A RANDOM-WALK SIMULATION MODEL
OF ALLUVIAL-FAN DEPOSITION

by

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SIGNED: William Evans Price, Jr.

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ABSTRACT

A digital model based on a random walk was used in an experiment to determine how well such a model is able to simulate alluvial-fan deposition. The model is in three dimensions and is dynamic with respect to both time and space. Two principal stochastic events were employed, (1) a relative uplift of the mountain area that is the source of the fan sediments, and (2) a storm event of sufficient magnitude to result in the deposition of material on the fan. These two events are assumed to follow independent Poisson processes with exponentially distributed interoccurrence times. The pattern of deposition is determined by a random walk from the canyon mouth at the mountain front, and each depositional event is assumed to occur instantaneously. The direction that each step in the walk takes is determined probabilistically by the gradient in the direction of flow, the momentum of flow, and the boundary conditions stipulated in the model. The type of flow, whether a depositing debris or water flow, or eroding water flow, depends upon the thickness of erodible material in the source basin. Deposition is assumed to occur over the entire route of flow either as a bed tapered in the direction of flow or as a bed of uniform thickness. The particle-size distribution of the water-flow deposits is governed

by the slope in the direction of flow. Erosion is considered negative deposition and results from the exponential decline in elevation of the main stream channel at the fan apex during periods of no uplift, or from water flows containing little basin sediment. Results from the computer runs were printed as geologic maps of the fan surface, and geologic sections through the deposits; these indicate that, at least qualitatively, a random-walk model provides a reasonable basis for simulating alluvial-fan deposition.

INTRODUCTION

Objective of Study

Alluvial fans are an important source of ground water in many western states, and recharge to many ground-water basins is through alluvial-fan deposits. Hence, a better knowledge of the relation of geologic processes to spatial variations in the permeability of water-bearing beds in alluvial fans would prove helpful in estimating aquifer parameters in undeveloped areas and in interpreting well-log data and pumping-test results. A new approach to the study of the hydrogeologic fabric of fans is to simulate the processes of erosion, sediment transport, and deposition on a digital computer. The primary task of this study was to design such a model based on a random walk. The practical consequences of such a study may be:

1. A better understanding of the types of data and data-collection systems needed to adequately define the alluvial-fan hydrologic system.

2. Where little or no well data are available, the possibility of estimating aquifer parameters more accurately, and perhaps more cheaply, than could be done by a hydrogeologist using conventional methods.

3. More accurate interpretations of pumping tests.

4. A basis for study of the probable accuracy of correlations made from one well to another in alluvial-fan material.

Definition and Methodology of Simulation

Definition

Simulation is difficult to define, in part because the word was adopted from colloquial language (Evans, Wallace, and Sutherland, 1967). Brennan (1968, p. 6) defines it as "the development and use of models to aid in the evaluation of ideas and the study of dynamic systems." McMillan and Gonzales (1968, p. 23) favor defining simulation as a "dynamic representation achieved by building a model and moving it through time." However, in this study we are concerned with an application which makes use of a digital computer; hence simulation of this type is usually called "computer simulation," or, more precisely, "digital computer simulation" (Evans, Wallace, and Sutherland, 1967, p. 7). As applied to the present study, then, the writer defines simulation as "the development and use of a digital computer model to aid in the study of a dynamic system."

Methodology

General. The methodology of computer simulation is fundamentally the same for a wide variety of possible applications. The following flow chart (fig. 1) illustrates the steps that might be taken in formulating and operating a digital computer model such as that for alluvial-fan deposition.

The first step is to define the problem. The objectives of this study of alluvial-fan deposition have been described earlier in this section. It is also possible to state the goals of the study in the form of questions to be answered. The questions asked are: How well can a random-walk model simulate the process of alluvial-fan deposition? Assuming that a random-walk model satisfactorily simulates alluvial-fan deposition, what will be the effect of changing the magnitude of model parameters on the form, structure, and permeability distributions within the fan? Specifically, what will be the effects of increasing or decreasing the uplift rate relative to the frequency of storms in the source basin, or to the rate of downcutting of the main stream channel above the fan apex? What will be the effect of different lithologies in the basin upon the type and character of material deposited on the fan? How will an increase in the rate of production of erodible material, or in the area of erodible material, affect deposition on the fan? These are not the only questions that may be asked, but they are some of the principal ones whose answers may give us some insight into the relation of geologic processes and the geohydrologic fabric of alluvial fans.

The second step is to collect and process data from the real world. In this study, data were obtained largely from the literature

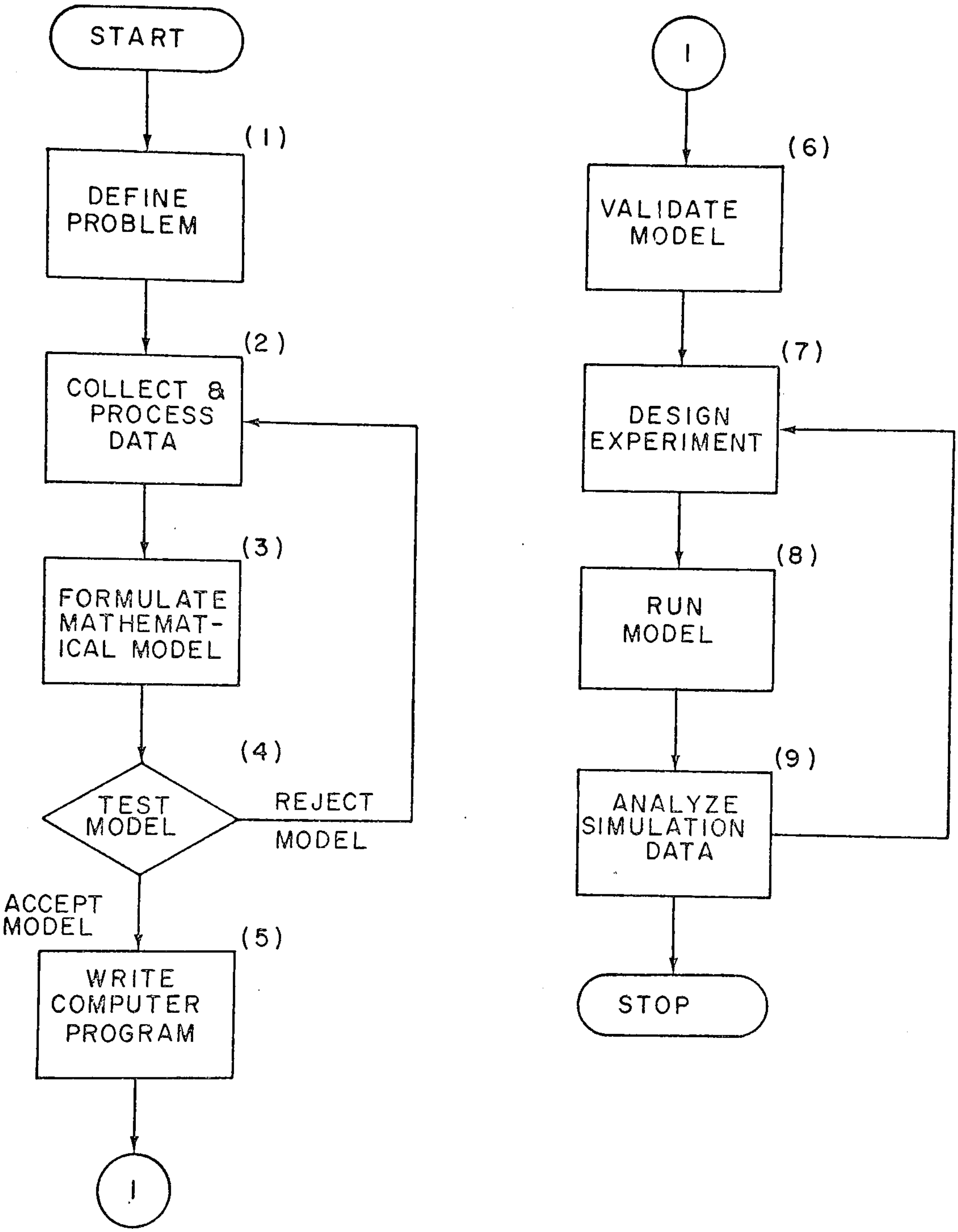


Figure 1.--Flow chart for formulating a computer simulation model and conducting experiments on it.

Adapted from Naylor, Balintfy, Burdick, and Chu, 1968.

and were used to determine some of the mathematical relationships in the model and the ranges of the principal variables.

The third step is to formulate the mathematical model. Requirements for successful formulation are a complete knowledge of the system being modeled, proficiency in mathematics, experience, and luck. Naylor, Balintfy, Burdick, and Chu (1968, p. 30-32) list six major factors which should be carefully considered in building a mathematical model for computer simulation:

(1) The number of input variables to be included in the model. Too few input variables may lead to invalid models, whereas too many input variables may complicate the program unnecessarily or result in a program that exceeds the memory capacity of the computer.

(2) The complexity of the model. The more complex a model, the more realistic it can be. On the other hand, the designer must minimize computational and programming time.

(3) Computational efficiency. By computational efficiency we mean the amount of computer time required to generate the output variables or to achieve some predetermined level of statistical precision.

(4) Computer programming time. This may be reduced by the use of a specialized simulation language. Reasons for the choice of the particular language used in this simulation are given later in this section.

