independently. Such behavior accounts for some of the scatter of points in figure 2; the rest is attributed to second order lithologic, tectonic, and climatic variations among source areas and to the difficulty in determining fan boundaries.

This model implies that ideally the rate of deposition should be the same on all fans in a particular bolson. On the west side of San Joaquin Valley rates of deposition, averaged over the past 600,000 years, have varied from 0.8 ft/1000 yrs on some fans to 1.5 ft/1000 yrs on others (Bull, written commun., Dec. 1967). These rates are based on the thickness of fan deposits overlying the Corcoran Clay Member of the Tulare Formation (Miller, 1963). An ash bed immediately above the Corcoran has been dated at $600,000 \pm 20,000$ yrs by K/A methods (Janda, 1965).

The Corcoran is gently folded in this area, and some of the variation in rate of deposition is due to these tectonic effects. For instance if one fan (B in fig. 4B) were dropping at a constant rate of 0.5 ft/1000 yrs and if the rate of deposition on adjacent fans were 1.0 ft/1000 yrs, then the area of fan B would adjust, by the mechanism illustrated in figure 4A, until the rate of deposition on fan B was 1.5 ft/1000 yrs.

Part of the observed difference in rates of deposition may also be due to incomplete adjustment toward equilibrium. The rate of migration of fan boundaries is very slow, and long periods of time are required to establish equilibrium by adjusting fan areas. For instance if T_1 and T_2 are the thicknesses of material deposited on fans 1 and 2 in a unit length of time (say 1000 yrs) then the rate of lateral migration, x , of the boundary will be

$$x = \frac{T_2 \cos \theta_1 - T_1 \cos \theta_2}{\sin(\theta_1 + \theta_2)}$$

where θ_1 and θ_2 are as defined in figure 4C. For most fans θ_1 and θ_2 are small, and x can be approximated by

$$x = \frac{T_2 - T_1}{S_1 + S_2} = \frac{\Delta T}{S_1 + S_2} \quad (2)$$

where S_1 and S_2 are transverse slopes of the fans. In the San Joaquin Valley transverse slopes of fans are about 0.01 ft/ft and a difference of 0.5 ft/1000 yrs in the rate of deposition would result in a rate of migration of about 25 ft/1000 yrs. This rate will decrease as ΔT decreases and equilibrium is approached. A simple numerical integration shows that if initially the fans each had areas of 10 square miles, and if the common boundary between them were 4 miles long, approximately 100,000 years would be required to reduce ΔT from 0.5 to about 0.2 ft/1000 yrs, and an additional 100,000 years would be required to reduce ΔT from 0.2 to 0.02 ft/1000 yrs. Thus it is not surprising to find some differences in rates of deposition among fans. A long time would be required to eliminate

such differences completely, and if sporadic tectonic activity continues to disrupt the system, rates on adjacent fans, though tending toward equality, may never be exactly equal.

In a closed basin containing an aggrading playa surrounded by fans, there will be a tendency for the rate of deposition on the playa to equal that on the fans. For instance, if the playa were too large with respect to the volume of material supplied to it per unit time, it would increase in thickness more slowly than adjacent fans. The fans would encroach upon the playa, thus decreasing its area and increasing its rate of thickening, so long as the volume of sediment supplied per unit time remained constant. This process would continue until the rate of increase in thickness of the playa equaled that on the bordering fans.

This model assumes that playas are currently aggrading, contrary to opinions expressed by Blackwelder (1931, 1946), Ekblaw (ms), and Bassett and Kupfer (1964, p. 34-35). Arguments for deflation are not convincing, and features ascribed to deflation can probably be explained in other ways. Virtually every closed basin in the desert contains playa clays and silts. This includes depressions of 10 or 15 square feet formed by road embankments as well as bolsons the size of Death Valley. The occurrence of recently deposited playa sediment in virtually all man-made depressions and the absence of basins in which fans have overlapped and buried a central playa suggest that playas are aggrading today as they have in the past. Radiocarbon dates and pollen stratigraphy from several playas (Smith, 1962; Eardley, 1962, p. 8; Clisby and Sears, 1956) also indicate net deposition in post-pluvial times. For these reasons I shall assume that playas are aggrading. However, most of the basic conclusions reached in the subsequent discussion would be applicable, with slight modification, to a situation in which the playa was degrading.

In conclusion, the steady-state model requires that the area of each fan be proportional to the volume of debris contributed to it per unit time, V . The constant of proportionality is the rate of deposition or rate of increase in thickness, dT/dt , thus

$$V = \frac{dT}{dt} A_f \quad (3)$$

Writing the expression in differential form emphasizes our concern with increments added to the fan; for most purposes the time of origin of the bolson, the total depth or volume of debris, and the subsurface shape of the fan-bedrock contact are immaterial. Furthermore, consideration of fans as conical piles of debris built over a playa is meaningless. Instead, because the rate of sedimentation on playas has undoubtedly varied through time (Stuiver, 1964), at times being somewhat faster and at times slower than the rate on fans, we should expect to find that fan gravels interfinger with playa sediment and that playa-fan boundary has shifted back and forth through time. Such interfingering relations may

be observed in dissected bolson fillings as in Ridge Basin, California (Hooke, 1967, p. 453).

