PROCESSES ON ARID-REGION ALLUVIAL FANS[1]

ROGER LeB. HOOKE
Department of Geology and Geophysics, University of Minnesota

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 parts of four fans and reconnaissance work on over one hundred additional fans. Features mapped included the nature and age of deposits, material size, and channel pattern. In the laboratory small alluvial fans were built of mud and sand transported through a channel into a 5-foot by 5-foot box under controlled conditions.

Material is transported to fans by debris flows or water flows that follow a 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. The main channel emerges onto the surface near a midfan point, herein called the "intersection point." On 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 depositional relation probably also occurs on natural fans.

On fans deficient in fine material large discharges may infiltrate completely before reaching the toe of the fan. Coarse debris is then deposited as lobate masses, herein called "sieve deposits." In many respects sieve deposits resemble debris-flow deposits, but they lack primary fine material, and fresh lobes are highly permeable.

INTRODUCTION

The object of this study was to understand processes acting on fans and the features produced by these processes. The conclusions reached are based on reconnaissance and detailed fieldwork and on a concurrent laboratory study. The reconnaissance work included qualitative observations of features such as debris size and lithology, and channel form on more than one hundred fans in the deserts of California. Measurements of fan area and slope were made in some instances.

Four fans were selected for detailed fieldwork; three of them are discussed in this paper (fig. 1). The detailed study involved geomorphic mapping by plane-table methods or on large-scale aerial photographs, measurement of channel cross-sections, and study of weathering phenomena.

The laboratory study focused attention on aspects of fan morphology that might otherwise have been overlooked or misidentified in the field, and also led to qualitative relationships among fan slope, water discharge, debris-flow behavior, and depth of fanhead incision. However, exact modeling of a specific fan cannot, at present, be used to obtain quantitative data, because scaling relationships for sediment transport by streams and debris flows are not sufficiently well known. Consequently fans built in the laboratory were treated as small fans in their own right, not as scale models of natural fans.

NATURAL FANS STUDIED IN DETAIL

Each of the three fans studied in detail (figs. 2, 3, and 4) had six distinguishable ages of alluvium (table 1). The youngest unit on each consisted of material in the presently active main channel. Abrasion during transport has given this debris a light gray color. A slightly older channel on Trollheim Fan also contains abraded gravels but is separated from the main channel by a 2-foot high levee.

The second unit also consists of abraded gravels either in abandoned channels or in terraces 2–10 feet above the main channel. However, the abrasion coating is perceptibly duller, and channel banks have slumped owing to the absence of frequent cutting. The beds of these channels are higher than that of the main channel where the two diverge; thus they will carry flow only if exceptionally high floods occur or if the main channel aggrades.

[1] California Institute of Technology contribution no. 1393. Manuscript received October 18, 1966.

In the third unit is placed the oldest material clearly related to channeling. The abrasion coating has been removed by weathering, and in its place there is a brown weathering rind or, on Shadow Rock Fan, a light-brown desert varnish. On Gorak Shep Fan this unit consists of terraces 1–4 feet above the younger channel deposits. On the other two fans it is an old channel that widens down fan and diverges from the main channel at an elevation of 4 feet or more above the latter's bed. Topography in these channels is much more irregular than that on still older creep-smoothed surfaces.

Once channel deposits have been mapped, the remainder of the fan can usually be separated into two or three additional units. An important characteristic for distinguishing these units from each other and from channel deposits is the extent to which open pore space, commonly found in fresh gravels, has been filled by secondary fines during post-depositional weathering. Owing to lithologic differences in the source areas, pore-space filling proceeds at different rates on different fans, and the youngest unit in which the pore space appears to be filled will vary in relative age from fan to fan. For instance on Trollheim Fan the oldest

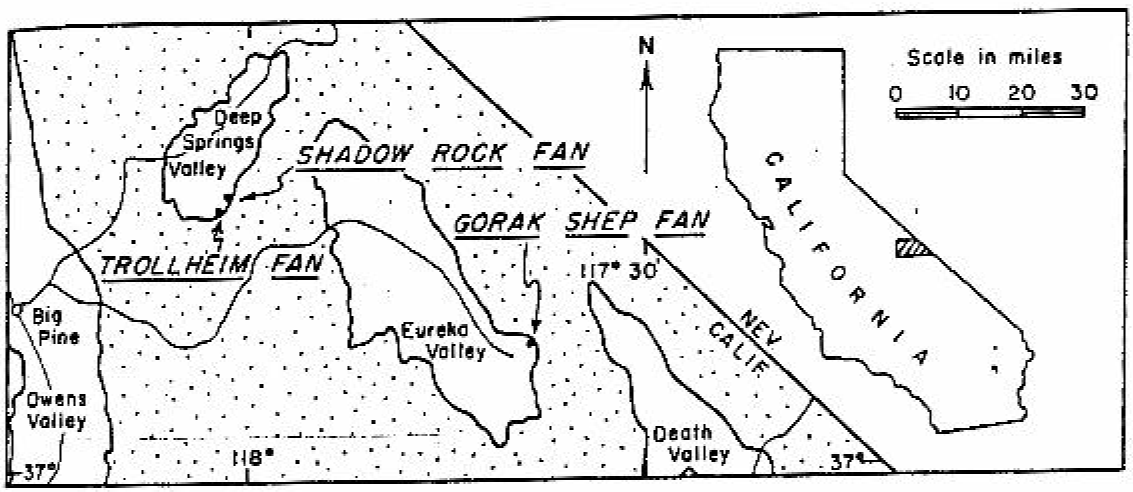

FIG. 1.—Index map showing locations of fans studied in detail. Exact locations are given in the Appendix

TABLE 1

UNITS MAPPED ON NATURAL FANS

Relative Age*	Gorak Shep Fan	Shadow Rock Fan	Trollheim Fan
1......	Recent channel deposits	Present channel	Present channel Overflow channel
2......	Overflow channel deposits	Terrace and/or older channel	Older channel material
3......	Oldest channel deposits	Oldest channel	Oldest channel material
4......	Youngest fan surface	Youngest fan surface	Younger fan surface
5......	Older fan surface	Older fan surface	Older fan surface
6......	Oldest fan material	Oldest fan surface	

* Correlations shown do not necessarily reflect absolute age.

channel material (table 1, unit 3) has been filled, but on Gorak Shep Fan it still has open pore space. The extreme is represented by Shadow Rock Fan, where open pore space occurs on the oldest fan surface. Because filling of the pore space promotes creep, older surfaces are generally smoother than channel bottoms, and desert pavements are commonly developed on them.

Additional weathering characteristics and topographic position were also used for distinguishing older units. For instance, on Gorak Shep Fan three units are identified by their positions in successively higher terraces near the fanhead. Terracing results from intermittent uplift on a fault (fig. 2). In contrast the three older units on Shadow Rock Fan are distinguished primarily by weathering phenomena. The first two of these units were identified by the relative darkness of desert varnish. In some places the contact was well defined, both on air photographs and on the ground, but elsewhere the age assignments were very subjective. Rocks in the oldest unit have an even darker desert-varnish coating. Furthermore, the unit occurs as low terraces and has a "softer texture" on air photographs. This textural difference probably results from vegetative differences, which in turn reflect the presence of additional secondary fines and thus greater weathering.

The relative age assignments of the three oldest units on Shadow Rock Fan are supported by the areal ratio of patches of fine detritus to areas of coarse material (fig. 3). Because the fines are secondary, older units should have proportionally more fine terial.

Weathering characteristics also prov a basis for distinguishing the two ol units on Trollheim Fan. Quartzite boul in the oldest unit have a distinctly da desert-varnish coating than those on younger fan surface, and many carbo boulders on the older surface have b reduced to crumbly fragments while th in the younger surface retain their orig form. The older surface is also smoot and supports a denser vegetation cover.

SEGMENTATION

Gorak Shep and Trollheim fans h segmented profiles (fig. 5). Bull (1964*b*) shown that segmentation may result fr tectonic disturbance of the fan-source s tem. For instance, uplift of the source ar or a decrease in fan slope by tilting, m cause a new fan to be built out over t head of the old fan.

On both Gorak Shep and Trollheim fa the segmentation is of this type; that the youngest segment has developed ne the fanhead, probably as a result of o of the above-mentioned causes. The co clusion that the upper segment is young in these two cases is based on: (1) appare overlapping of material in the lower se ment by that at the toe of the upper segme (pl. 1*E*), (2) weathering characteristics su gesting that the upper segment contai fresher material (esp. fig. 4), and (3) gradi of the main channel to the slope of the upp segment. In cases where a lower segment

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PLATE 1

Laboratory apparatus and natural fans.

A, Water source for laboratory apparatus.

B, Working area of laboratory apparatus. Letters and dashed lines are referred to in text.

C, Exposure of gravels on Gorak Shep Fan in southeast bank of main channel upstream from fault scarp Stratification is well defined. Void space in a lens of gravel (*arrow*) near the top of the bank has not yet bee filled with secondary fines. There is no evidence of debris-flow action.

D, Sieve deposition on Shadow Rock Fan. In this instance the hummocky topography results from siev deposition, but similar topography can be formed by debris-flow action. Note lighter color of more recen deposits to left of center.

E, Sieve deposition on Gorak Shep Fan. Note the bank in the foreground (*outlined*) emerging from beneat the sieve lobes. This bank is the "youngest fan surface material" in the vicinity of *P* on figure 2. *Arrow* fault scarp near fanhead (see fig. 2).

youngest, the upper segment is usually deeply incised, the channel being graded to a lower one (Bull, 1964*b*, p. 102 and fig. 66).

Although Trollheim Fan has four segments (fig. 5), Shadow Rock Fan, about a mile northeast of Trollheim, is apparently unsegmented. Both fans should have experienced the same tectonic history. The absence of segmentation on Shadow Rock Fan is attributed to the coarseness of material and importance of infiltration (sieve deposition) on this fan. Under these conditions fan slope appears to be less sensitive to tectonic influences.

MEASUREMENTS OF WEATHERING PHENOMENA

On Gorak Shep and Shadow Rock fans measurements were made that substantiate the age distinctions discussed above. On the latter, gradients of fronts of many sieve lobes (fig. 9) were measured, and steep slopes were found on a higher percentage of lobes in younger units (table 2). Because these lobes were probably deposited at or very near the angle of repose, and because the slopes would be expected to decrease with age due to creep, the data agree with age distinctions based on desert-varnish development.

On Gorak Shep Fan carbonate cobbles and boulders commonly contain quartz inclusions. Because quartz is more resistant to weathering than carbonate, quartz bands and knobs stand out in relief on more weathered rocks. Rocks showing such differential weathering were sought and the *maximum* relief measured. With the exception of one area where only ten such rocks could be found, between seventy and seventy-seven (usually seventy-five) measurements were made in each of the nine areas studied (table 3). Actual relief was not recorded, but measurements were put in class intervals, and a mean was calculated

TABLE 2

SLOPES OF SIEVE LOBES ON SHADOW ROCK FAN

Unit (See Fig. 6)	% of Slopes Greater than Indicated No. of Degrees		
	32°	30°	28°
Present channel	9	30	39
Terrace above present channel and older channel	7	22	34
Oldest channel	0	13	25
Youngest fan surface	3	5	19
Older fan surface	0	2	5
Oldest fan surface	*	*	*

* Data inconclusive.