(5) The validity of the model. Validation depends upon the character of the model and available data, but it is almost always a difficult task.

(6) Compatibility of the model with the type of experiments to be carried out with it. Because the principal reason for constructing the model is to conduct experiments with it, thought must be given to incorporating features of experimental design.

The fourth step is to test the model. We must ascertain if all the necessary input variables have been included as well as whether or not unnecessary variables are present which make the model needlessly complex. Assumptions made in the model should be reviewed for appropriateness, functional relations checked for correctness, and distributions examined for goodness of fit. At this stage we are primarily interested in testing the inputs, assuptions, relations, and distributions that will be programmed for the computer in the next step.

The fifth step is to write the computer program, called ALFAN for the model herein described. A complete listing of ALFAN with sample data cards is given in the Appendix. Two computer languages, FORTRAN and SIMSCRIPT, were considered. FORTRAN is a widely used computer language for scientific applications, whereas SIMSCRIPT is a specialized simulation language. Of the two, FORTRAN is the more flexible, but SIMSCRIPT is better for structuring and programming complex simulation problems. Versions of these languages available on the University of Arizona CDC-6400 computer are FORTRAN IV and SIMSCRIPT 1.5. Because of its ability to handle simulation problems in a straightforward manner, SIMSCRIPT was an appealing medium in which to write program ALFAN; however, the writer selected FORTRAN largely because he was already familiar with the language and believed that less time would be required to program the model for FORTRAN than to learn and program the model for SIMSCRIPT. Since that time, another simulation language, GASP II, has become available on the University computer. GASP II is FORTRAN-based, and the writer believes that it would be worthy of consideration for future models of the alluvial-fan type.

The sixth step is to validate the model. This is generally done by comparing the computer output with real-world data. In the present study this is accomplished by comparing the characteristics and morphology of simulated fans with those of real fans. Future studies should compare sections of strata from the simulated fans with historical sequences of beds revealed by borings or sections in existing fans. Such validation requires the use of statistical tests which are designed to handle dependent random variables and are beyond the scope of this paper.

The seventh step is to design experiments on the model. Despite the fact that experimentation is at the heart of simulation, relatively little attention has been given to the subject in the literature.

A simulation study focuses upon some real-world problem. Ideally, this problem is clearly identified and stated prior to development of the simulation model and experiment. For example, the purpose for which program ALFAN was developed is to give quantitative insight into the processes that result in the deposition of alluvial fans and to relate these processes to variations in permeability. In the model, these processes are controlled by parameters, such as mean uplift rate, average rate of development of weathered material in source basin, etc. (see section on input parameters). The experiments must answer questions such as: How well can alluvial-fan deposition be simulated by a random-walk model? What is the effect of varying model parameters on the physical characteristics of the modeled fan? How sensitive are these characteristics to such variations? How reasonable are the changes in the modeled fan as a result of the sensitivity analysis?

The eighth step is to run the model on the computer. This requires the assignment of values to the input variables and for the boundary conditions. Any options for the type of output must be stated at this time.

The ninth step is to analyze data from the simulation experiments. Analysis of experimental data from ALFAN is largely of a qualitative nature. If a quantitative analysis is to be made, statistical techniques must be employed. The problems encountered with this analysis are similar to those involved in validation of the model (step 6), viz. that data from simulation experiments are often autocorrelated (Fishman, 1966; Fishman and Kiviat, 1967). Because most standard statistical tests are designed for independently distributed random variables, these tests cannot be used, and others, such as spectral analysis, must be employed.

Lest the reader gain the impression that model design and validation is a facile and straightforward process, we conclude this section with a quotation from Naylor and others (1968, p. 279): "At this point, it is worth remarking that the normal course of a simulation is not described by modeling, programming, end of process but rather by modeling, testing, modeling, testing, etc., until an adequate model is developed."

Monte Carlo Methods. Monte Carlo methods comprise that branch of experimental mathematics that is concerned with experiments on random numbers (Hammersley and Handscomb, 1964). Monte Carlo methods can be used to solve two very different types of problems. The first type of problem is deterministic; the random numbers merely provide a convenient way to evaluate a quantity such as an integral. The second kind of problem is probabilistic or stochastic in nature. In this kind of problem random numbers are chosen in such a way as to directly simulate processes that behave in an apparently random manner.

The question as to whether or not the processes simulated by ALFAN are inherently random or only apparently random is both a moot and a philosophical question. The more classic view is that processes such as those represented in the model are basically deterministic, but, because of their number and complexity, and the lack of knowledge concerning them, they behave in an apparently random manner. With the growth of mathematical statistics, however, there has been a tendency to regard many processes as inherently random. This is not the place to debate the question, but those interested may wish to read the paper by Mann (1970a) and subsequent replies by Simpson (1970), Mann (1970b, 1970c), and Smalley (1970).

The Concepts of a System

A system is defined as an aggregation or assemblage of objects joined in some regular interaction or interdependence. This definition, and others which follow, are those employed largely by Gordon (1969). Thus, the alluvial fan under study here is properly defined as a system. The term entity is used to denote an object of interest in a system; the term attribute denotes a property of an entity. Any process that causes changes in the system is called an activity. Activities occurring within the system are endogenous, and activities occurring outside the system that affect the system are exogenous. The term state of the system describes all the entities, attributes, and activities as they exist at one point in time.

Other characteristics of a system are also of interest. A system for which there is no exogenous activity is said to be a closed system; it possesses clearly defined boundaries across which no import or export of materials or energy occurs. With a given amount of initial free or potential energy within the system, it develops toward a state with maximum entropy. In contrast, an open system does have exogenous activities; it needs an energy supply for its maintenance and preservation, and it is maintained by a constant supply and removal of materials and energy. The concept of the open system includes closed systems. The latter may be considered a special case of the former when transport of matter and energy into and out of the system becomes zero. An open system may attain a steady state in which the import and export of energy and material are equated by means of an adjustment of the form or geometry of the system itself. Another characteristic of the open system is that negative entropy, or free energy, can be imported into it. Open systems may also behave "equifinally"—that is, different end conditions can lead to similar end results (Chorley, 1962). If the outcome of an activity can be described completely in terms of its input, the activity is deterministic. When the outcomes of the activity vary randomly, the activity is stochastic. The alluvial fan is an open, stochastic system.

Systems may also be classified as static or dynamic and discrete or continuous. Dynamic systems change with time; static ones do not. The alluvial-fan system is a dynamic one. Changes in a continuous system are smooth, whereas changes in a discrete system are predominantly discontinuous. The ALFAN model is continuous with respect to time but discrete with respect to space. Event times are drawn from continuous distributions. The state of the system at each event is described by the path of a two-dimensional random walk consisting of discrete steps, each of which is assumed to occur instantaneously in time. One must distinguish, however, between a system and the description of the system. Although the alluvial-fan system is continuous in nature, it is here described as a discrete one to permit digital computation. The description of the system, therefore, is more important than the actual nature of the system.

The Nature of the Model

Oertel and Walton (1967), in a carefully made study of the feasibility of constructing a digital model of a coal-bearing delta, concluded that because of the complexity of the natural system and the lack of knowledge of the processes involved in its construction, it was not presently possible to construct such a model. Their conclusion certainly would cause some trepidation on the part of the neophyte who would essay a model of an alluvial fan, a natural feature which is in many ways comparable to a delta. In this study, we hope to deal with, at least to some extent, the difficulties of complexity and uncertainty by constructing a stochastic model which is Markovian in nature with respect to both time and space.

Previous Work in Modeling Alluvial Fans

Physical Models

Laboratory models of alluvial fans were studied by Hooke (1967, p. 446-447; 1968, p. 621-627). In Hooke's first series of laboratory studies, 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 a channel just above the fanhead. Sixteen fans were made; each was built with between 10 and 66 depositional episodes. Hooke did not intend his laboratory fans to be scale models of a natural fan, but small fans in their own right. Nevertheless, gross scaling relationships between debris size and discharge were met, as indicated by the similarity between slopes on laboratory and natural fans. Good agreement was found between laboratory and field data, particularly in regard to sieve deposition (see section on "Characteristics of Deposits") and fanhead incision. In his second series of experiments, Hooke enlarged the working area to a 1.5 by 2.7-m rectangle, which enabled him to build complete fans with a radius of 1.35 m. He used sediment with a log-normal size disposition. Each fan in the second series was built with between 24 and 103 depositional episodes. In all but one case, the discharge was held constant for a 5-minute period. In the one case, discharges were randomly selected from a log-normal distribution. In this second series of experiments, Hooke found that the slope of laboratory fans decreased as discharge increased and increased as grain size and sediment increased.

Mathematical Models

Scheidegger (1959, p. 32-34; 1961, p. 81-83, 85) suggested a two-dimensional model for the accumulation of sediments in an alluvial fan. Scheidegger's model is based on two assumptions: that the sediment-carrying capacity of a stream increases with the velocity ($v \sim c$) and that the velocity of water is proportional to the instantaneous slope over which it travels ($v \sim s$). He derives the equation

$$\frac{\delta \zeta^2}{\delta t} = a' \frac{\delta^2 \zeta^2}{\delta x^2} \tag{1}$$

where x = horizontal coordinate,

y = vertical or upward coordinate,

t = time,

a' = some constant, and

$\zeta = -\frac{\delta y}{\delta x}$.