Over a sufficiently long period of geologic time, denudation of the source area becomes significant, and fans that have reached a steady-state condition among themselves will still increase in area by burying the base of the mountain front. This secular change in fan area does not represent a deviation from the steady-state herein defined.

Erosion of material from fans.—Denny (1965, p. 23-24; 1967, p. 81-90) discusses the importance of erosion and redistribution of material on a fan and envisages a steady-state relationship in which the rate of deposition equals the rate of erosion. In such a system, material eroded from a fan and deposited on a playa must subsequently be removed from the playa. Otherwise the playa would grow in thickness faster than the fans and would thus encroach upon them. As fan area is restricted, deposition on fans would be concentrated in a smaller area, and the rate of deposition dT/dt (eq 3) would increase. At the same time erosional processes would have a smaller area on which to operate, and the rate of removal of material would be decreased accordingly until dT/dt was positive on the fans and equaled dT/dt on the playa. Thus in the absence of significant deflation, it is unlikely that $dT/dt = 0$ as Denny suggested. This is not to deny that erosion and redistribution of material is important; indeed most material reaching a playa probably has had a substantial residence time on the fan. It is simply argued that total erosion does not equal or exceed total deposition.

Denny's type area for such erosion, the alluvial slope northwest of Shadow Mountain, presents a slightly different problem in that the slope borders a through-flowing ephemeral stream, Carson Slough, rather than a playa. In this situation erosion could equal deposition, but evidence for such equality is lacking.

The main error in Denny's otherwise fine analysis appears to be that he considers a fan as an open system and does not pay sufficient attention to the larger source area-fan-playa system. The enormous thicknesses of sediment found in many closed desert basins demonstrates that these larger systems have acted as closed systems in the past, and there is no reason to believe that they do not still behave in this way.

Factors influencing c in $A_f = cA_d$.—The primary factor influencing c is the ratio of depositional area to erosional area in a bolson. In an area such as the Mojave Desert of southern California, residual mountain masses are small relative to the large alluvial basins. Consequently c is relatively large. A similar situation exists in the San Joaquin Valley of California (Bull, 1964a) where coefficients range from 0.96 to 2.1 (fig. 3). In contrast, coefficients in the areas of small valleys and large mountain masses with which this study deals range from 0.15 to 1.05.

There are at least two explanations for variations of c within a single bolson. Firstly, lithologic variations among nearby drainage basins may influence sediment yield. In San Joaquin Valley Bull (1964a, 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. 3). Bull attributed this to greater erodibility of the shale. Similarly in Deep Springs Valley, fans with predominantly quartzite source areas are about one third the size of fans with source areas underlain by dolomite and quartzite (fig. 2). If fans from both types of source area increase in thickness at essentially the same rate, the size differences must reflect a lower sediment yield from the quartzite source areas. The quartzite fans are composed of cobbles and boulders with little interstitial fine material (Hooke, 1967, p. 438-444, 455). Thus only the largest discharges transport significant amounts of debris. In contrast fans draining the partially dolomitic source areas have abundant fine material. Thus a lower sediment yield from the quartzite drainages is reasonable.

Secondly, tectonic movements may affect different parts of a bolson in different ways. For instance, eastward tilting of the Panamint Range-Death Valley block (Maxson, 1950, p. 113; Denny, 1965, p. 38; Drewes, 1963, p. 66) has caused fans on the west side of the valley to be extended, whereas those on the east have been restricted by the playa. This is nicely illustrated in figure 2 by the difference in coefficients for groups of fans on opposite sides of the valley, a relationship recognized independently by Denny 1965, p. 38). The values of c are 1.05 and 0.15, respectively.

Restriction of fans on the east side of the valley is inferred to involve interfingering of playa and fan deposits rather than simple on-lap of playa material. The rate of deposition on the east side of the playa should increase during tilting due to diversion of flow and sediment to the down-tilted side of the basin. Deposition of fan material will continue on the lower parts of east-side fans but will not occur at an increased rate as on the adjacent playa. In this situation, the playa-fan boundary will migrate toward the fan, and fan deposits will interfinger with playa material in vertical section. The rate of deposition on the fans will increase slowly and approach the rate of deposition on the playa.

Because the Panamint Mountains on the west are substantially higher than the Black Mountains on the east and therefore receive more rainfall, the differences in fan area on opposite sides of Death Valley undoubtedly reflect, at least in part, a higher sediment yield from the Panamints. That this is not the only factor influencing c is indicated by the fact that fans on the west are segmented due to tilting, and at present deposition on them is restricted to the lower twenty percent or so of the fan area (Denny, 1965, pl. 5). Much of the difference in values of c results because upper portions of these fans have been abandoned as areas of active deposition and yet are included in measurements of fan area.