PLATE 2

Laboratory fans. Scale in *B* is graduated in inches; those in *E–H* are in centimeters.

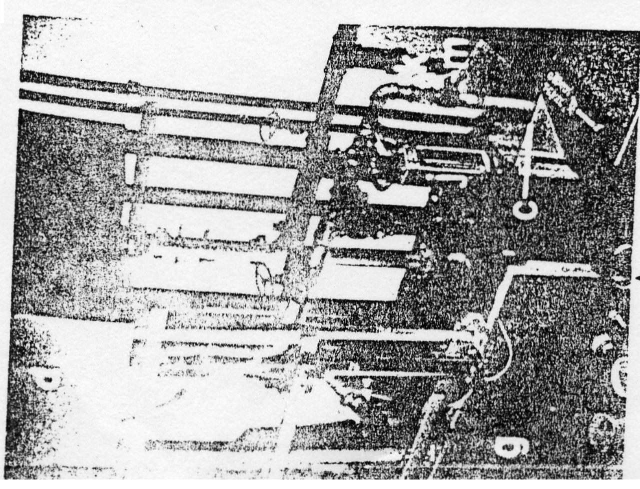
A, Sieve deposition on fan A-1 after eighth episode.

B, Fan B-1, built entirely with debris flows.

C and *D*, Fan B-2, channel after episode 17 (*C*) and debris flow of episode 18 that followed this channel (*D*). Note lobe of debris that left channel at bend.

E and *F*, Fan B-2, debris flow of episode 38 (*E*) is being eroded by flow in *F*. Note debris-flow levees in *E* and distributary flow pattern below intersection point in *F*.

G and *H*, Fan B-3 at or near end of episodes 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 level in *H*, and both fans are extensively braided, even near the fanhead.



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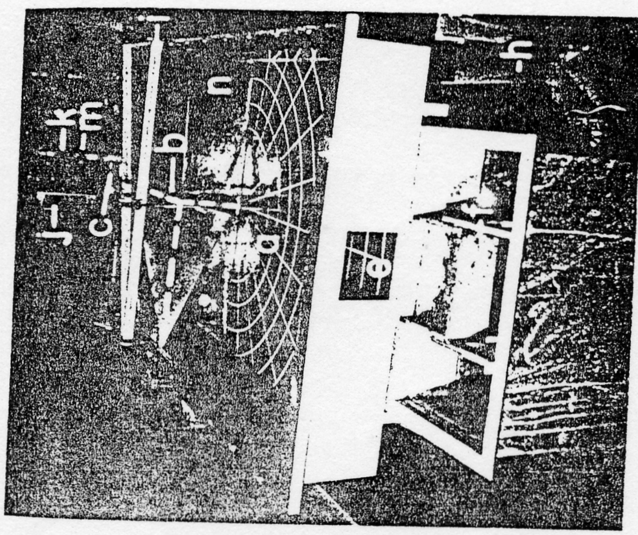

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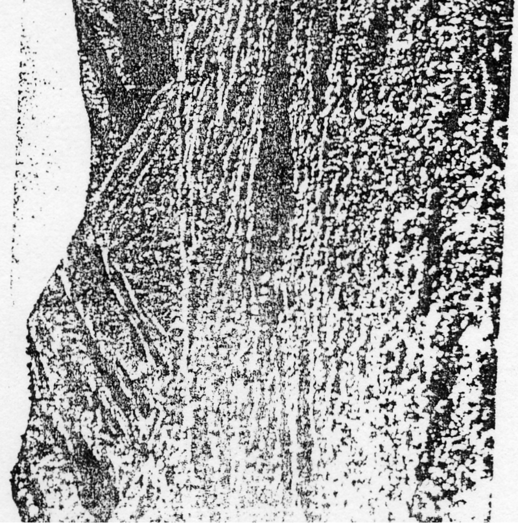

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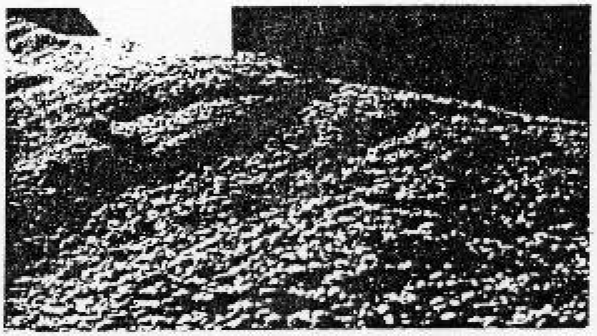

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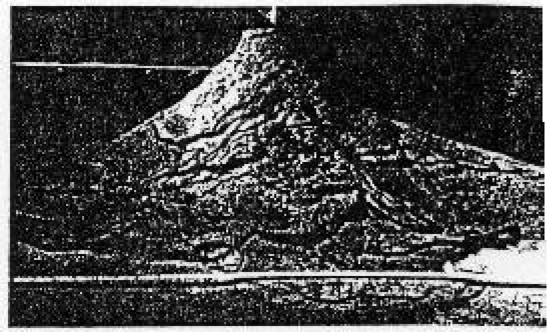

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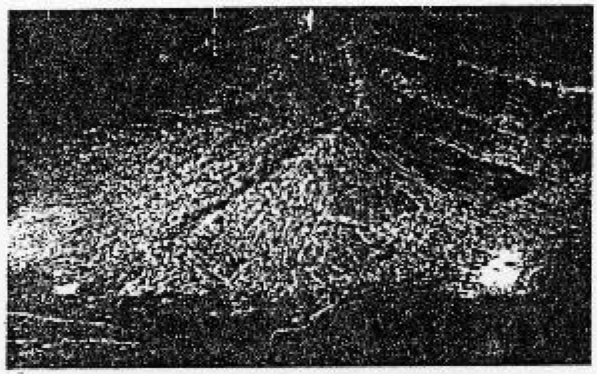

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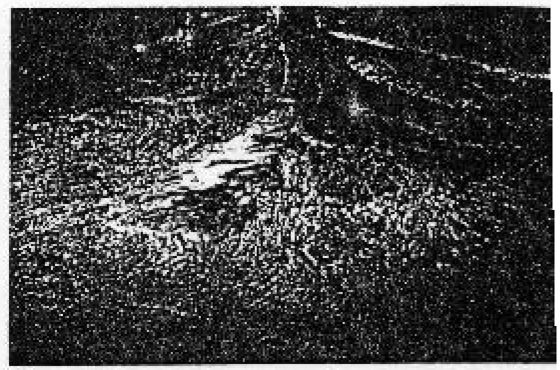

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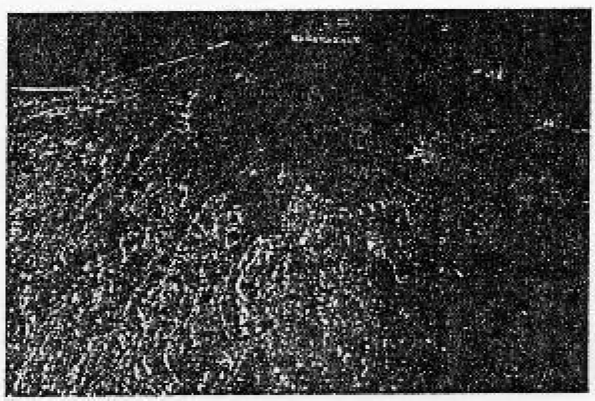

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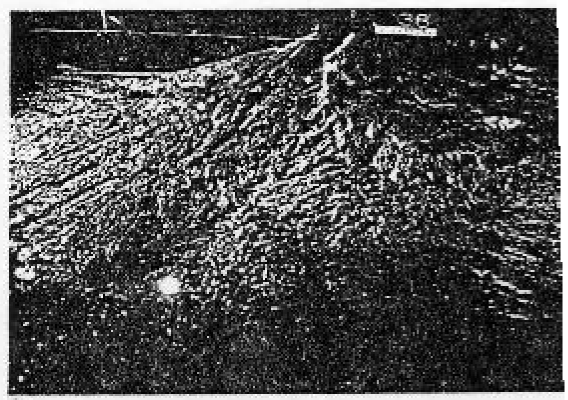

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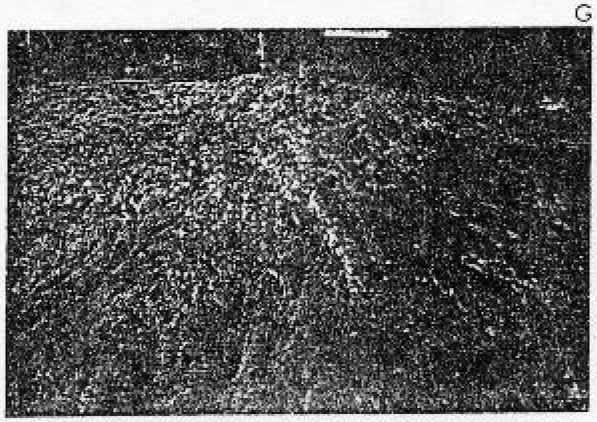

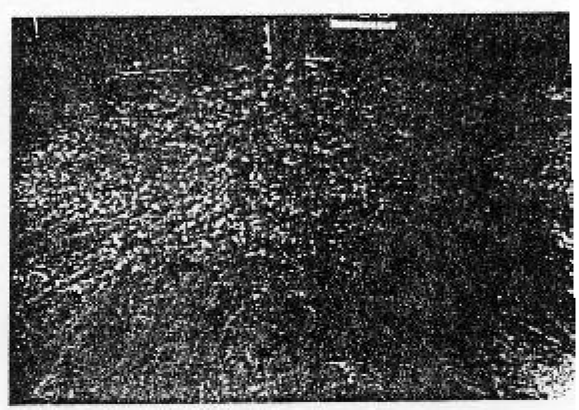

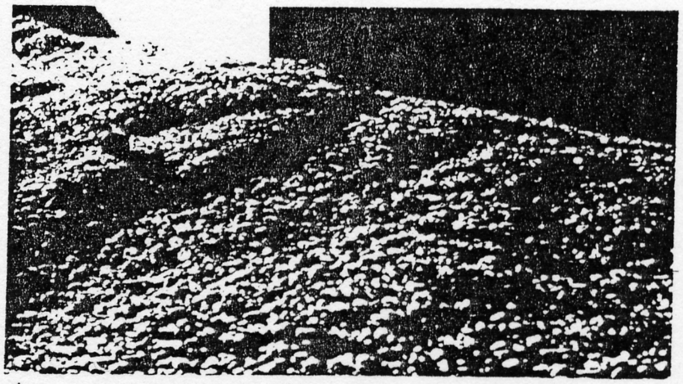

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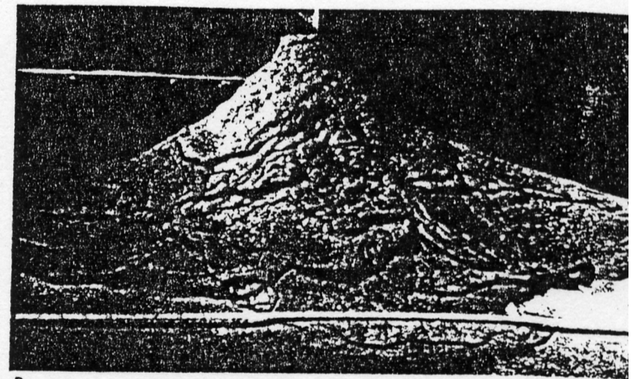