Linearizing equation (1) and solving it with the following boundary condition: $\zeta(t, 0) = \zeta_1$ = constant and $\zeta(0, x) = \zeta_0 = 0$, he obtains

$$s \cong -\zeta_1 \sqrt{\operatorname{erfc}\frac{x}{\sqrt{4a't}}} \quad \text{for the slope;}$$

$$v \sim v_1 \sqrt{\operatorname{erfc}\frac{x}{\sqrt{4a't}}} \quad \text{for the velocity;}$$

$$\text{and } y \sim -\int_{\infty}^{x} \sqrt{\operatorname{erfc}\frac{x}{\sqrt{4a't}}}\, dx \quad \text{for height of accumulation.}$$

In a later publication, Scheidegger (1970, p. 115) concluded that because alluvial fans are quasi-conical structures they cannot be described by simply giving their profile. He does, however, state that the slopes of most volcanoes and pediments fit the postulated profile, although no actual data are given.

Culling (1960, p. 336-344) proposed a two-dimensional model of alluvial-fan development based on an analogy with the linear flow of heat. Culling's model, which considers the movement of material in the x dimension only, is based on the equation

$$\frac{\delta^2 y}{\delta x^2} = \frac{1}{K}\frac{\delta y}{\delta t} \qquad (2)$$

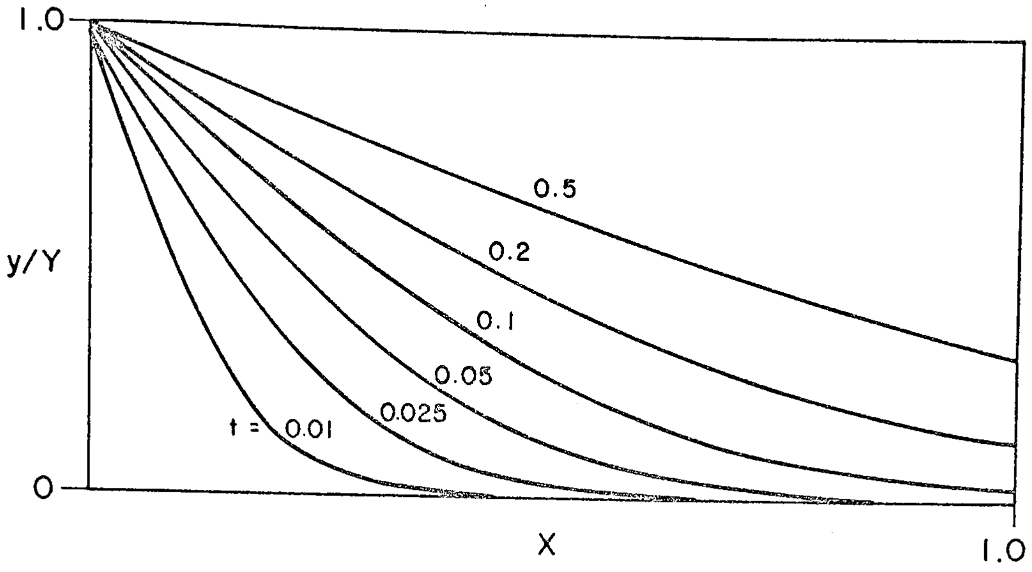
where y is the amount of material, and therefore elevation, K is a constant which represents the mobility of the surface cover; and t is time. The solution to equation (2) depends upon the boundary conditions. For a semi-infinite region extending from the plane $x = 0$, initially at zero elevation and with the point $x = 0$ maintained at a constant elevation $y = Y_0$, the solution may be stated in the form

$$y = Y_0 \operatorname{erfc}\left(\frac{x}{2\sqrt{Kt}}\right) \qquad (3)$$

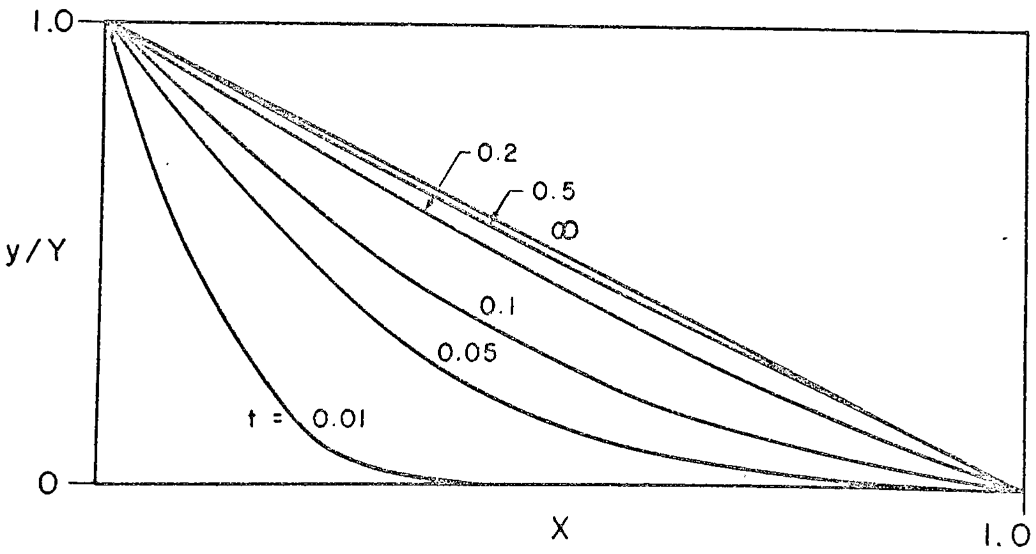
According to Culling (1960, p. 340), this solution is applicable to the building of an alluvial fan out from the mouth of an up-faulted valley onto a plain large enough for the region to be regarded as infinite. A series of curves for equation (3), for selected values of time, is shown in figure 2A. If the plain onto which the fan is built is of limited extent or if the fan extends down to a river which supplies a stable base level, then the solution for the semi-infinite region is no longer appropriate. The solution required must fit a finite region $0 < x < \ell$, with boundary conditions specified at both end points. For the aggradation of an alluvial fan, the initial elevation is zero, and

$$\begin{array}{lll} y = 0 & t = 0 & 0 < x < \ell \\ y = y_1 & x = 0 & t > 0 \\ y = 0 & x = \ell & t > 0 \end{array}$$

for which the solution is:



A. EQUATION (2) FOR SEMI-INFINITE REGION.



B. EQUATION (3) FOR FINITE REGION.

Figure 2.--Curves representing the development of an alluvial fan for different periods of time, t.

From Culling, 1960.

$$y = y_1\left(1 - \frac{x}{\ell}\right) - y_1\frac{2}{\pi}\sum_{1}^{\infty} x\frac{1}{n}\sin\frac{n\pi x}{\ell}\, e^{-Kn^2\pi^2 t/\ell^2} \qquad (4)$$

A series of curves for equation (4) for selected values of time is shown in figure 2B.

Culling (1963, p. 160-161), who modeled soil creep as a random-walk process, states that his solutions for three-dimensional models with radial symmetry may provide a reasonable approximation of alluvial-fan development. The pertinent diffusion equation in cylindrical coordinates is

$$\frac{\partial^2 z}{\partial r^2} + \frac{1}{r}\frac{\partial z}{\partial r} = \frac{1}{K}\frac{\partial z}{\partial t}$$

where z is the elevation of the surface of the land. Solutions of this equation represent the degradation of an isolated hill with an approximately circular base of radius r = a. Culling (1963) also states that use of this model may be justified by regarding the movement of material on the fan as being governed by an equation similar to the Langevin equation. This equation, which may be written as follows, takes into account the effect of frictional and gravitational forces, which the diffusion equation does not:

$$\frac{d\vec{u}}{dt} = -B\vec{u} + \vec{A}(t) + \vec{K}(t)$$

where $\vec{u}$ is the velocity of the particle; $-B\vec{u}$ denotes the dynamical friction; $\vec{A}(t)$ is the stochastic term due to random motion; and $\vec{K}(t)$ represents the action of an external field of force (gravity).

The essential difference between equation (1) of Scheidegger and equation (2) of Culling is that the velocity in equation (1) is the velocity of the sediment-carrying water, whereas the velocity in equation (2) is the mass flow velocity. In either case, the models of Scheidegger and Culling are highly idealized and describe only the general form that the deposits should take. ALFAN, on the other hand, by simulating the stochastic processes involved, gives us a record of the form and character of the different deposits making up the fan and allows us to relate the geohydrology of these deposits to the processes responsible for their formation.

A second shortcoming of the models of Scheidegger and Culling is that they attempt to describe sediment transport and deposition by streams with a single mathematical relation. According to Maddock (written commun., 1971), two equations are required,

$$VS \times 10^{-3} = \phi(d)C^{3/4} \qquad (5)$$

where V = mean velocity of water and sediment, in feet per second;

S = slope or energy gradient;

$\phi(d)$ = a function of the median grain size of the moving sediment;

C = concentration of the sediment, in parts per million by by weight;

and

$$V \propto B^2 \frac{DS}{d^{1/2}} \tag{6}$$

where D = mean depth of flow, in feet;

d = median grain size of the sediment, in mm;

S = slope or energy gradient;

B = energy-dissipation coefficient.

But even with equations (5) and (6), a mathematical model of alluvial-fan deposition cannot be constructed because width and depth of flow are generally not known and water and sediment discharge vary unpredictably with time and in space. Therefore, a model embodying random elements, such as the random-walk model described in this paper, is the only solution.