Factors influencing n in $A_f = cA_d^n$.—Observed values of n are generally less than unity (figs. 2 and 3). The weighted-mean value is 0.90, a value comparable to that of 0.85 for sediment yield from water-

sheds of varying size in the midwest (Brune, 1948, fig. 3). The weighted-mean was calculated by assigning to each fan in a group the value of n for that group and averaging over all fans represented by lines in figures 2 and 3.

Values of n less than unity imply that larger basins supply less debris per square mile than smaller basins. But the larger basins are composed of a number of smaller basins, each of which might be expected to supply as much debris per unit area as basins of comparable size that drain directly onto a fan.

Several factors may be responsible for the lower sediment yield of larger watersheds. Firstly, larger basins are less frequently covered by a single storm (Langbein and Schumm, 1958, p. 1079). Runoff from a small tributary drainage will dump sediment into the trunk channel of the main basin. However, if there is little additional flow from other tributaries, and particularly if the trunk channel has a lower slope than the tributary channel, this sediment may not be carried out onto the fan. Subsequent large flows in the trunk channel will have to remove this debris supplied by tributaries during earlier small flows in addition to sediment supplied from valley-side slopes directly above the trunk channel. Therefore debris may remain on these slopes longer, inhibiting weathering and reducing the sediment supply. Thus slopes adjacent to higher order channels should be undercut less frequently and should supply less debris per unit area than equally steep slopes adjacent to lower order channels.

Secondly, valley-side slopes in larger basins are generally lower than in smaller basins (fig. 5; Langbein and Schumm, 1958, p. 1079). This too may contribute to lower sediment yields and slower weathering rates on slopes adjacent to higher order channels.

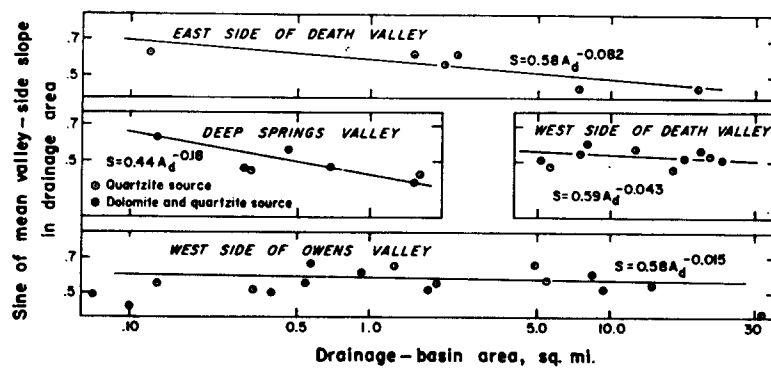


Fig. 5. Relationship between drainage-basin area and mean valley-side slope in the drainage basin. Statistical slope measurements were made on 15-minute topographic maps with the use of a grid sampling pattern containing between 5 and 150 points depending on basin area. The slope of the ground surface normal to the contours was determined at each point. Regression lines fitted by eye.

There are, in figures 2 and 3, some marked departures of n from the mean value of 0.90. In many cases such departures can be accounted for by peculiarities of the individual bolsons. For instance in the case of Little Cowhorn Valley (fig. 2), the contact between alluvium and bedrock parallels strike in the bedrock. As a result, a larger fraction of the area of smaller drainages is underlain by a stratigraphically lower unit, the quartzitic Hines Tongue Member of the Reed Formation (table 1) (Nelson, 1966a). The Hines Tongue appears to be more resistant than the dolomite of the upper member of the Reed Formation which becomes increasingly important in larger drainages. The dominating influence of the Hines Tongue in smaller drainages probably results in a lower sediment yield per unit area from these basins and hence in the uncommonly high n of 1.13 (fig. 2).

TABLE 1

Variation of 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

An unusually low n (0.62) is associated with fans draining quartzite and dolomite source areas in Deep Springs Valley. Lithologic variations appear to be in the wrong direction to account for the observed values, because a greater percentage of the larger drainages is underlain by less resistant dolomite (Nelson, 1966a, 1966b). However, topographic-map study suggests that the intermediate-sized basin may have recently captured about half the smallest basin. If the smaller drainage was twice as large before capture, and if the two points on figure 2 are adjusted accordingly, the data fit the line much better, and n increases to about 0.83. This interpretation further assumes that the time since capture has been insufficient to reestablish a steady-state condition.

Summary.—An explanation has been offered for the empirical relationships shown in figure 2 and represented by the equation $A_t = cA_d^n$. These relationships require the existence of some physical mechanism "built into" the fan-source system that acts to maintain the proportionality between A_t and A_d^n . The mechanism hypothesized (fig. 4) follows directly from purely geometrical arguments if deposition is uniform. Thus the evidence for the existence of a steady-state fan area

consists of (1) the arguments for uniform deposition, and (2) the relationships in figure 2.