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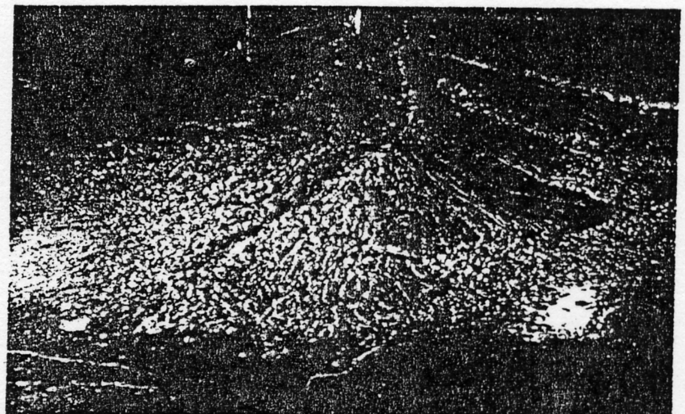

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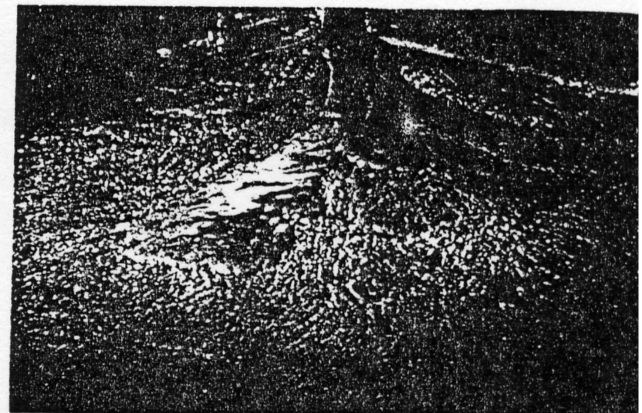

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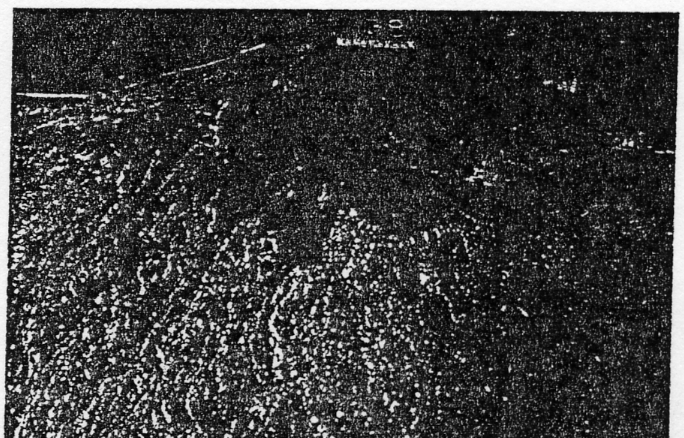

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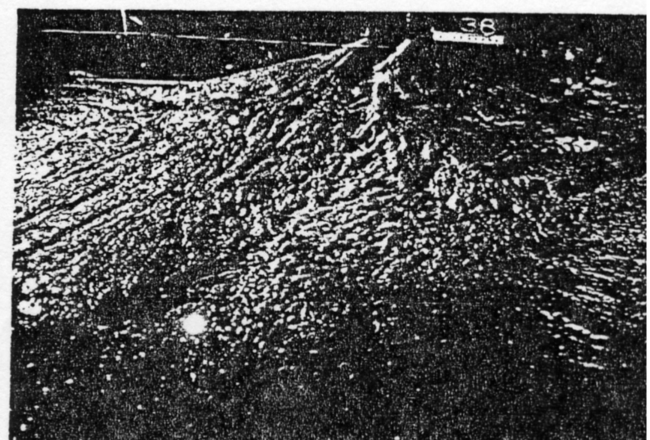

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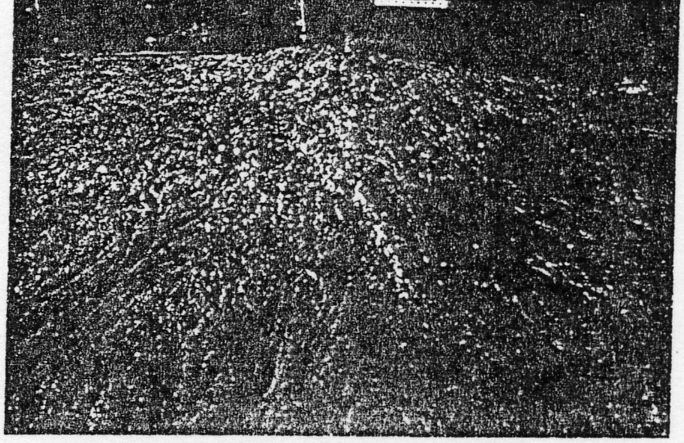

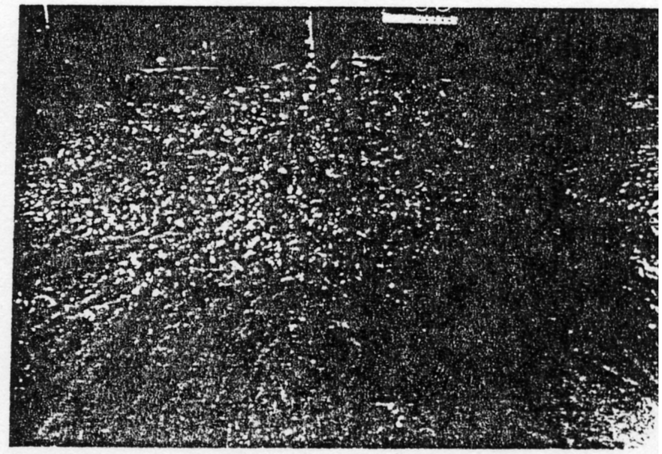

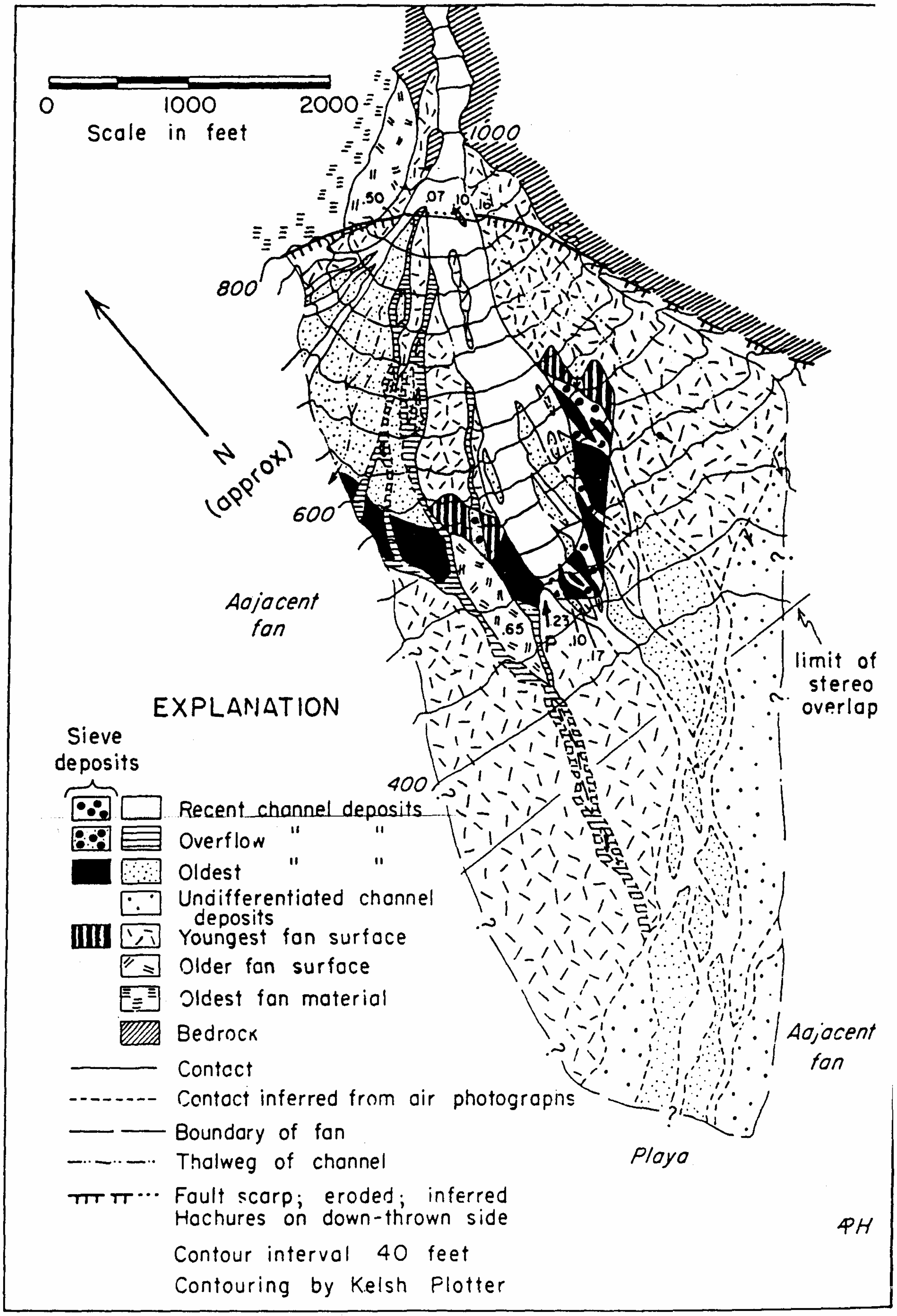

FIG. 2.—Map of Gorak Shep Fan constructed in the field on hazy, high-altitude air photographs. *P*, location of photograph in plate 1*E*. Numbers are discussed in text and table 3.