THE ALLUVIAL FAN

Definitions and General Features

An alluvial fan is an accumulation of detritus at a place where a debris-carrying wash from a highland becomes free to migrate from side to side (Denny, 1965, p. 42). In its most characteristic form the alluvial fan is a low cone-shaped heap, steepest near the mouth of a valley, and sloping gently outward in a series of segments with ever decreasing gradient. However, many alluvial fans are not fan-shaped, because their lateral development is restricted by adjacent alluvial fans. A feature that lacks the distinctive form of one or more coalesced alluvial fans may be designated as an alluvial slope (Hawley and Wilson, 1965, p. 8).

Distribution in Space

Alluvial fans have been found on all the continents of the world (Blissenbach, 1954, p. 176). For example, Russell (1954) has described fans in Turkey, and Drew (1873) discussed fans at the base of the Himalayas in Kashmir. Although most widespread in the drier regions, they also occur in humid areas, such as Canada (Winder, 1965) and in the valleys of the European Alps (Derruau, 1965). In the United States, alluvial fans occupy large portions of the states of Nevada, Utah, New Mexico, Arizona, and California (Lawson, 1913, p. 326). It is these fans, in the arid and semiarid Southwest, with which this paper is primarily concerned.

Conditions Favoring Formation

The principal conditions favoring alluvial-fan formation are climatic and topographic in nature. Favorable climatic conditions are commonly found in arid and semiarid regions, where rainfall is infrequent but intense and streams are ephemeral rather than perennial in nature (Lawson, 1915, p. 28; Blissenbach, 1954, p. 177; McKee, 1957, p. 1728).

Vegetative cover, a variable which depends upon climate, favors alluvial-fan formation if the cover is scanty (Beaty, 1963, p. 519). In an interesting study, Schumm (1965, p. 784-785) shows that sediment yield is a maximum at about 12 inches of precipitation and then recedes to lower values with lesser and greater amounts of precipitation (see fig. 3, p. 40). This variation in sediment yield with precipitation can be explained by the interaction of precipitation and vegetation on runoff and erosion. As precipitation increases above zero, sediment yields increase at a rapid rate, because more runoff becomes available to move sediment. Opposing this influence is that of the vegetation, which increases in density as precipitation increases. At about 12 inches of precipitation, the transition between desert shrubs and grass occurs.

Above 12 inches of precipitation, sediment-yield rates decrease under the influence of the more effective grass and forest cover.

In northern countries such as Canada (Legget, Brown, and Johnston, 1966), Alaska (Anderson and Hussey, 1962), and Sweden (Hoppe and Ekman, 1964), snowmelt may provide the abundant, erratic flow of water that is conducive to the formation of alluvial fans. Melt-water from snowfields and glaciers in high mountain regions such as the Himalayas (Drew, 1873) may build fans at the mouths of valleys de-bouching into arid plains below. Trowbridge (1911) believed that the great alluvial fans in the Owens Valley at the base of the Sierra Nevada were formed in this manner. Fans constructed in wetter areas, such as the Swiss Alps, may also owe their origin to the melting of winter snows. The frost action and glaciation characteristic of colder regions were believed to be important in preparing debris needed for fan build-ing (Drew, 1873; Trowbridge, 1911; Hoppe and Ekman, 1964; Legget and others, 1966). Melton (1965) postulated that the colder winters present in southern Arizona during the Pleistocene glacial stages accounted for the large quantity of coarse and bouldery material present in fans in this region, which are now largely inactive. Lustig (1965) disagreed, attrib-uting the coarse material to the greater competency of streams at that time.

Favorable topographic conditions for the development of alluvial fans are bold relief (Blissenbach, 1954, p. 177; McKee, 1957, p. 1728-

1729; Hawley and Wilson, 1965, p. 32-33) and the repeated uplifts characteristic of structurally disturbed regions (Blackwelder, 1931, p. 136-138; Hawley and Wilson, 1965, p. 31).

According to Bull (written commun., 1971), thick alluvial fans are found only in tectonically active areas where the differential uplift is large enough to permit the accumulation of thousands of feet of fan deposits. Where the differential uplift is not great enough, erosion will prevail along all the reaches of a given stream, and there will be no accumulation of fan deposits in spite of favorable climatic conditions. A good example of this condition is the pedimented landscape that presently exists in a large portion of southern Arizona. The climate is suitable for the deposition of alluvial fans, but there have been no uplifts. Therefore, erosion prevails and large modern alluvial-fan deposits are not present.

Cause of Deposition

Reduction in stream velocity caused by a decrease in slope of the channel as the stream leaves the mountain canyon and flows onto the relatively gentle valley floor commonly has been given as a principal cause of alluvial-fan deposition (Grabau, 1913, p. 583; Pack, 1923, p. 349; Blissenbach, 1954, p. 178; Balchin and Pye, 1956, p. 168; Beaty, 1963, p. 516; Allen, 1965, p. 159; Derruau, 1965, p. 61; Denny, 1967, p. 83), although under some conditions it may actually increase with a decrease in slope (Maddock, written commun., 1971). Even though Dutton attributed deposition to reduction in channel slope, as long ago as 1880 (p. 220) he recognized that the transition from the generally steep slope of the mountain area to the predominantly gentle slope of the valley area is characteristically not abrupt, but gradual and smooth. Longwell and Flint (1962, p. 173), Bull (1964b, p. 17), and Legget and others (1966, p. 27) therefore attribute deposition under these conditions to the spreading out of the streamflow on the fan when the end of the channel is reached. Deposition may also be aided by loss of water from the stream by infiltration through the fan surface (Trowbridge, 1911, p. 738; Blissenbach, 1954, p. 178; Beaty, 1963, p. 516; Bull, 1968, p. 102).

Loci of Deposition

During the construction of an alluvial fan the stream channel shifts along both the contours and the radial lines of the fan (Bull, 1968, p. 102). Lateral migration of the stream channel occurs when deposition has raised the fan surface sufficiently to favor shifting of the stream channel to a lower part of the fan or as a result of erosion at the apex of the fan. As a result, minor changes in the angular position of the stream channel near the fan apex cause large changes in stream-channel position on the lower parts of the fan. Migration of the loci of deposition along the radial lines of the fan occurs as a result of entrenchment or backfilling of the stream channel extending from the source area.

Characteristics of Deposits

Classification and Definitions

The classification used in this paper is based upon the nomenclature of Hooke (1967), who recognized two fundamentally different types of alluvial-fan deposits, water-flow deposits and debris-flow deposits. Water-flow deposits are those laid down by running water. Braided distributary channels are characteristic of water flows (Bull, 1968, p. 102), and the resulting sheetlike deposit consists of shallow bars of poorly bedded gravel or crossbedded sand that are generally parallel to the direction of flow. Deposition within the larger stream channels is generally coarser grained than the adjacent sheetlike deposits.

If fan material is sufficiently coarse and permeable, or if the area over which infiltration may take place is large, the entire water flow may infiltrate before reaching the toe of the fan. If the source basin produces coarse material, a lobe of pebble to boulder-sized material may be 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. Hooke (1967) calls these lobate masses "sieve lobes" or "sieve deposits," and the mode of deposition, "sieve deposition."

If a stream incorporates sufficient sediment, it may become a debris flow. According to Sharpe (1938, p. 49) the term "debris flow" should be used as a general designation for all types of rapid flowage involving debris of various kinds and conditions. Debris flows have higher specific densities and much higher viscosities (1,000 or more poises) than do water flows (Sharp and Nobles, 1953, p. 552-553). According to Hooke (1967, p. 451-452), it is the point of irreversible sediment entrainment that separates debris flows from water flows. Water flows may vary their sediment load readily by deposition and erosion, but a debris flow cannot selectively deposit any but the coarsest fragments. Therefore a debris flow cannot turn into a water flow by deposition, unless water is added to the flow.

A mudflow is a type of debris flow that consists mainly of sand-size and finer sediment (Bull, 1968, p. 102). The term "mudflow" as used in the literature, however, often refers to processes and deposits that would here be classified as debris flows (e.g., Blackwelder, 1928; Sharpe, 1938; Blissenbach, 1954; and Bull, 1964b). Equivalent terms employed by other authors are "mud-rock flows," "rock flows," "debris-floods," or "mud-rock floods."

Grain Size and Sorting of Fan Deposits

Alluvial-fan deposits vary widely in texture and degree of sorting. Fans are formed of detrital material which may range in texture from clay-size particles to boulders as much as 30 feet in diameter (Trowbridge, 1911, p. 722). With the exception of fan materials derived wholly from certain equigranular source rocks, deposits within a given fan vary widely in degree of sorting. Water-flow deposits are generally moderately well sorted, but most debris-flow deposits are very poorly sorted. A common measure of sorting is the Trask sorting coefficient, which is expressed as

$$S_o = \sqrt{\frac{Q_{75} \text{ (larger quartile diameter)}}{Q_{25} \text{ (smaller quartile diameter)}}}.$$

Bull (1964b, p. 65-66) found values of S_o ranging from 1.1 to 25 in 100 samples from alluvial-fan deposits in Fresno County, California.