Consideration of the mean value of n and of the variability of n and c suggested physical relationships between these quantities and the hydrologic, lithologic, and topographic characteristics of watersheds in general and of these drainage basins in particular. The physical relationships so defined depend on the mechanism hypothesized for adjustment of fans toward a steady-state area.

FAN SLOPES

Field and laboratory data suggest that fan slope is controlled primarily by debris caliber and by the nature and size of debris-transporting processes. Thus fan slope is determined by conditions in the source area. The existence of such a steady-state slope was recognized by Bull (1964a, p. 100).

Laboratory procedure.—Several conclusions discussed in this section are based on laboratory work. The author's first laboratory studies, designated as series A and B, have been described previously (Hooke, 1967, p. 446-447). Briefly, debris was placed in a channel debouching into a 1.5- by 1.5-m working area. Water from a constant-head tank was then run through the channel entraining the debris and depositing it as a fan in the working area. Discharge was regulated by a pair of valves, one of which could be preset for a particular discharge while the other was used to turn the flow on and off. Debris flows were generated by mixing a slurry of mud in a can and pouring it into the channel just above the fanhead. Sixteen fans were made; each was built during between 10 and 66 depositional episodes.

More recent experiments, designated as series C, have been conducted with the use of a similar laboratory set up but with a 1.5- by 2.7-m working area. The channel enters the working area near the middle of one of the 2.7-m sides; thus complete fans with a radius of 1.35 m can be built. The sediment used for fans of series C had a geometric mean sieve diameter of 0.56 mm and a geometric standard deviation of 2.33; the size distribution was approximately log-normal. Each fan in series C was built with between 24 and 103 discrete depositional episodes, each of which lasted five minutes. With the exception of fan C-1, the discharge was held constant during all episodes in the construction of a given fan.

In contrast, discharges on fan C-1 simulated natural floods. Each episode had a different peak discharge, and the discharge decreased during the episode. Specifically, the episode was started using a certain peak discharge. After one minute the discharge was reduced, and after two additional minutes reduced again. The two decreases in discharge were equal in magnitude, and together they reduced the flow either to one-third of the peak discharge or to 44 cm³/sec, whichever was highest. Forty-four cm³/sec was the lowest discharge measurable with the flow-rator used. The peak discharges for each episode, when plotted as a cumulative frequency curve, approximated a log-normal distribution and

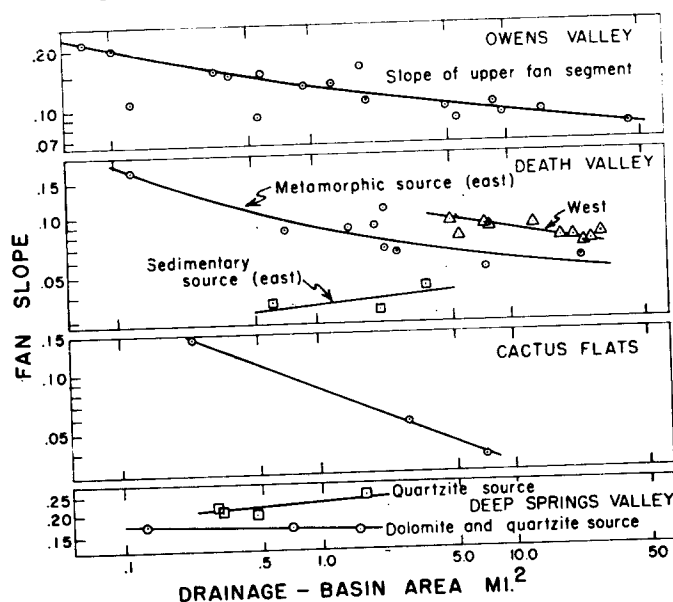


Fig. 6. Relationship between overall slope of individual fans and drainage-basin area. Regression lines fitted by eye. Overall slope is defined as the slope of a straight line from a point at or near the toe of the fan to the fanhead.

ranged from 44 to 435 cm^3/sec . The peak discharge to be used for any given episode was selected at random from the series of discharges making up the log-normal distribution and was in no way related to discharges in the preceding or following episodes.

Dependence of fan slope on discharge.—Eckis (1928, p. 234) and Melton (1965, p. 24) noted that fan slope decreases with increasing fan area. It follows that fan slope must also decrease with increasing drainage-basin area as indicated by figure 6 and by Bull (1964a, fig. 54B). This decrease in fan slope is attributed to the proportionally higher storm discharges from larger source areas.

Larger discharges generally have higher flow velocities and higher bed shear stresses and thus should transport on a lower slope the same material transported by smaller discharges on a higher slope. An example of this is found on Gower Gulch Fan in Death Valley about 3 miles south of Furnace Creek Inn. About 1931 Furnace Creek Wash was artificially diverted into Gower Gulch at a point of imminent capture. Thus discharges presently reaching the fan are much larger than those that built it, and deep fanhead incision has resulted. The slope of the incised channel is 0.032 and that of the fan surface near the fanhead is 0.040. Gower Gulch Fan is the only fan in this part of the valley that has an incised fanhead.