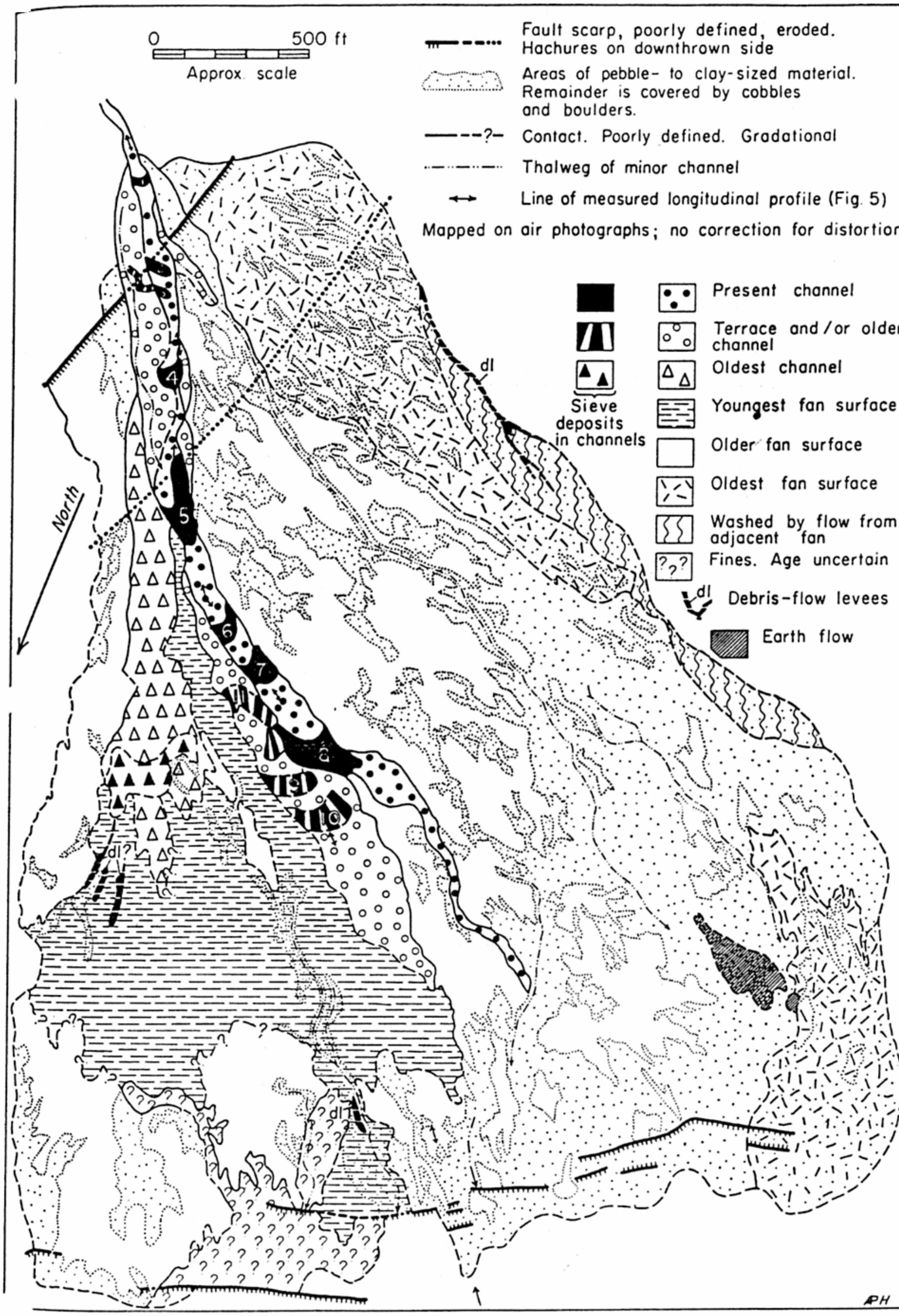

FIG. 3.—Geomorphic map of Shadow Rock Fan

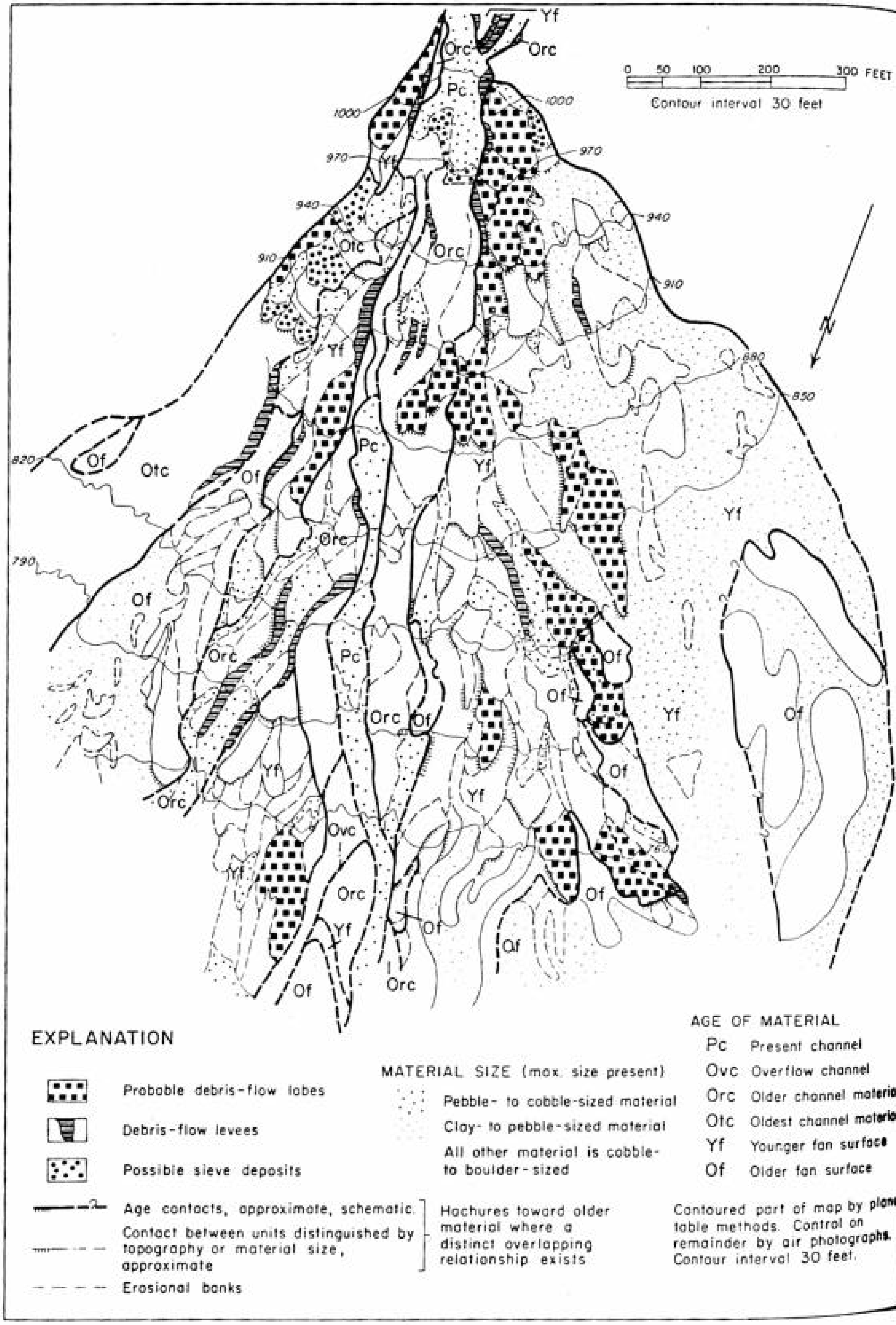

FIG. 4.—Geomorphic map of the upper (most recent) segment of Trollheim Fan. Relationship between younger and older fan surfaces reflects segmentation (fig. 5). Other contacts are based on material size and topographic (frequently lobate) form. Debris-flow and sieve deposits are tentatively identified using criteria described in the text. Identification of sieve lobes is much more tenuous than identification of debris-flow lobes. Where no distinction is made, deposits are either fluvial or are of much less certain origin.

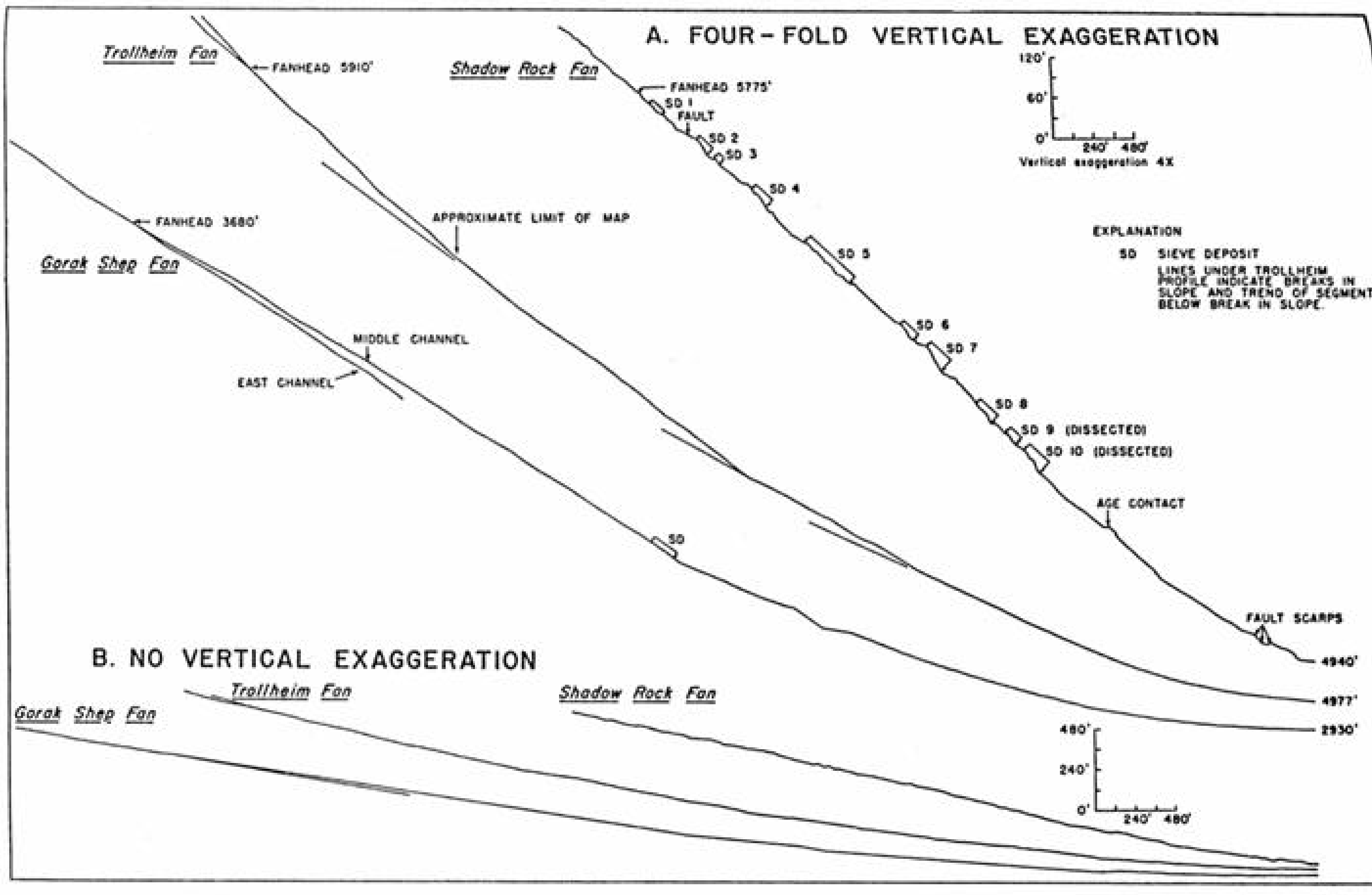

FIG. 5.—Longitudinal profiles of fans. Profiles were measured in the field with alidade and plane table. Lower limit of map of Trollheim Fan (fig. 4) is shown on Trollheim profile.