Principal factors controlling the grain size and sorting of alluvial-fan deposits are (1) nature of the source rock, (2) slope of the fan-building channels, (3) competence of the transporting medium, (4) duration of weathering, (5) distance from fan apex, and (6) channel entrenchment. The texture of fan sediments depends to a large extent on drainage-basin geology. Hawley and Wilson (1965, p. 53) found that alluvial fans located at the mouths of gullies and arroyos cut in fine-grained sediments of the Lahontan Valley Group in Nevada were themselves fine grained. In New Mexico Ruhe (1967, p. 40) contrasts the large boulders of monzonite found in the Jornada sediments with the silty clay sediments underlying the Organ surface that were derived from limestone, sandstone, and shale. The effect of lithology on the sorting of alluvial-fan deposits is well shown by some of the alluvial fans in the Black Hills region of Arizona (Blissenbach, 1954, p. 183), whose well-sorted material is due to the breakdown of plutonic rocks of granitic texture into an equigranular detritus.

There is a relation between debris caliber and slope, although the correlation is better on some fans than others. Blissenbach (1952, p. 26; 1954, p. 182) and Anderson and Hussey (1962, p. 318) concluded that a good relationship exists. Allen (1965, p. 159) presents graphs based on data from Blissenbach (1954) and Eckis (1928, p. 233) that also show good correspondence. Denny (1965, p. 42, 55) and Lustig (1965, p. 167), however, found only a weak relationship.

A third important factor controlling grain size and sorting of alluvial-fan sediments is the competence of the transporting medium. Competence may be equated either with velocity or with tractive stress (Lustig, 1965, p. 165-167). Tractive stress may be expressed as:

$$\tau_o = \rho g d s \tag{7}$$

where τ_o is the tractive stress of the debris flow in shear, ρ is the density of the flow, g is the gravitational acceleration, and d and s are the depth and gradient of the flow, respectively. Thus, τ_o is a measure of competence when applied to a transporting medium, and it increases with increasing values of ρ, g, d, and s.

A fourth factor determining grain size and sorting of alluvial-fan sediments is weathering. Bluck (1964, p. 396-397) and Ruhe (1967, p. 44) concluded that weathering, as well as sediment transport, can be an important factor in comminuting fan materials. Interestingly enough, Ruhe found the Organ sediments, which show a linear decrease in size downfan, are essentially a size sorting of raw sediment in alluvial transport downslope, whereas the Jornada sediments, whose size decrease is curvilinear, have been affected by weathering.

The fifth factor controlling alluvial-fan lithology is the distance of transport. Generally, there is a decrease in the grain size of fan material from the apex to the toe, as indicated by Dutton (1880, p. 220), Grabau (1913, p. 584), Lawson (1913, p. 326-327), Vaughan (1922, p. 340-341), Troxell and others (1942, p. 322), and others. Bull (1964a, p. 100; 1964b, p. 34, 36) found a general decrease in maximum and median grain sizes in 200 surface and subsurface samples from fan deposits in western Fresno County, California. Although Melton (1965, p. 23) refers to Blissenbach's (1952, p. 26; 1954, p. 182) curve of maximum grain size versus distance from fan apex as exponential, a plot by Allen (1965, p. 159) of Blissenbach's data on semilogarithmic paper is not a straight line. Melton (1965, p. 23) pointed out, however, that the fan in question was so thin as to reflect the underlying pediment surface, and that the highest deposit at the apex is a colluvium considerably coarser and younger than the remainder of the fan. Other data obtained by Blissenbach (1952, p. 27-28) for alluvial fans at the base of Aubrey Cliffs, Arizona, suggest a linear relation between maximum particle size and distance. In southern New Mexico, Ruhe (1964, p. 153-154) found that alluvial-fan sediments underlying the Organ and Jornada surfaces showed a systematic decrease in median particle size related to distance from the mountain source. In Organ sediments median diameters decrease linearly with distance as expressed by the equation $Y = 1.9416 - 0.1948x$; in Jornada sediments median diameters decrease as the logarithm of distance from the source as expressed by the equation $Y = 2.2482 - 1.2447 \log x$, where Y is the median particle size in millimeters and x is the distance in miles.

The sixth and final factor controlling alluvial-fan lithology is channel entrenchment. The coarsest material in an alluvial fan usually is deposited near the end of the stream channel (Buwalda, 1951, p. 1497; Bull, 1968, p. 103). If the end of the stream channel has remained near the mountain front during the formation of a fan, a general decrease in particle size in the downslope direction will be present. If the end of the channel is downfan away from the mountain front, deposition of coarse material will take place in an area where fine material previously was laid down. In this case an orderly progression of material from coarse to fine down the slope of the fan will not occur.

Age

The age of most alluvial fans studied and described in the literature is Pleistocene or Holocene. Eckis (1928, p. 244) reports that the fans in the Cucamonga district of California, still growing, are mainly of Pleistocene or earlier age. Blissenbach (1954, p. 180) states that the fans at the southern base of the Santa Catalina Mountains in Arizona are Pleistocene and Holocene in age. In western Fresno County, California, the geomorphic and sedimentary characteristics of the alluvial fans were determined by Coast Range orogeny, which is generally accepted as being of Pliocene and Pleistocene age (Bull, 1964a). Pyle (California Department of Water Resources, 1963) considered the alluvial fans in many valleys of northeastern California to be of Holocene age. In the Rio Grande valley in New Mexico, Ruhe (1964, p. 159) studied fans ranging from mid-Pleistocene to Holocene in age. Melton (1965, p. 16-17) regards many fans in Arizona as being of Pleistocene age. Legget and others (1966, p. 19) considered the fans they investigated in northern Canada to be predominantly postglacial. In the White Mountains of California and Nevada, Beaty (1970, p. 54) estimated the Milner Creek fan to have a maximum possible age of 700,000 years. All these are, of course, only a sample of the total number of alluvial fans that exist on the earth's surface, and do not invalidate Lustig's statement (1965, p. 184) that data on the age of alluvial fans in the Basin and Range province are generally unavailable.

Many older fans are present in the stratigraphic record, but these have not been nearly so extensively or intensively studied as those easily recognized surficial deposits in the recent geologic past. However, a study of these older fans provides much sedimentological data that would be of value to workers in the field of ground-water hydrology (Bull, written commun., 1971).

Theories of Alluvial-Fan Formation

Lustig (1965, p. 182) has suggested that theories of alluvial-fan formation may be conveniently grouped into three general categories: (1) evolutionary, (2) equilibrium, and (3) climatic hypotheses.

Evolutionary Hypothesis

The concept that landforms result from a geographic cycle that proceeds through the successive stages of youth, maturity, and old age is commonly termed "Davisian philosophy." One failing of this concept is its inability to emphasize fluvial processes and thereby gain insight into the mode of formation of a given landform. The evolutionary hypothesis, however, provides a reasonable description of alluvial fans in their initial and ultimate stages of development (Lustig, 1965, p. 182).

Equilibrium Hypothesis

The equilibrium hypothesis relates the Davisian stage of the landform with the processes acting upon it. The landform is assumed to be part of either an open system or a closed system (Von Bertalanffy, 1950).

Open System. In the open system, materials, energy, or both can be exchanged with outside environments. According to Strahler (1952), most landforms represent open dynamic systems that tend toward an equilibrium or steady state. With regard to alluvial fans, dynamic equilibrium or steady state requires that erosion or deposition be equal so that the fan will not diminish or increase in volume. Denny (1965, p. 48) suggests that alluvial fans in the Death Valley region have attained or nearly attained a steady state, but he concedes that this cannot be proved because rates of deposition and erosion on the fans are not known. Beaty (1970, p. 74-75) equates the Davisian concept of physiographic maturity with the concept of steady state.

Closed System. Closed systems are those which possess clearly defined boundaries, across which no import or export of materials or energy occurs. Few, if any, natural systems are closed. Davis' view of landscape development contains elements of closed system thinking, such as:

(1) The belief in the sequential development of landforms, resulting in the progressive and irreversible evolution of landscape geometry.

(2) The idea that uplift initially provides a given amount of potential energy and that, as degradation proceeds, the energy of the

system decreases until there is a minimum of free energy and a maximum of entropy at the final stage of peneplanation.

Climatic Hypothesis

There is little doubt that climatic changes have taken place during the development of alluvial fans in the Basin and Range province (Lustig, 1965, p. 183-184). However, studies of erosional and depositional history in many parts of the West have produced widely differing conclusions concerning the effects of these changes (Hawley and Wilson, 1965, p. 32). Theories of the climatic causes of alluvial-fan formation in nonglacial areas may be divided into three groups: (1) formation in response to intensified mechanical weathering due to frost action during times of climatic cooling; (2) deposition in hot and arid climates during times of deficient runoff, and dissection during cool, wet climates; and (3) aggradation during more humid or pluvial climates due to relatively abundant and frequent precipitation, and trenching during drier periods.

Melton (1965) invoked the first theory to account for the large fans composed of predominantly bouldery alluvium found in southern Arizona. He attributed their development to intensive frost action in the cold climates of higher mountain elevations, combined with frequent intense rainfall. Lustig (1966, p. 95-102) took issue with the interpretation of Melton, suggesting that a Pleistocene-Holocene contrast in stream discharge and competence may be the most probable explanation for the occurrence of coarse alluvial deposits of Pleistocene age.