The influence of discharge on the slope of laboratory fans was readily observed; fans built with lower discharges had steeper slopes than those built with higher discharges (fig. 7). Furthermore, increasing

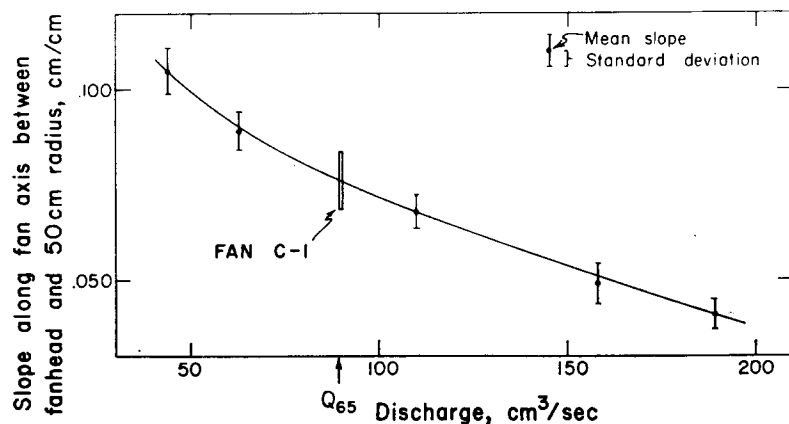


Fig. 7. Relationship between discharge and slope on laboratory fans. Data for fan C-1 were not used to draw curve; instead bar for fan C-1 was placed on curve at point where curve indicated slope of 0.076 and dominant discharge (Q_{65}) was read from curve. Larger standard deviation for slopes on fan C-1 results from use of distribution of discharges to build this fan.

the discharge on a particular fan generally resulted in regrading of that fan to a lower slope.

The process by which the slope of a natural fan is adjusted by discharges of varying magnitude can be inferred from study of the loci of deposition during different discharges on fan C-1 (fig. 8). The peak discharge during episode 102 (fig. 8A) was of small to moderate size. It was in the 32nd percentile ($Q_r = Q_{32}$) or in other words was equaled or exceeded by 68 percent of the peak discharges used during construction of the fan. Figure 8A shows that deposition during this episode was concentrated in the mid-fan region and near the fanhead. In contrast a much higher peak discharge, equaled or exceeded by only 9 percent of the peak flows used, caused some erosion near the fanhead and considerable deposition near the toe during episode 103 (fig. 8B). At some intermediate discharge we might expect to find nearly equal amounts of deposition at the fanhead and at the toe.

From these results it is inferred that the smaller discharges on natural fans will deposit material primarily near the fanhead, while larger discharges will deposit more material near the toe. The actual slope that the fan assumes will be determined by a balance between these tendencies. Thus we may expect that the slope of any given natural fan has varied through time. These variations would not be as large as those observed on fan C-1 (fig. 7), because discharges on laboratory fans are often large enough to deposit material on more than half the fan surface, whereas discharges in nature are rarely this large. Thus on a natural fan, slope changes during a single storm would be almost imperceptible, but on a laboratory fan, slope changes during a single runoff event are easily measurable.