(table 3). Because the maximum relief was measured on each rock, the calculated mean of these values is referred to as a *mean-maximum* value. In general only rocks greater than 6 inches in diameter were measured, but this requirement was relaxed in small or relatively unweathered areas where suitable rocks were difficult to find.

Measurements on the upper segment were consistent with age relationships based on terracing and pore-space filling, the depth of differential weathering being progressively greater on successively older units. The good agreement between the two measurements on the youngest fan surface in this segment (0.16 and 0.17 inches) suggests that other differences, though small, are significant.

TABLE 3

MEAN-MAXIMUM DEPTH OF DIFFERENTIAL WEATHERING ON GORAK SHEP FAN

Map Unit (See Fig. 2)	Mean-Maximum Depth of Weathering (Inches)	
	Upper Segment	Lower Segment
Recent channel deposits.....	0.07	0.10
Oldest channel deposits.....	0.10*	0.17
Youngest fan surface.......	0.16 0.17†	0.23
Older fan surface...........	0.50	0.65

* Only ten rocks measured.

† Measurements on opposing members of a paired terrace.

Measurements on the lower segment are also consistent with mapped age relationships in this segment, but these units all appear to be older than those with which they are correlated on the upper segment. Because the upper segment is the youngest, this greater differential weathering is not surprising. Water crossing the upper segment has reworked and abraded material in the lower segment, but existing weathering relief on rocks was not completely smoothed during the reworking. Thus this older material retains some evidence of its greater age.

Correlation of the two areas of "older fan surface," one in the upper segment and the other in the lower, is based largely the data in table 3. The material o: age in the lower segment may be pari presegmentation fan surface.

CONCLUSION

From this discussion of age relation two points should be emphasized. because fans are surfaces of contii deposition on a geologic time scale, an distinction is arbitrary, and gradat relationships are common. Second, "age" of an area is not so much a me of the time since deposition as it is o time since the material was last subj to abrasion by water.

LABORATORY APPARATUS AND PROCEDI

Small alluvial fans were built of mud sand in the laboratory apparatus show plate 1. Water was pumped into constant-head tank, *d*, (pl. 1*A*), when flowed through a series of pipes and v: into the inlet box *c*. The channel *b* (pl. leading from the inlet box to the wor area, *a*, was 4 inches wide and 50 in long and had a slope of 0.16. Debris picked up in the channel and deposite a fan in the 5-foot × 5-foot working a Water left the working area through outlet gate *e*, and sediment trap, *f*, returned to the reservoir, *g*, below constant-head source by way of the re pipe, *h*.

The working area had a slope of 0.0076 toward the outlet. However, the instrument carriage, *i*, carrying a point gage, rode on horizontal rails. Thus all elevation measurements were made with respect to a horizontal datum plane. Discharge was measured with a Fischer and Porter flowrater meter, *j*, and was regulated with the plug valve, *k*. Discharges on the order of 0.002 and 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.

SERIES A

The first series of experiments comprised twelve ***runs***. Each run consisted of eight to twelve or thirteen ***episodes***. Each episode involved packing the channel, *b*, with a fixed amount of material, and then opening the fast-action valve for a fixed length of time, *D*, with the discharge, *Q*, determined by the setting of the plug valve. During each run *Q* and *D* were held constant. Following the eighth episode in each run a contour map of the resulting fan was made, and morphological features were mapped (fig. 6).

The quantity of material used in each episode was held constant for the entire series of runs and amounted to roughly 17 lb. dry weight. This debris was in the coarse-sand to granule range on the Wentworth scale and was poorly sorted (fig. 7).

SERIES B

Finer sediment (fig. 7) and lower discharges were used in Series B experiments. 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 eliminated undesirable effects caused by asymmetry of the earlier arrangement.

Series B consisted of three runs, each involving thirty-five 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 4). A small amount of dry sediment was added to the channel before most water flows. This provided material for transport by the water and for backfilling of the channel to keep it graded to the level of the rising fanhead.

Debris flows were made by mixing a slurry of water and sediment in a graduated can, from which it was easily poured into the channel just above the bulkhead. Flow density was determined by weighing the can containing the known volume of slurry. This method of determining the density was used during the last half of run B-2 and during run B-3. Earlier density measurements, made on volumes 5–10 $cm.^3$, are less reliable. The range in density of flows is given in table 4.

Viscosity measurements were made on two samples with a Stormer Viscometer (table 5). Owing to a finite yield strength, flowage did not occur at low applied stresses. 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.

SIMILARITY OF PROCESS ON LABORATORY AND NATURAL FANS

Laboratory fans were not intended to be scale models of a natural fan but are treated as small fans in their own right. However, gross scaling relationships between debris size and discharge should be met, and the general equivalence of slopes on laboratory and natural fans indicates that they have been. Laboratory-fan slopes were usually between 4° and 8°, values that are about average for natural fans with a high percentage of cobbles and boulders. Under conditions of sieve deposition, slopes ranged from 7° to 13°, in good agreement with average slopes on Gorak Shep (9°) and Shadow Rock (13.5°) fans in regions of sieve deposition (fig. 5).

The use of observations on laboratory fans as a basis for conclusions regarding natural fans requires further justification.

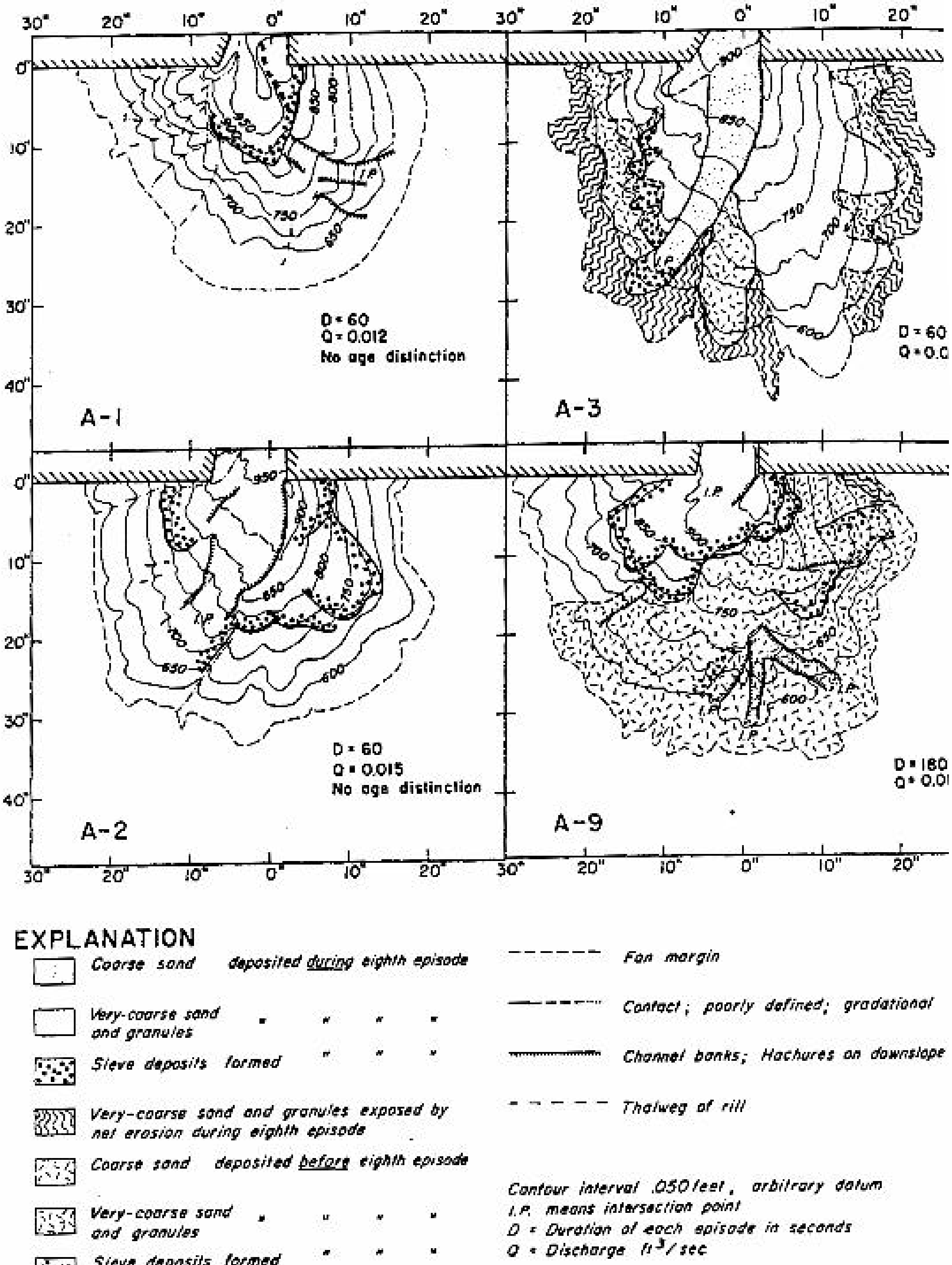

FIG. 6.—Maps of laboratory fans, Series A. Each map depicts a separate fan composed of materi cumulated during eight episodes of deposition. For any one fan each of the eight episodes had a fixe charge, Q, and lasted for a fixed length of time, D. For example, after the map of fan A-2 was draw working area (pl. 1B) was completely cleaned. A new fan, A-3, was then built, using eight episodes of 6 duration each and a discharge of 0.019 feet^3/sec. The fan surface prior to the eighth episode was identif a thin coat of spray paint. Erosion around the edge of the fan (e.g., A-3) is, in part, the result of float grains attached to a film of paint. In runs labeled "no age distinction" the surface was not painted pr the eighth episode.