The second theory, that of alluvial-fan formation in hot arid climates and dissection in times of cool wet climates, is espoused by Blissenbach (1954, p. 180), Hawley and Wilson (1965, p. 33), and Hunt and Mabey (1966, p. 97). Tuan (1962) found the theory compatible with the development of basin landforms during the glacial and postglacial period in Arizona and New Mexico. Hawley and Wilson (1965, p. 33), in their study of the Quaternary geology of the Winnemucca area, Nevada, state that aggradation of piedmont slopes appears to have occurred principally during semiarid interpluvial periods. With a change to a moister climate, initially upper parts of the piedmont slopes were eroded, fanhead trenches formed, and basin floors alluviated. As vegetative cover increased and while temperatures were still warm, a time of little erosion and deposition on piedmont slopes occurred. Later, as the waxing phase of the cycle progressed and the base level rose in the central part of the valley floor, deposition occurred farther and farther up on the piedmont slopes and in the mountain canyons. This cycle was repeated to some degree with each fluctuation of climate.

Krynine (1950, p. 185), however, takes issue with the theory of formation of alluvial fans under hot arid conditions by pointing out:

> Many of the American deserts used as illustrations of sedimentation under arid conditions are really freak deserts.

> It is true that they receive a very scant rainfall in their depressed portions, but the volume of water which enters these ultra-arid basins and controls sedimentation therein comes from a relatively considerable precipitation on the high mountain slopes. . . . To make matters worse, many of the sedimentary deposits found on the floor of desertic basins of the arid American Southwest are not at all the products of recent sedimentation under arid conditions. They were formed instead, barely 20,000 years ago, during the humid, pluvial period of the Pleistocene and have been, time and again, mistaken for recent deposits.

The third theory, that aggradation on fans took place when precipitation was more widespread and frequent than today, was suggested by Lustig (1965) from his work on the fans in Deep Springs Valley, California. He further postulated a climatic change from widespread to local precipitation and lesser frequency of precipitation, which led to a period of trenching in the catchment and upper fan areas by mudflows. The whole constitutes a climatic cycle during which the fans constantly grow—upwards during humid or pluvial periods and outwards into the basin during drier periods.

On the other hand, workers such as Eckis (1928), Denny (1965; 1967), and Beaty (1970) have concluded either that some fan characteristics attributed to climatic change may be better explained by other means or that climatic changes have had little effect on alluvial-fan formation. Eckis (1928, p. 237-238) offered a plausible explanation for fanhead trenching, which may take place as a normal consequence of stream and fan development unrelated to climatic change. When the stream above the fan becomes essentially graded, the point of stream distribution at the head of the fan becomes the critical point. As the distributaries are loaded with sediment, they build up the fanhead until the grade of the fan below the point of distribution is steeper than that of the stream above this point. A convexity develops in the stream profile about the point of distribution, which slowly moves upstream. In humid or moderately arid regions the rise of the point is too slow to counter-balance the reduction of grade in the mountain canyon. The result is an increasing convexity where the canyon grade and fanhead slope meet. Inevitably, a large flood will occur which will cut a single channel through the steeper fanhead and develop a lower grade. The grade of the new channel will then bring the channel onto the fan surface at a lower level.

Denny (1965, p. 24) found evidence of greater flooding in the past on fans of the Death Valley region, but he concluded that processes of erosion, transportation, and deposition on the Shadow Mountain fan have been in operation at more or less constant rates during the life of the fan, and that the mode of fan formation does not require that these processes were much more active during the last glacial stage than since that time. Later, Denny (1967, p. 94-95) questioned the hypothesis of climatic change proffered by Lustig (1965) as a result of his studies in the Deep Springs Valley, and observed that the fan characteristics observed by Lustig may also be explained by stream capture or by short-term variations in the magnitude and frequency of floods. Beaty

(1970, p. 64), in his study of the Milner Creek fan in the White Mountains area of California, concluded that climatic changes, even of the magnitude encountered during the Pleistocene glacial epoch, would have had little effect on the Milner Creek fan because runoff during periods of ice accumulation in the mountains was not conspicuously greater than at present.

The work of Langbein and Schumm (1958) and Schumm (1965) is very pertinent to the question of just how a given climatic change might affect aggradation or erosion on an alluvial fan. Langbein and Schumm (1958, fig. 2) defined the relation between annual sediment yield and effective annual precipitation for drainage basins averaging about 1,500 square miles in the conterminous United States for an annual mean temperature of 50°F (fig. 3). The curve reveals that sediment yield is at a maximum at about 12 inches of precipitation, decreasing sharply on both sides of this maximum, in one case owing to a deficiency of runoff and the other to increased density of vegetation. In order to determine the effect of a climatic change on sediment yields it is necessary to consider the nature of curves that might be derived for temperatures other than 50°F. Schumm (1965, fig. 2) did this for temperatures of 40°F, 60°F, and 70°F. These curves demonstrate an important fact: namely, that the effect of a climatic change on sediment yield depends not only upon the direction of climatic change, but also on the climate before the change.

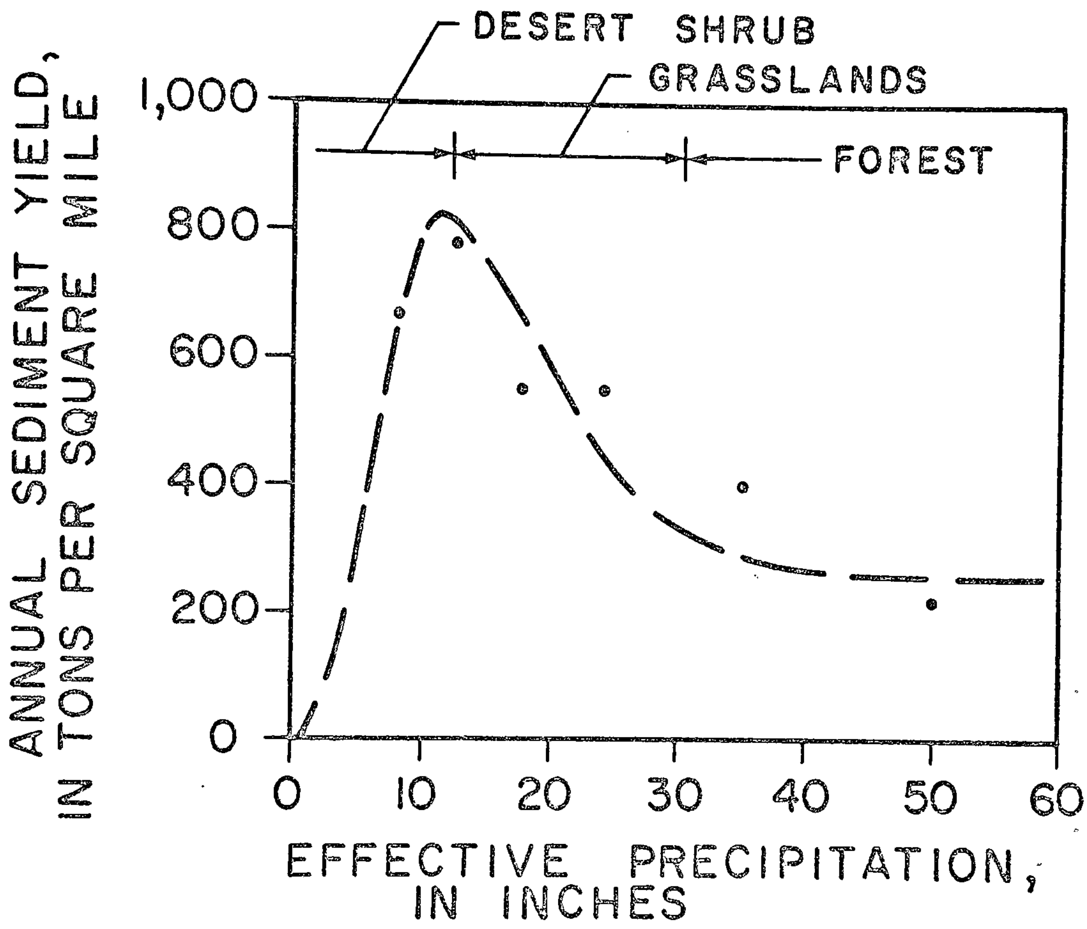


Figure 3.--Climatic variation of yield of sediment as determined from records at sediment stations.

From Langbein and Schumm, 1958, fig. 2.

In addition to the amount of sediment moved, its concentration in the water by which it is moved is important. Langbein and Schumm (1958, fig. 6) and Schumm (1965, fig. 3) show that as annual precipitation decreases, the concentration of sediment per unit of runoff increases. This suggests that increasing sediment loads associated with increasing dryness will cause aggradation, in an amount depending on the magnitude of the climatic change. An increase in load or decrease in discharge with constant load will result in aggradation and vice versa.

A decrease in annual runoff with decreased precipitation will necessitate an adjustment of stream gradient and shape such that the width and depth of the channel should decrease and the gradient increase. These changes are consistent with aggradation. An increase in precipitation might be expected to result in degradation and a decrease in sediment concentration. The increased discharge will result in an increase in channel width and depth and a decrease in gradient.

The entire question of the influence of climatic changes on landforms and sedimentary deposits such as those found in alluvial fans is aptly summarized by Schumm (1965, p. 792-793):

> Although interrelations among hydrologic phenomena as developed from modern observations are still incomplete, it may be possible to predict the direction and possibly the magnitude of a change in hydrologic variables resulting from a climatic change. These tentative relationships also suggest that the effect of the hydrologic changes on landforms and sedimentary deposits may be quite different depending on the original climate of a region prior to the change, the importance of glacial and periglacial erosion within the region, and base

level changes. Each landform and deposit needs to be studied in relation to its own environment, and the conclusions resulting from a local or regional study should be extended beyond the limits of the investigation only with great care.