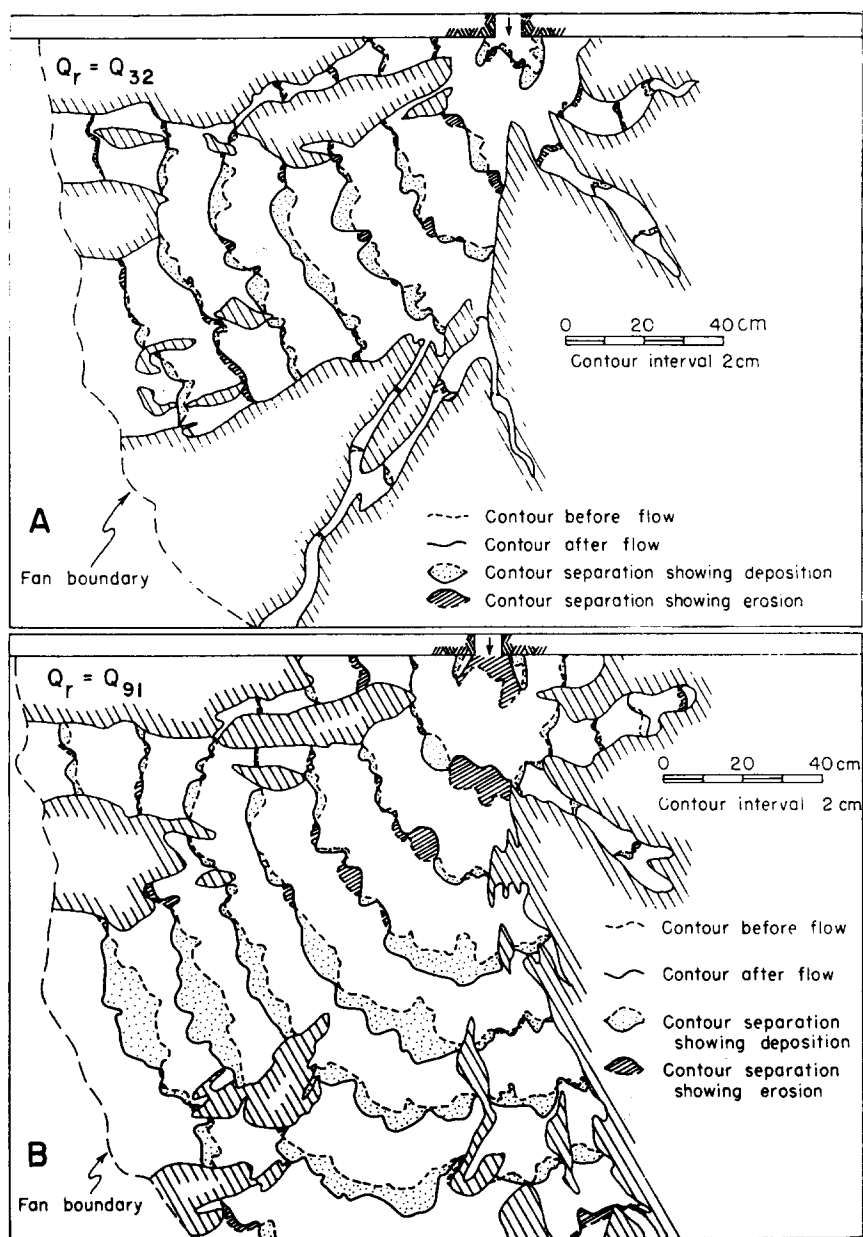


Fig. 8. Maps showing deposition during episodes 102 (map A) and 103 (map B) on fan C-1. Flow during these episodes did not cover uncontoured areas.

Consideration of the influence of discharge on slope suggests the possibility of defining a *dominant discharge* as being that discharge which, if it alone occurred, would produce a fan having the same slope as a fan built with a distribution of discharges. The magnitude of the dominant discharge on fan C-1 can be estimated by comparing the mean slope of this fan with the slopes of other fans in figure 7. It appears that a constant discharge of 90 cm³/sec would build a fan having the same mean slope as fan C-1. This discharge was equaled or exceeded 35 percent of the total time during which flow occurred during construction of fan C-1. (Note that this is *not* equivalent to the phrase, "equaled or exceeded by 35 percent of the peak discharges".) It is not known whether the dominant discharge has a similar frequency on natural fans.

Once the importance of discharge is recognized, other influences on fan slope may be studied by comparing fans draining watersheds that are nearly equal in area. Such fans will have been built by discharges of roughly the same size.

Effect of source-area lithology on fan slope.—Source-area lithology can influence fan slope in three ways: (1) by controlling debris size; (2) by controlling depositional process; and (3) by controlling sediment concentration in flows reaching the fan. All three of these factors have been observed to influence slopes of laboratory fans, and natural situations have been identified in which each one of them is inferred to be responsible for slope differences between specific groups of fans.

The influence of debris size on slopes of laboratory fans is illustrated in plate 1 by an abrupt decrease in slope associated with the change from coarse sand and granules on the upper part of the fan to finer sand and silt on the lower part. This break in slope was persistent and was not related to debris-flow action, as it occurred in the absence of debris flows on the fan in plate 1.

On natural fans the influence of debris size was observed on the east side of Death Valley where three fans with source areas underlain by Oligocene to Recent sedimentary and volcanic rocks (Jennings, 1958) have distinctly lower slopes than fans with drainage basins of the same size underlain by Precambrian metamorphic rocks (fig. 6). Mean grain size on the three fans with low slopes is visibly less than on the steeper fans draining metamorphic terrane.¹ Similarly the two larger fans in Cactus Flats are composed of material that is finer than that on most fans studied, and these fans have lower slopes than most other fans with drainage basins of similar area plotted in figure 6.

¹ As part of currently continuing NSF-sponsored research, T. R. Raster and the author made mechanical analyses of sediment samples from ten of these fans. The samples were taken from the present channel near the fanhead. On eight fans draining metamorphic terrane, the geometric-mean particle diameter ranged from 2.1 to 46 mm and averaged 11.5 mm. On the two fans draining sedimentary terrane, the geometric-mean particle diameters were 1.3 and 1.8 mm. Sample sizes ranged from 40 to 50 kg on the fans draining metamorphic terrane and were about 10 kg on fans draining sedimentary terrane.