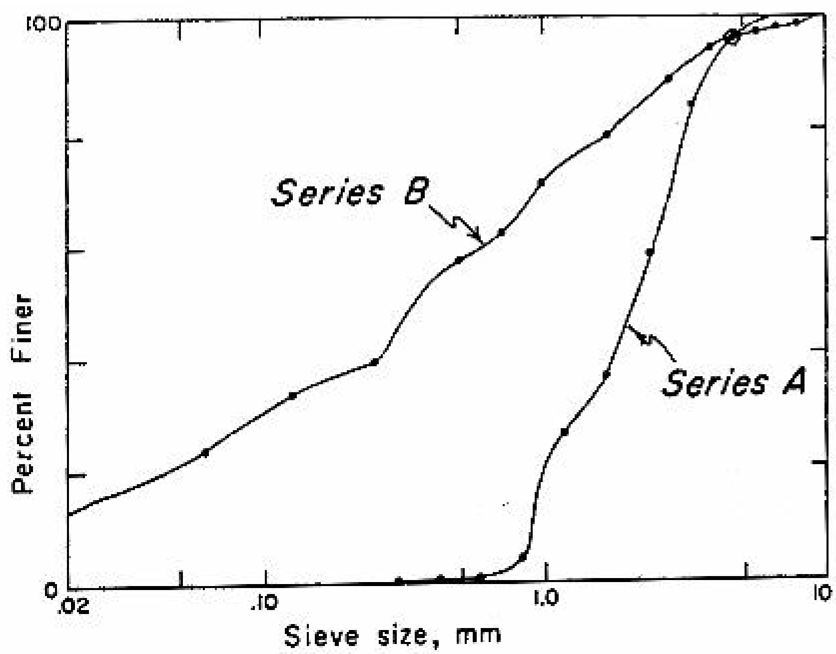

FIG. 7.—Size distribution of material used in the laboratory experiments

TABLE 4

RANGE OF VARIATION OF PARAMETERS BETWEEN EPISODES IN SERIES B

No. of Episodes	Debris-Flow Data		Water-Flow Data		
	Volume (Liters)	Density (Gm/Cm³)	Discharge (Cfs)	Duration (Minutes)	Amount of Dry Debris Added (Pounds)
	Run B-1				
35	0.5–4.0*	1.49–1.85	No water flow	No water flow	No water flow
	Run B-2				
43	0.5–1.5	1.52–1.69	0.002	2	1.5
	Run B-3				
66: 1–34	No debris flow	No debris flow	0.002–0.004	Usually 2 or 4; rarely 6 or 12	2.0
35–66	0.7–1.5	1.54–1.73	0.002–0.004	Usually 2 or 4; rarely 6 or 12	0.5

* Average 1.5 liters.

This procedure is based upon the postulate that processes in the laboratory are similar to those in nature and that the morphologic effects of these processes are the same on both laboratory and natural fans. The following laboratory examples of such processes and effects are followed, in parentheses, by a reference to a paper describing the same feature or characteristic in nature.

Runoff events during Series B usually began with a debris flow and ended with a water flow of substantially longer duration from the channel when the flow became de enough to overtop the banks (pl. 2*D*), a wide lobes formed below the intersecti point (Beaty, 1963, p. 520). When labor tory flows overtopped the channel ban without forming diverging lobes, leve were left as the flow receded (pl. 2*E* Contacts between fresh laboratory flows an the older fan surface were always sharp (p 2*B*, *D* and *E*), as in natural flows unmodifie by flood waters (Blackwelder, 1928, p. 47(Jahns, 1949, p. 13).

TABLE 5

RESULTS OF VISCOMETER TESTS

	Test 1	Test 2
Density, gm/cm^3	1.42	1.48
Viscosity at applied stress ≈ twice the yield strength, poises	0.42	0.92, 1.02*

* Viscosity increased during the test for unknown reason.

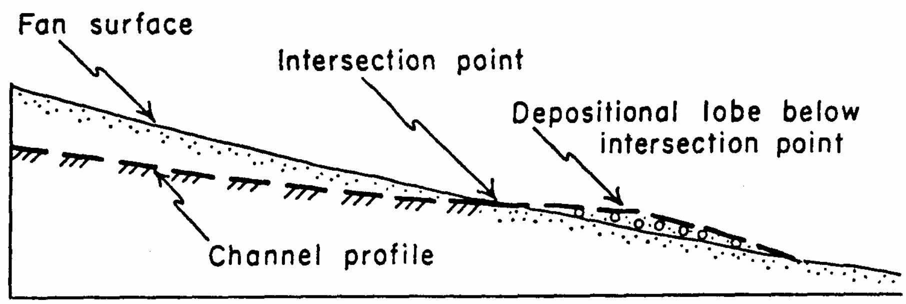

FIG. 8.—Idealized sketch of intersection-point relationships

(Pack, 1923, p. 355; Beaty, 1963, p. 520–521). The debris flows had steep, rounded fronts; deeper parts moved faster than shallow parts, and surges moved more rapidly than the front (Jahns, 1949, p. 12–13). Fresh flows were remobilized by subsequent surges if insufficient drying time was allowed (Sharp and Nobles, 1953, p. 551). If the front was not remobilized, the surges caused small pressure ridges to develop parallel to the flow borders (Jahns, 1949, p. 13). The main body of laboratory flows followed the existing main channel (pl. 2*C* and *D*), but small lobes diverged

The main channel on laboratory fans had a slope less than the slope of the adjacent fan surface and thus merged with the surface at a point commonly near midfan and herein called the ***intersection point*** (fig. 8). Material deposited here is generally coarser than the average material found in the channel and in some instances forms a small secondary fan on the surface below the intersection point. Sometimes several small channels head in this deposit (pl. 2*F*). Diversion of the main channel was often caused by plugging with debris-flow material (pl. 2*C*–*E*), and channels disappear beneath such deposits upstream (fig. 6, runs A-1 and A-9) (Beaty, 1963, p. 527–528). Abandoned main channels were also observed to end upstream at the banks of deeper channels. These channel patterns are all common in nature.

In several instances laboratory study has been used as a basis for interpretation of field observations. The agreement of laboratory and field data in these cases is further support for similarity of process. The best examples of such agreement are found in the ensuing discussions of sieve deposition and fanhead incision and in the dependence of fan slope upon discharge, debris caliber, and depositional process (Roger LeB. Hooke, manuscript in preparation).

DEBRIS FLOWS AND FLUVIAL PROCESSES

MECHANICS OF SEDIMENT TRANSPORT

Early workers (Gilbert, 1882, p. 183–184; Trowbridge, 1911, p. 738–744) assumed that fans were built by running water alone. The importance of debris flows was not widely recognized prior to Blackwelder's (1928) discussion of this process. Since then knowledge of sediment transport has increased to the point where some differences between water and debris flows can be discussed.

Natural debris flows may have viscosities of over 1,000 poise and densities of 2.0 to 2.4 (Sharp and Nobles, 1953, p. 552–553). 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, the response of water to an applied stress, τ, can be represented by

$$\tau = (\mu + \eta)\,\frac{du}{dy},$$

where du/dy is the rate of shear in turbulent flow and μ and η are the molecular and eddy viscosities, respectively. The eddy viscosity generally *increases* with rate of shear, but the molecular viscosity is constant (Rouse, 1950, p. 88). In contrast, debris flows behave as quasi-plastic substances, and their rate of deformation under stress is represented by

$$(\tau - \tau_0) = \mu(\tau)\,\frac{du}{dy}, \qquad \tau \geq \tau_0,$$

where τ_0 is the yield strength, and $\mu(\tau)$ indicates that the apparent viscosity, μ, is a function of the applied stress (Leopold, Wolman, and Miller, 1964, p. 31). No flow occurs until the yield strength is exceeded, but then the viscosity *decreases* gradually with increasing applied stress until a constant value is reached. The value of τ_0 and the form of the function $\mu(\tau)$ differ among flows, owing to differences in flow density and in mineralogy of the silt-clay fraction. This is the behavior observed in laboratory debris flows, but natural flows are probably not fundamentally 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 per cent, relative to its submerged weight in water, and bed shear forces are increased. Furthermore, the combination of the low-density contrast between rocks and mud and the 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 the settling velocity of the sediment and net upward transport of material by turbulent eddies (Vanoni, 1963). With the reduced settling velocity in debris flows, coarser material can be maintained in suspension. Dispersive pressure forces (Bagnold, 1954, 1955) may also keep material in suspension in debris flows with high concentrations of pebbles to boulders.

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 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 streams and debris flows.

FIELD CRITERIA USED TO RECOGNIZE DEBRIS-FLOW DEPOSITS

Debris-flow deposits consist of cobbles and boulders imbedded in a matrix of fine material. They are generally poorly sorted, and individual flows are unstratified. Recent debris flows have flat tops, steep sides, and a lobate form. The base makes an abrupt contact with underlying material. Rain and rill erosion, creep, and weathering eventually modify this distinctive morphology and internal character. Cobble and boulder accumulations with low relief are commonly the only remaining evidence, but their position as levees along channels or as lobes diverging from channels usually leaves little doubt as to their origin, especially after debris-flow behavior is seen in the laboratory.

EFFECTS OF DEBRIS FLOWS ON FAN MORPHOLOGY

Transportation of coarse material and levee formation.—One characteristic feature of many alluvial fans is a large number of cobbles and boulders. The occurrence of this material in levees and lobes and its association with material of recognizable debris-flow origin suggest that much of it is transported to the fan by debris flows.

Coarse material frequently accumulates at the front of a debris flow and is shoved aside by the advancing snout, forming levees that confine the remainder of the flow (Sharp, 1942, p. 225). The bouldery, sharp-crested levees common on many fans were probably formed in this way.

Levees also form when a debris flow at peak discharge overflows channel banks. Levees of this type were observed on laboratory fans (pl. 1*E*) and on debris flows on Surprise Canyon Fan in Panamint Valley, California. Such levees are generally wider and have more rounded crests than tho described by Sharp,

A distinct sorting of stones, with pebbl on the inside (toward the flow) and coars material on the outside, was observed c several natural debris-flow levees. Th sorting probably does not result from sele tive deposition of coarser material by slow flow because the size difference is not larg and the coarser material is probably nc heavy enough to be dropped independentl of the main body of the flow. Instead, coar er material may selectively migrate to th surface. Either the higher surface velocit or the sliding and rolling processes describe by Sharp (1942, p. 225) then move it to th front and edges of the flow, where it i deposited when the edges stop moving.

Radial variations in alluvial-fan stratig raphy.—Because mud has a finite yielc strength, debris flows stop when the shea stress on the bed, τ_0, no longer exceeds th yield strength of the mud, τ_c, or

$$\tau_0 = \rho g d S < \tau_c ,$$

where g is the gravitational acceleration and ρ, d, and S are the density, depth, and hydraulic gradient of the flow, respectively. Laboratory observations suggest that this condition may result from a loss of water to the underlying dry fan material, thus increasing the yield strength, or from a decrease in either the hydraulic gradient ($\approx$ fan slope), or flow depth, as the flow moves down fan and spreads out. Thus the areal extent of a debris flow is limited by its volume and yield strength and by the slope of the fan surface. Furthermore, its downfan extent is determined in large part by the degree to which existing channels prevent lateral spreading at the fanhead.

Consequently, most deposition near the toe of fans is probably not by debris flows but by running water, although the material deposited may have been eroded from debris-flow deposits higher on the fan. In contrast, much of the deposition near the fanhead is probably caused by debris flows overtopping the channel banks. Thus the stratigraphy of fans on which debris-flow deposition has been important should be inhomogeneous; debris-flow deposits nearer the fanhead should interfinger in the midfan region with water-sorted material deposited nearer the toe. This variation was observed on laboratory fans B-2 and B-3.