Alluvial-Fan Deposits in the Stratigraphic Record

Alluvial fans selected for study by present-day workers, particularly those interested in gaining an understanding of processes on fans, have been almost exclusively of Quaternary age. Nevertheless, descriptions of geologically ancient fans are present in the literature. Recognition of these fans is more difficult not only because their surface morphology has been buried or destroyed by erosion, but because their identification hinges upon a knowledge garnered from the study of the sedimentary characteristics of contemporary fans. Because of this, care must be taken in applying information gained from the study of ancient fan deposits to computer models, for example, as the danger of circular reasoning is always present.

Some examples of ancient alluvial-fan deposits in the stratigraphic record range from Pennsylvanian to Tertiary in age. Deposition of the Fountain Formation, which crops out along the Front Range in Colorado and southern Wyoming, is believed to have taken place as a piedmont or as a series of coalescing alluvial fans of Pennsylvanian and Permian age (Hubert, 1960, p. 227, 229; Maughan and Wilson, 1963, p. 96). Arkosic sandstone and conglomerate in the formation represent deposition in or near stream channels, whereas siltstone represents deposition away from major stream channels. Fanglomerates of Triassic age have been studied by Krynine (1950) in Connecticut and by Klein (1962) in Nova Scotia and New Brunswick. In Wyoming, Sharp (1948) considered the poorly cemented Moncrief Gravel of Eocene age to represent an ancient alluvial fan.

The Alluvial Fan as an Aquifer

The hydrologic properties of alluvial fans vary with the type of rock furnishing the material for the fan and the processes of weathering, transportation, and deposition. For example, a fan consisting of sand derived from the disintegration of granitic mountains may be pervious, whereas another constructed of material supplied by formations which disintegrate into clay and silt may be largely impervious (Tolman, 1937, p. 524). Each alluvial fan, therefore, has its own hydrologic character, and each should receive individual study.

The water supply of an alluvial fan depends upon the size of the drainage area tributary to the stream building the fan and upon the rainfall. Large water supplies, therefore, are found in the fans along the higher ranges. Deficient water supplies may be expected in the smaller fans bordered by small ranges. The quantity of water that actually gets underground, however, is controlled by the geologic structure of the fan, especially by the permeability of the channel of the feeding stream, and by the amount of rainfall on the basin.

The overall depositional pattern of an alluvial fan has a significant effect on its characteristics as an aquifer. Apex areas may be relatively permeable or impermeable, according to the particular fan. If highly permeable, as in fans in northeastern California (California Department of Water Resources, 1963, p. 64-65), the apex may be important as a recharge region and may also furnish large supplies of unconfined water to wells. If, however, the apex area is composed of older, weathered material or is dominated by debris flows, the average permeability may be considerably lower than that of the deposits farther down the fan (Davis and DeWeist, 1966, p. 396-397).

The deposits in an intermediate position tend to be reworked by streamflow and have moderate or high permeabilities despite smaller grain sizes. Water may be confined or unconfined.

The distal parts of alluvial fans generally consist of fine-grained material and interfinger with playa deposits if these are present. The zone as a whole is less productive than that of the central part, but beds of sand may yield supplies of confined water. In some areas, as in the Owens Valley, water moves down conduits to the lowest part of the fan and under natural conditions is discharged by leakage to the surface to form a swamp.

In fans composed largely of debris flows, these fine-grained layers constitute aquitards which impede ground-water movement. The only aquifers in such fans are divergent stream-channel deposits of gravel which are supplied by seepage from streams debouching from the mountains at the apex of the cones. Because the channel deposits are narrow and irregularly distributed, wells not far apart may differ notably from each other in the depth at which water is reached. Such conditions are characteristic of the great alluvial fans bordering the Sierra Nevada in the Owens Valley (Tolman, 1937, p. 62).

According to Bredehoeft and Farvolden (1964), the most productive aquifers in desert basins have been generally related by most workers to alluvial-fan deposits whose complex depositional pattern made the distribution of aquifers almost unpredictable. Bredehoeft and Farvolden found, however, in their study of the intermontane basins of northern Nevada, that the best aquifers were associated with the major tributary or tributaries of each valley. From this they concluded that alluvial-fan deposits are only a source of coarse material, and that sorting during the formation of flood-plain deposits is more important than the sorting which occurs as a result of normal alluvial-fan deposition.

THE SIMULATION MODEL

Geologic Setting

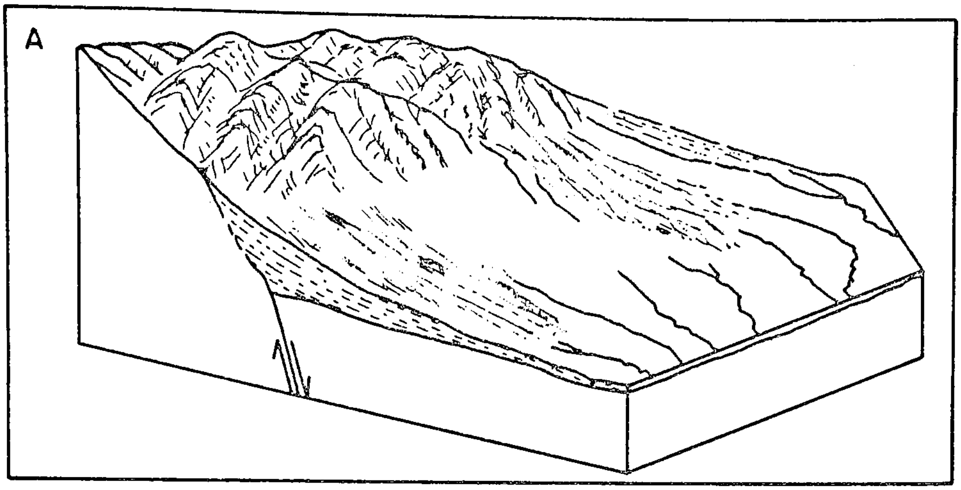
Initial Conditions

Because a relief differential between mountains and valley must be present in order for an alluvial fan to form, it is obvious that either upfaulting of the mountain block or downfaulting of the basin block must occur to initiate deposition of the fan sediments at time t_0. The magnitude of this initial uplift is designated as H'_0 and represents the elevation of the stream channel immediately north of the fault which forms the boundary between the uplifted mountain block on the north in the model and the depositional basin on the south. The initial node, or node where the model flow events originate, lies in this stream channel immediately north of the fault. Although the stream channel may lie at any distance x' east of the western boundary of the model, it is most convenient to place the node in the middle of the northern boundary at x' = 2, 150 feet, which corresponds to the coordinates I = 1, J = 22 in ALFAN. Finally, an initial value must be given to the thickness of immediately erodible material, y_s, in the source basin. If m_s is the maximum average thickness of immediately erodible material in the basin, then $0 \geq y_s \geq m_s$.

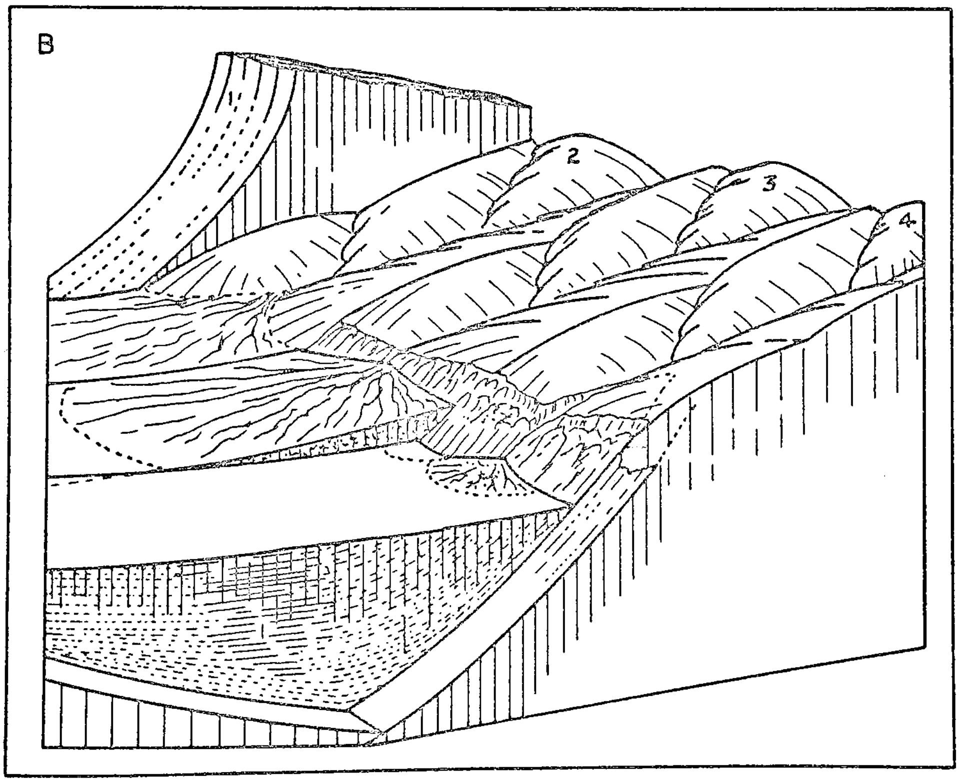
Boundary Conditions

Boundary conditions represent environmental restrictions on the operation of the alluvial-fan system. The boundaries consist of a mountain front at the apex of the fan, bedrock or other older strata beneath the fan, a playa, other fan, or free boundary at the foot of the fan, and other fans or free boundaries at the sides. Because of the nature of the model, the boundaries must perforce be somewhat generalized and diagrammatic. Two block diagrams, taken from the literature, that show alluvial-fan boundaries are given in figure 4. Boundary relationships similar to those shown in figure 4 are shown in a cross-sectional sketch of the Milner Creek fan (Beaty, 1970, fig. 3). The side boundaries of ALFAN may have any physical configuration. The basal or subfan boundary, however, is a horizontal plane at $z = 0$.