TABLE 2

Effect of depositional process on fan slopes

Area	Highest slopes → Lowest slopes		
	Deep Springs Valley: quartzite source area	Deep Springs Valley: quartzite and dolomite source areas	Other valleys studied
Predominant type of deposition	Sieve	Debris-flow	Fluvial
Subordinate type(s) of deposition	Debris-flow	Fluvial and minor sieve	Debris-flow

The effects of depositional process on laboratory fans were observed in connection with both debris-flow deposition and sieve deposition. (Sieve deposits (Hooke, 1967, p. 453-456) are steep-fronted lobes built when fan material is so coarse that the entire flow infiltrates before reaching the toe of the fan.) Laboratory fans on which either debris-flow or sieve deposition occurred were up to five degrees steeper than fans built by fluvial deposition alone but under otherwise equivalent conditions.

The comparable effect in nature is illustrated by fans in Deep Springs Valley. The slope differences shown in figure 6 are judged to be due primarily to the differences in predominant depositional process listed in table 2.

The influence of sediment concentration was observed qualitatively in the laboratory: inlet conditions could be adjusted so that different amounts of sediment were carried by the same discharge. Flows with higher sediment concentration built steeper fans. A comparable effect in nature was described by Bull (1964a, p. 94-95) from San Joaquin Valley. Bull found that fans draining source areas underlain by mudstone and shale were generally steeper than those with source areas of comparable size underlain predominantly by sandstone. Bull attributed this to a greater erodibility of the mudstone and shale. That the mudstone and shale is more erodible is demonstrated by the fact that fans derived from mudstone and shale source areas are larger than those derived from sandstone source areas (fig. 3).

Dependence of fan slope on drainage-basin slope.—In order to investigate the dependence of fan slope on mean valley-side slope in the source area, the slope measurements in figure 5 were plotted against fan slope. To eliminate the effect of relatively flat areas which probably contribute small amounts of debris, the means of the highest 25 and 50 percent of the slopes were also calculated and plotted. The results indicate that any dependence of fan slope on valley-side slope is weak and probably negligible, a conclusion also reached by Bull (written commun. July 1965) in San Joaquin Valley.

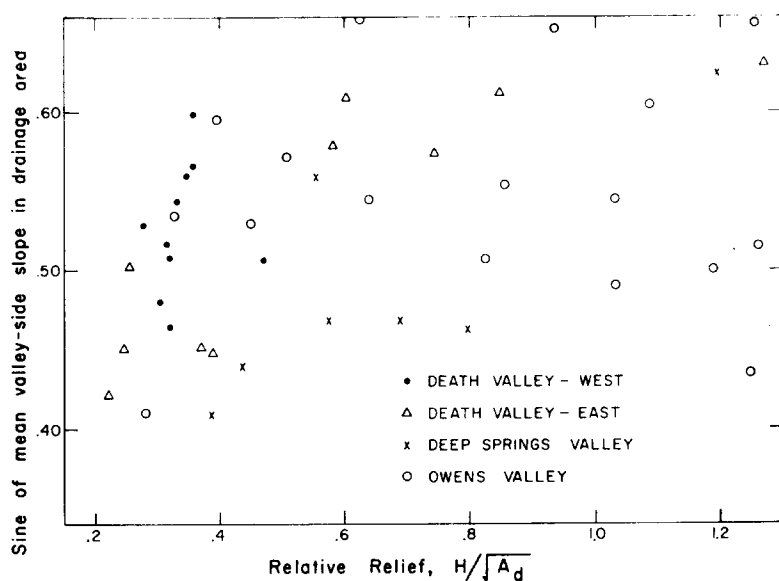


Fig. 9. Relationship between mean valley-side slope in the drainage area and relative relief ratio. Determination of mean valley-side slope is described in caption of figure 5.

On the other hand, there is often a good relationship between overall drainage-basin slope, defined as the slope of a straight line from the fanhead to the highest point in the drainage basin, and overall fan slope. 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 independence of the various mean drainage-basin slopes and fan slope, neither $H/\sqrt{A_d}$ nor overall drainage-basin slope can be interpreted as statistical measures of valley-side steepness in the arid watersheds which I have studied (fig. 9). Instead, owing to the natural concavity of most stream profiles, both of these quantities are roughly proportional to channel gradient in the source area. Fan profiles are generally continuous with the profiles of the alluvial channels above the fanhead (Denny, 1965, fig. 3; Hooke, 1967, fig. 5), and there is, therefore, a correlation between fan slope and this channel slope. Because channel slopes in the source area are presumably adjusted to transport the load supplied with the available discharge, fan slope also would appear to be a slope of transportation controlled by debris caliber and discharge.

Summary.—An increase in discharge with drainage area is probably responsible for the decrease in fan slope with increasing drainage area in figure 6. Fan slope also appears to vary directly with grain size and to be higher on fans on which either debris-flow or sieve deposition are important. Mean drainage-basin slope has no apparent effect on fan slope in the areas studied.