Natural radial inhomogeneity was observed in the Pliocene Ridge Basin Group (Crowell, 1954), a dissected alluvial-fan basin filling about 75 miles north of Los Angeles. The unit nearest the source area, the Violin Breccia (Crowell, 1954), is an unbedded to poorly bedded cobble and boulder conglomerate with a matrix of sand- to clay-sized material. This unit is probably of debris-flow origin. Outward from the source area it grades into fluvially bedded conglomerate with smaller clasts, thence into well-bedded, rarely cross-bedded, sandstone with interbedded shale, and finally into shale. The conglomeratic rocks interfinger with the sandstone, and the sandstone with the shale, as observed on laboratory fans. The shale is near the center of the basin, about 4 miles from the source, and presumably represents playa deposition.

RELATIVE SIGNIFICANCE OF DEBRIS FLOWS AND WATER FLOWS

As Blackwelder (1928, p. 473–474) observed, the proportion of recognizable debris-flow material in and on fans varies widely. Shadow Rock and Gorak Shep fans (figs. 2 and 3) have practically no recognizable debris-flow deposits, but Trollheim Fan (fig. 4), about a mile south of Shadow Rock Fan, consists predominantly of debris-flow material. These differences appear to be lithologically controlled. The source area of Gorak Shep Fan is underlain by resistant carbonate rocks, and valley-side slopes are steep. Thus material is quickly transported to the fan with little pretransport weathering. As a result there is little fine material in the source area, and debris-flow formation is inhibited. Similarly, the drainage area of Shadow Rock Fan is underlain predominantly by resistant quartzite of the Campito Formation (Nelson, 1966), and fine material is again lacking. In contrast, exposures of readily weathered sandy dolomite of the Reed Formation (Nelson, 1966) in the source area of Trollheim Fan contribute substantial amounts of fine material and are thought to be responsible for debris-flow deposition on this fan. Climatic and topographic factors do not vary significantly between Trollheim and Shadow Rock fans and hence are unlikely to be responsible for the differences in mode of deposition.

Volumetric estimates of the role of debris flows in transporting material to a fan are difficult to make. Characteristically heterogeneous debris-flow deposits are commonly sorted and stratified by subsequent water flows. This may be partially responsible for the lower percentage of debris-flow material recognized by Blissenbach (1954, p. 179) on fans in areas of higher precipitation. Furthermore, the best exposures of fan stratigraphy are usually in the main channel above the intersection point. Because debris-flow deposition is likely to be more common near the fanhead, estimates may be biased in its favor.

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; Bull, 1964*a*, p. 17). However, Bull (1964*b*, p. 104) has shown that water on some fans composed of fine material does not percolate below the root zone of vegetation.

Laboratory observations suggest that permanent features attributable to infiltration will not be found on fans unless moderately large water flows infiltrate completely before reaching the toe of the fan. Surficial wetting of dry fan material may cause deposition during small flows or in the initial stages of large flows, but the amount of such deposition is small, and any features produced will be minor and will be destroyed by subsequent higher discharges.

However, if the fan material is sufficiently coarse and permeable, as in laboratory fans of Series A (fig. 7), the entire flow may infiltrate before reaching the toe of the fan. Under these conditions a lobe of debris is deposited at the point where water is unable to effect further transport. Because water passes through rather than over such deposits, they act as strainers or sieves by permitting water to pass while holding back the coarse material in transport. I call the lobate masses thus formed "sieve lobes" or "sieve deposits," and the mode of formation is sieve deposition.

Extensive deposits inferred to have been formed in this way were found on seven natural fans. Four are in the southeast corner of Deep Springs Valley, California, one of which, Shadow Rock Fan (fig. 3; pl. 1*D*), has been mapped in detail. Two others, including Gorak Shep Fan (fig. 2; pl. 1*E*), are in the southeast corner of Eureka Valley, California. The last is about 2,800 feet N. 16° E. of Badwater in Death Valley.

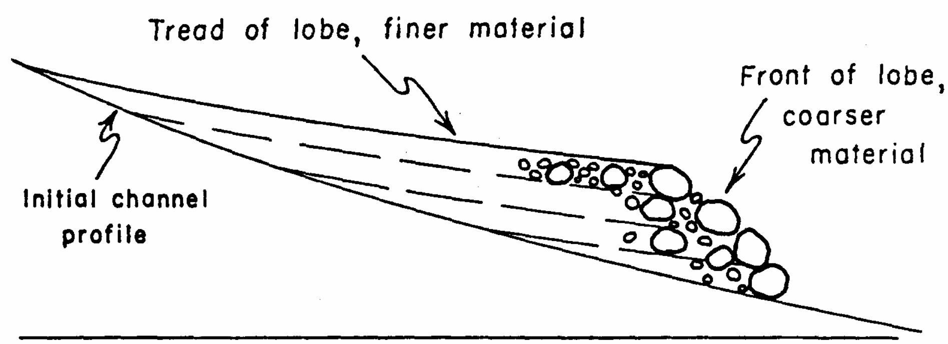

FIG. 9.—Schematic sketch of growth of a sieve lobe

LABORATORY OBSERVATIONS

On laboratory fans, sieve deposition is initiated by deposition of granules which form an initial debris barrier. The channel slope immediately upstream from this barrier is reduced by backfilling (fig. 9), and further deposition ensues. Deposition does not actually occur in layers as represented in figure 9, 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 just up fan from the preceding one.

Deposition of coarser material along the lateral edges of a lobe, where competence is reduced, may confine the flow temporarily. However, lateral shifting of the flow, a decrease in infiltration as fine material is deposited upstream, or a slight increase in discharge can result in diversion of the flow over the lobe's flanks or front. In such cases rapid erosion ensues, and a fluidized debris mass shoots down fan a few centimeters and stops. Backfilling behind the mass proceeds until this part of the lobe is built up to the elevation of the remainder.

Sieve deposition occurred both near midfan and at the toe of laboratory fans. In the first case, initial deposition resulted from infiltration, and the infiltrating water continued as subsurface flow until it encountered the impermeable bed of the laboratory apparatus and emerged around the toe of the fan. In the second case deposition was instigated by the break in slope at the toe of the fan, and water passing through a lobe emerged immediately below it.

The radial position of sieve lobes on laboratory fans was controlled by a balance between discharge and infiltration rate. For instance, with decreasing discharge and increasing fan thickness (increasing infiltration rate) the deposits on fans in figure 6 are found progressively nearer the fanhead. Note also on fan A-3 that the sieve lobe at the end of the main channel is farther down fan than the lobes deposited earlier during the same episode. This is because the infiltration rate was decreased by deposition of fines near the end of the episode.

In summary, sieve deposition on laboratory fans is a consequence of the coarseness of material and resulting high infiltration rate. Sieve deposition may be initiated either by complete loss of discharge through infiltration, as is the case for sieve deposition near midfan, or by a break in slope, as at the toe of laboratory fans. Sieve deposition on natural fans is a result of the same factors, as the subsequent discussion of two examples will demonstrate.

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 (Nelson, 1966). This rock is resistant to weathering as evidenced by a dark desert varnish on rocks on older parts of the fan and by the paucity of fine material in both recent and older deposits (fig. 3). Consequently infiltration rates are high in the older deposits as well as in recent sieve lobes, and sieve deposition can occur anywhere on the fan (fig. 5). The location of a given sieve lobe is determined by the size of discharge; larger discharges continue farther down fan before loss of water is sufficient to cause 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. 3), as it does below the sieve deposits on Gorak Shep Fan (fig. 2).

In this situation sieve lobes formed by low discharges are commonly modified by subsequent higher flows. Modification involves dissection of the original deposit, which is usually as wide as the channel that formed it, leaving several small disconnected lobes. For instance, deposits 5 and 6 on Shadow Rock Fan (fig. 3) apparently were dissected during construction of deposit 7, whereas lobes 1–4 are relatively unaltered and thus postdate 7. Modification of lobes is an important process, as unmodified deposits are rare on older parts of the fan surface.

SIEVE DEPOSITION ON GORAK SHEP FAN

Sieve deposition on Gorak Shep Fan occurs at the down-fan limit of the upper segment (figs. 2 and 5). Since the upper segment is youngest, its slope is the steady-state slope of the fan under present conditions. The decrease in competence at the break in slope between the two segments presumably causes deposition and is believed to be responsible for the existing sieve deposits.

The source area of Gorak Shep Fan is underlain by a thick section of resistant early Paleozoic (?) carbonate rocks, primarily dolomite. Slopes are steep, have virtually no soil cover, and supply the fan with pebble- and cobble-sized debris, with a minimum of fines. On the other hand, older deposits on the fan have a matrix of sand- to clay-sized particles produced by postdepositional weathering. The individual pebbles appear to be in contact with their neighbors (pl. 1*C*) and would not need to readjust and settle if the fines were removed. Furthermore, a few layers of coarse-pebble gravel with unfilled pore space were observed in vertical exposures of the "youngest fan surface" material (pl. 1*C*). In at least three instances (pl. 1*C*) such layers are overlain by granule-sized material in which the void space is filled. These relationships suggest that the fines are secondary and that they were trapped by the granule layer during illuviation.

Because recent channel deposits rest on older material in which the void space is filled, infiltration alone is not sufficient to instigate sieve deposition. A break in slope, as at the toe of laboratory fans, is also necessary. Water passing through sieve deposits on Gorak Shep Fan emerges below them and continues down fan as surface runoff, as the extensive channel development on the lower segment indicates (fig. 2). Thus sieve deposition on Gorak Shep Fan occurs in a restricted zone, in contrast to the ubiquitous occurrence of such deposits on Shadow Rock Fan. This contrast reflects the coarser debris and much greater resistance to weathering of the quartzite on Shadow Rock Fan, where older deposits still have open pore space.

DISTINGUISHING BETWEEN DEBRIS-FLOW AND SIEVE DEPOSITS

Both sieve and debris-flow deposition may take place on the same fan. However, for debris flows to form, substantial amounts of fine material must be present in the source area. Conversely sieve deposition cannot occur if too much fine material is available. Therefore, one process usually predominates, and conclusive evidence that one is significant usually implies that the other is much less important. For instance, Shadow Rock Fan is predominantly composed of sieve deposits, but four linear ridges (fig. 3) are probably debris-flow levees, possibly built by flows originating on the fan. A fifth levee, the long, branched one on the south side of the fan, was apparently built by a debris flow originating in the dolomitic terrane between Shadow Rock Fan and the fan to the southwest. Similarly there are lobes of material among the debris flows of Trollheim Fan that have been mapped as possible sieve deposits (fig. 4).

Distinguishing between materials deposited by these two processes after they have been modified by erosion and downslope movements is not easy. Only a few of the units mapped on Trollheim Fan could be identified with any confidence. The following criteria were developed through comparison of the deposits on Trollheim Fan with each other and with those on Shadow Rock Fan:

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.

2. Sieve deposits rarely contain the especially large boulders (> 3-foot diameter) found in many debris flows.

3. Relatively unmodified debris flows on Trollheim Fan are 2–10 feet thick and several times as wide. In contrast, the fronts of sieve deposits on Shadow Rock Fan are commonly 10–30 feet high, but, owing to dissection, their treads are usually narrow and rounded in cross-section.

4. Contacts between debris flows and the underlying material are usually sharp and well defined, and flows appear to overlap the older deposits. Contacts between sieve deposits and underlying material are generally gradational and rarely give the impression of an overlapping relationship.