ACKNOWLEDGMENTS

The writer is indebted to R. P. Sharp for many helpful suggestions and stimulating discussions during the work and preparation of the manuscript. V. A. Vanoni and N. H. Brooks offered valuable suggestions on an early draft of the paper and made available space and facilities of the W. M. Keck Laboratory at the California Institute of Technology for part of the laboratory work. The paper has also benefited from critical reading by C. S. Denny, J. T. Hack, L. K. Lustig, H. E. Wright, and especially W. B. Bull. Cheerful assistance during various phases of the laboratory and field work was rendered by E. Daly, R. DeVault, M. McDonald, J. Koerner, and my wife. I am also indebted to my wife for drafting.

The research was supported by a grant from the Arthur L. Day Fund of the Geological Society of America, by research funds and a fellowship from the National Science Foundation, and by research funds from the Graduate School of the University of Minnesota. Part of this paper is based on the author's Ph.D. thesis at the California Institute of Technology.

REFERENCES -

- Bassett, A. M., and Kupfer, D. H., 1964, A geological reconnaissance in the southeastern Mojave Desert, California: Calif. Div. Mines and Geology, Spec. Rept. 83, 43 p.
- Blackwelder, Eliot, 1931, The lowering of playas by deflation: Am. Jour. Sci., 5th ser., v. 21, p. 140-144.
- 1946, Evolution of desert playas [abs.]: Geol. Soc. America Bull., v. 57, p. 1179.
- Brune, G. M., 1948, Rates of sediment production in midwestern United States: U. S. Dept. Agr. Soil Conserv. Service Tech. Pub., 65, 40 p.
- Bull, W. B., 1964a, Geomorphology of segmented alluvial fans in western Fresno County, California: U.S. Geol. Survey Prof. Paper 352-E, p. 89-129.
- 1964b, Alluvial fans and near-surface subsidence in western Fresno County, California: U.S. Geol. Survey Prof. Paper 437-A, p. A1-A70.
- Clisby, K. H., and Sears, P. B., 1956, San Augustin Plains — Pleistocene climatic changes: Science, v. 124, p. 537-539.
- Denny, C. S., 1965, Alluvial fans in the Death Valley region: U.S. Geol. Survey Prof. Paper 466, 62 p.
- 1967, Fans and Pediments: Am. Jour. Sci., v. 265, p. 81-105.
- Drewes, H., 1963, Geology of the Funeral Peak Quadrangle, Calif. on the east flank of Death Valley: U.S. Geol. Survey Prof. Paper 413, 78 p.
- Eardley, A. J., 1962, Gypsum dunes and evaporite history of the Great Salt Lake Desert: Utah Geol. and Mineralog. Survey Spec. Studies 2, 27 p.
- Eckis, Rollin, Alluvial fans of the Cucamonga district, southern California: Jour. Geology, v. 36, p. 224-247.
- Ekblaw, G. E., ms, 1927, Clastic deposits in playas: Ph.D. dissert., Stanford University, Stanford, California, 127 p.
- Hooke, R. L., 1967, Processes on arid region alluvial fans: Jour. Geology, v. 75, p. 438-460.
- Janda, R. J., 1965, Quaternary alluvium near Friant, California: Internat. Assoc. Quaternary Research Cong., 8th, U.S.A. 1965, Guidebook for Field Conf. 1, p. 128-133.
- Jennings, C. W., compiler, 1958, Geologic map of California, Death Valley sheet.
- Langbein, W. B., and Schumm, S. A., 1958, Yield of sediment in relation to mean annual precipitation: Am. Geophys. Union Trans., v. 39, p. 1076-1084.
- Maxson, J. H., 1950, Physiographic features of the Panamint Range, California: Geol. Soc. America Bull., v. 61, p. 99-114.
- Melton, M. A., 1965, The geomorphic and paleoclimatic significance of alluvial deposits in southern Arizona: Jour. Geology, v. 73, p. 1-38.

Mille
T
o
Nelso
C
C
Smith
C
Stuive
I

- Miller, R. E., 1963, Map showing structure of the Corcoran Clay member of the Tulare Formation, Los Banos-Kettleman City area, California: U.S. Geol. Survey open-file map, scale, 1:250,000.
- Nelson, C. A., 1966a, Geologic map of the Waucoba Mountain Quadrangle, Inyo County, California: U.S. Geol. Survey Map GQ528.
- 1966b, Geologic map of the Blanco Mountain Quadrangle, Inyo and Mono Counties, California; U.S. Geol. Survey Map GQ529.
- Smith, G. I., 1962, Subsurface stratigraphy of Late Quaternary deposits, Searles Lake, California: U.S. Geol. Survey Prof. Paper 450-C, p. C65-C68.
- Stuiver, Minze, 1964, Carbon isotopic distribution and correlated chronology of Searles Lake sediments: *Am. Jour. Sci.*, v. 262, p. 377-392.