5. Debris flows can generally be traced some distance up fan and have a slope approximately equal to the fan slope, whereas sieve lobes typically have short treads with slopes less than the fan slope (figs. 5 and 9).

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

7. Fresh sieve deposits are clearly related to a channel from the fanhead, but fresh debris flows may not be related to any visible channel.

CHANNELS AND DEPOSITION ON ALLUVIAL FANS

Over short periods of time, deposition on both laboratory and natural fans is localized (figs. 2–4 and 6). However, shifting of the locus of deposition on laboratory fans results in relatively uniform deposition over the entire fan surface, and deposition on unsegmented natural fans is probably also uniform if the time scale involved is sufficiently long. On segmented fans, deposition can be considered uniform only on the active segment.

If long-term deposition occurs uniformly over the entire fan, whereas short-term deposition is localized, then periodically debris must be transported across upper parts of the fan and deposited at points more distant from the source area. Such transportation is accomplished primarily by flows in channels. This interpretation explains the apparent contradiction of a depositional fan whose most obvious surficial features are channels, a fact also recognized by Tolman (1909, p. 157), and provides a framework within which to discuss deposition.

POSITION OF THE INTERSECTION POINT

The intersection point on laboratory fans is commonly near midfan. This appears to be because fluvial deposition predominates near the toe and occurs without down-fan migration of the intersection point, while overbank debris-flow deposition predominates near the fanhead. Thus 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 a fan. Measurements on laboratory fan B-3 support this conclusion. The average distance of the intersection point from the fanhead during the first thirty-four episodes, during which water flows alone were used, was 19 cm., and the average for the remaining thirty-two episodes, each of which began with a debris flow, was 41 cm. The fan radius was about 80 cm. This difference is obvious in plate 2*C* and *H*.

The situation on natural fans is complicated by segmentation, and no general statement is possible without more detailed study of the relationship between segment boundaries and the intersection point. On fans on which the most recent segment includes the fanhead (figs. 2 and 4, and east side of southern Death Valley), the intersection point is often nearer the lower boundary of the segment than might be expected from laboratory observations. This apparently reflects the ability of water flows to transport substantial volumes of debris across the gentler slopes of lower segments. Thus lower segments must be aggrading, but more slowly than the upper segment.

The intersection point on laboratory fans shifted gradually due to debris-flow and fluvial deposition. The intersection point would migrate up fan as low banks of the main channel were buried. Subsequent water flows then eroded a new channel offset laterally from the previous course. Similar processes have been described by Eckis (1928, p. 234–235) and Bull (1964*a*, p. 27–28) from observations during waterfloods on natural fans. Such shifting is necessary for uniform deposition.

Diversion of the main channel near the fanhead helps distribute debris-flow material over upper parts of the fan and also results in a rapid shift of the intersection point. Remnants of older channels from which the flow has been diverted (figs. 3 and 4) testify to the importance of this process. Beaty (1963, p. 527–528) has discussed some common causes of diversion.

FANHEAD INCISION

In this report a fanhead is 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 the areas investigated the discharges so calculated are totally unreasonable in terms of the area and hydrologic characteristics of the drainage basins. For example, a discharge of approximately 33,000 cfs would be required for overbank flooding on Gorak Shep Fan, which is incised about 4 feet and has a drainage area of less than 1 sq. mile. Using this definition, a wide or steep channel, such as that on Gorak Shep Fan, need not be especially deep to be incised.

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 (e.g., Lustig, 1965, p. 171). Observations on laboratory fans suggest that incision can be the natural result of an alternation of debris flows and water flows (pl. 2*E* and *F*) and that fanheads are, so to speak, "born incised." This idea was first suggested to the author by David Schleicher. Owing to the high viscosity and finite yield strength of debris flows, the hydraulic gradient required for their movement is greater than that required by water for transport of much of the finer material in them. 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. 470) on a debris flow in Utah. Pack (1923, p. 355) reports that "in places the debris deposited by the preceding mudflows was incised sufficiently to permit the water to flow . . . 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 exceed the channel depth and deposit broad sheets of material on the fan surface above the intersection point. This occurred repeatedly on laboratory fans. Such overbank deposition need not result in diversion of subsequent water flows, as once the peak discharge has passed, the level of flow commonly receds, and water tends to follow the original course (pl. 2*E* and *F*).

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 prevailing discharge and sediment-caliber conditions. Incision due to this process alone lasts only until the low area is built to the level of the rest of the fan. On natural fans headward erosion and capture of the main channel by channels heading on the fan (Denny, 1965, p. 16, 38) may result in this kind of incision.

The depth of incision produced in these ways, and uninfluenced by any other factors, may be 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, resulting in segmentation. Climatic change and tectonic movement are two common causes of such disturbance (Bull, 1964*b*, p. 100–113). Abnormally deep fanhead incision is not so 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 exa have been deeply incised as a result of ward tilting of the valley.

Depth of normal fanhead incision.— ratory run B-3 was designed to stud tors affecting the depth of normal fa incision. It was already clear from results of run B-1 (pl. 2*B*) that no in would occur on laboratory fans buil tirely by debris flows with no interveni subsequent water flows. During the half of run B-3 only water flows were The main channel was incised (i.e., de than bank-full flow) at the end of onl out of the first twenty-six episodes (fig pl. 2*G* and *H*). In five of these episodes 18, 20–22) the flow had just shifted part of the fan that had not received de for several episodes, and incision was to the steeper slope toward these areas described above. The same explana probably holds for incision following epis 26, but the cause was not as clear in instance.

The duration of water flow was increa three times during these first twenty episodes, but simultaneous changes in depth of the channel were not observ Furthermore, the flow at the end of e sodes 19 and 25 was clear, rather th muddy, and sediment transport was sm This suggests that the flow was unable transport the material armoring the chan bed and thus could not erode the channel a lower slope. Thus the absence of incisi cannot be attributed to lack of sufficie time for erosion.

Following the twenty-sixth episode t discharge was doubled. As a result, t slope of transportation was decreased a the fan regraded. This accounts for t incision observed at the end of episodes 2 29, 32, and 33 (fig. 10) and for the relative constant elevation of the fanhead duri these episodes. During episodes 30, 31, a 34 the fan was already regraded in t direction of flow, and the channel was longer incised. Shifting of the flow to steeper part of the fan accounts for t incision during episodes 32 and 33.

Starting with 35, each episode began wi

a debris flow and was followed by a water flow that was carrying sediment. The rapid increase in depth of incision and in elevation of the fanhead are clearly shown in figure 10. During episodes 35–47 the steady-state depth of incision was approximately 0.090 feet. When deposition in the channel caused the depth of incision to drop 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. 10).

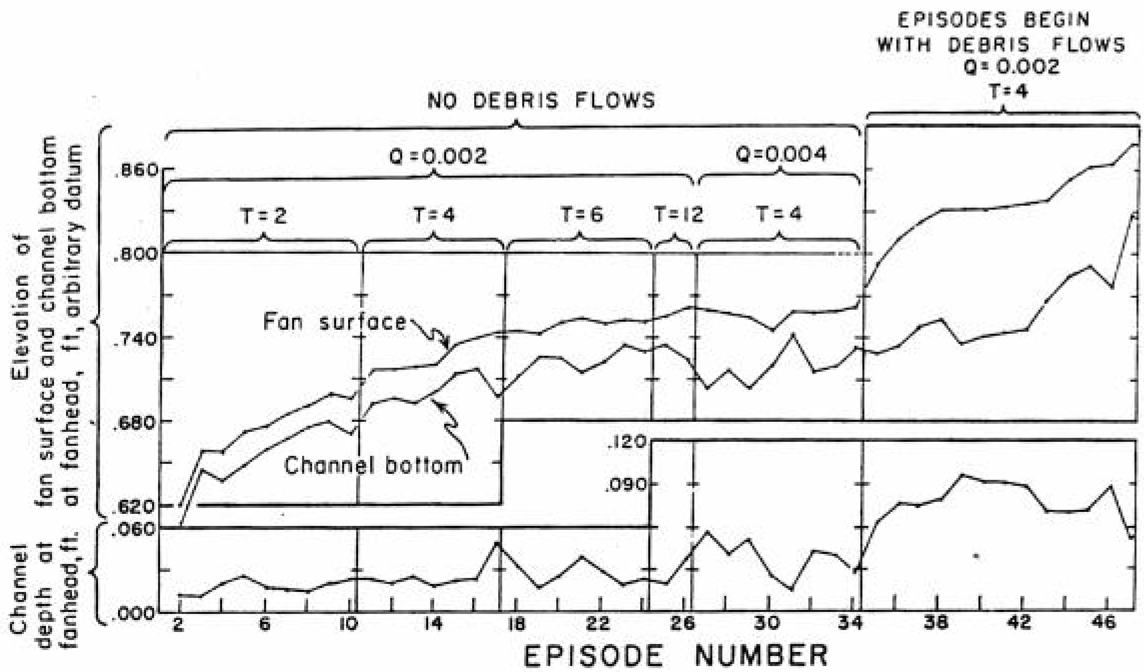

FIG. 10.—Changes in fanhead elevation and depth of incision during laboratory run B-3. T is the duration of water flows in minutes, and Q is the water discharge in cubic feet per second.

The depth of incision is 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 then elsewhere on the fan, the depth of incision should increase until depositional rates are again equal.

As a result of this laboratory study, it is inferred that the primary factor affecting the depth of *normal* incision on natural fans with a significant amount of debris-flow deposition is the magnitude of debris flows. 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 great that overbank deposition does not occur for a geologically long period of time, deposition farther down fan should eventually result in backfilling in the channel above the intersection point.

ACKNOWLEDGMENTS.—I am indebted to Robert P. Sharp for my interest in alluvial fans and arid-region geomorphology and for many helpful suggestions and stimulating discussions in the field and during preparation of the manuscript. Vito A. Vanoni and Norman H. Brooks read a draft of the manuscript and willingly discussed hydraulic and hydrologic problems that arose. They also made available the facilities of W. M. Keck Laboratory at the California Institute of Technology for the laboratory study. The paper has also benefited from critical review by W. B. Bull, C. S. Denny, and H. E. Wright.

R. DeVault and my wife rendered cheerful assistance during a hot summer in the field, and my wife drafted the figures. F. Cammack,

B. Carter, R. Greenway, S. Savin, and especially E. Daly assisted in certain aspects of the field- and laboratory work.

The research was supported by a grant from the Arthur L. Day Fund of the Geological Society of America and by research funds a fellowship from the National Science Fou: tion. This paper is the first of two based u the author's doctoral thesis at the Califo Institute of Technology.

APPENDIX: LOCATION OF FANS

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-min. Quadrangle.

Shadow Rock Fan is located in the NW ¼ sec. 16, T. 8 S., R. 36 E., on the Blanco Mountain 15-min. Quadrangle, California, and is in so: eastern Deep Springs Valley.

Trollheim Fan is located in the E ½ NW ¼ 20, T. 8 S., R. 36 E., on the Waucoba Moun 15-min. Quadrangle, California, and is in sou eastern Deep Springs Valley.

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