Mountain Front at Apex of Fan. A simple type of mountain-front boundary to model is a recent, geologically speaking, fault scarp, as shown in figure 4B. Such a scarp is relatively straight, and if assumed vertical, is the simplest possible mountain-front boundary to model. However, most faults are inclined at some angle to the vertical, and such representation is more realistic. In the Basin and Range province, dips of normal faults range from about 40° to 80° basinward and average about 60° near the surface (Hamilton and Myers, 1966, p. 527). The face of the fault may be curved, as shown in figure 4B, or eroded back to form a fault-line scarp, as in figure 4A. If the fault scarp is fresh,



A. FROM GREGORY, 1918, FIG. 114.



B. FROM DAVIS, 1925, FIG. 1.

Figure 4.--Block diagrams showing alluvial fans and boundary conditions.

the strike of the fault may be represented by a straight line (sections 3 and 4, fig. 4B). As erosion of the fault scarp takes place and the fan builds up, an embayment at the fanhead will be developed (section 2, fig. 4B).

Bedrock or Other Older Strata Beneath Fan. A fan may be underlain by faulted bedrock as shown in figure 4, or, less likely, by older strata of little or no dip, such as alluvium or a playa deposit. As Lustig (1965, p. 134) points out, it is not reasonable to assume that downfaulted basin floors are horizontal in the light of much seismic evidence to the contrary. On the other hand, if a depositional surface must be assumed, as in ALFAN, it is not unreasonable to assume a flat horizontal surface, as opposed to any other configuration. Although ALFAN in its present form does not provide for a different configuration of the initial depositional surface, the program could be modified to include a depositional base of any shape. It is of interest that Beaty (1970, p. 55) described the Milner Creek fan as probably underlain by an approximately horizontal bed of tuff. Alluvial fans deposited on essentially horizontal surfaces are also found in those areas where fan deposits have encroached upon undeformed lake clays (Bull, written commun., 1971).

Playa, Other Fan, or Free Boundary at Foot of Fan. If an alluvial fan is bounded on its lower end by a playa or fan from the opposite side of a closed basin, the boundary may be assumed to tend toward a steady-state condition as suggested by Hooke (1968, p. 616-617). Fluctuation of the boundary in response to changing conditions of sediment within the basin could be simulated by the addition of a stochastic component to the steady-state mean value of the boundary. If the boundary at the foot of the fan is free, growth of the fan is determined by the parameters and scale of the model.

Other Fans or Free Boundaries at Sides of Fan. The alluvial fan may be bounded on its sides by other fans, forming part of a coalescing system, or it may be unbounded and therefore able to grow freely. If the fan is part of a coalescing steady-state system, the boundary may be assumed to remain relatively stable, as suggested by Hooke (1968, p. 614-616).

Input Parameters

Input parameters are those variables which may be assigned values arbitrarily and which control the performance of the model. The parameters and their assigned values are given in the program output (see fig. 6). A listing of the parameters, with a brief discussion of some of their characteristics, is given below:

Grid spacing—In the examples of computer output given here, a 100-foot spacing is used.

Location of mouth of fan-building canyon—The canyon mouth is located in the center of the northern edge of the grid. The mouth could be located anywhere along the northern border, but its location in the center permits the development of symmetrical fan shapes.

Maximum length of fan-building period—This period represents the maximum possible time, in years, that the model may simulate. The actual period simulated may be much less than this if the number of flow events specified is reached first, or if the computer running time (CPU time) ends first.

Mean uplift rate—This rate refers to uplift of the mountain block relative to the basin of deposition as the result of an earthquake; it is given in uplifts per year.

Length of locus of points of maximum displacement along fault—The locus of points of maximum displacement of the fault is considered to lie along that portion of the fault centered about the canyon mouth supplying material to the fan. The length of the locus, in feet, is a parameter of the model. Any length may be specified, but the longer the length, the less the probability that the mountain block in the vicinity of the channel will be significantly affected by the earthquake.

Mean peak-flow rate—The value of this parameter, which is measured in cubic feet per second, is instrumental in determining the distance over which erosion may occur.

A constant relating peak-flow rate to number of steps in random walk—The purpose of the constant is to relate the degree of erosion by flow events to the mean peak-flow rate.

Mean rate of flow occurrence—This rate, in flows per year, is the frequency with which a certain class of storms visits the basin. This class is defined as consisting of all storms of sufficient magnitude to produce significant flows upon the fan.

Immediately erodible area of basin—That portion of the basin which supplies sediment to the debris flows and water flows is the immediately erodible portion. The immediately erodible area of a basin may be equal to the entire area of the basin, but it is generally much less. Examples of relatively small areas of the basin which may supply large amounts of sediment to flows, particularly debris flows, are trunk channels of the main stream, landslide areas, burned-over parts of the basin, or portions of the drainage area in which the rocks are particularly weak.

Average rate of development of weathered layer—This parameter is related to the immediate erodibility of rocks in the basin; the higher the rate, the greater the immediate erodibility.

Critical thickness of weathered layer in basin with regard to debris flow—If the thickness of weathered material, in feet, in the basin is greater than this critical amount, and a storm event strikes the basin, a debris flow will occur; if it is less than this amount, a water flow will take place.

Critical thickness of weathered layer in basin with regard to water flow—If the thickness of weathered material in the basin, in feet, is greater than this critical amount, a water flow will deposit sediment on the fan. If the thickness is less than this quantity, the water flow will erode previously deposited sediments.

Maximum thickness of weathered layer in basin—This parameter represents the greatest thickness of erodible material, in feet, that can accumulate in the basin. In basins in which debris flows occur frequently, it represents the thickness of accumulated material along the trunk channels and lower hillslopes.

Average rate of streambed erosion where fault crosses main stream channel—This parameter is particularly important when the rate of downcutting exceeds the rate of uplift. In this case the streambed is lowered to an elevation beneath the top of the fan deposits at the apex, and incision results.

Momentum coefficient—This coefficient expresses the fact that water flowing in a given direction has a tendency to continue flowing in the same direction, rather than turn. The value of the coefficient increases with increasing average stream discharge and decreases with increasing roughness of the topography and heterogeneity of the deposits. Values of the coefficient may be 1.0 or larger and are assigned on a qualitative basis. In ALFAN this value represents an average for a given fan; it is therefore the same for each flow event.

<u>Mean thickness of debris-flow deposits</u>—Most debris-flow deposits are a foot or more in average thickness and thin in the downstream direction.

<u>Mean thickness of water-flow deposits</u>—Most water-flow deposits are thinner than those of debris flows, averaging less than a foot in thickness.

<u>Lower limit of initial depositional thickness of debris flow</u>—The initial depositional thickness of a debris-flow deposit is set equal to the height of the fault scarp if the height of the fault scarp is less than the initial depositional thickness (stated as a parameter) and is equal to or greater than some arbitrarily established lower limit (DLIMIT). If the height of the fault scarp is less than DLIMIT, the debris flow will not be deposited until the random walk has traveled far enough down the fan that the elevation of the top of the deposit is not greater than the elevation of the top of the scarp where it crosses the stream channel. If this condition is never attained, i.e., if the elevation of the top of the deposit should always be greater than the top of the fault scarp, no deposition will take place on the fan.

<u>Lower limit of initial depositional thickness of water flow</u>—The initial depositional thickness of a water-flow deposit is set equal to the height of the fault scarp if the height of the fault scarp is less than the initial depositional thickness (stated as a parameter) and is equal to or greater than some arbitrarily established lower limit (WLIMIT). If the

height of the fault scarp is less than WLIMIT, the water flow will not be deposited until the random walk has traveled far enough down the fan that the elevation of the top of the deposit is not greater than the elevation of the top of the scarp where it crosses the stream channel. If this condition is never attained, i.e., if the elevation of the top of the deposit should always be greater than that of the top of the fault scarp, no deposition will take place on the fan.

Standard deviation of debris-flow bed thickness—Values are arbitrarily assigned to this parameter because little information is available.

Standard deviation of water-flow bed thickness—Values are arbitrarily assigned to this parameter because little information is available.

Coefficient of fixation—This parameter expresses a simple relation between grain size and slope.

Mean depth of erosion—This parameter expresses the average depth to which eroding water flows will remove deposits from the upper part of the fan. This same material will then be redeposited on a lower part of the fan.

Flow Chart and Output Data for Main Program

The flow chart in figure 5 describes the steps in the main program of ALFAN. Output data from the main program include title

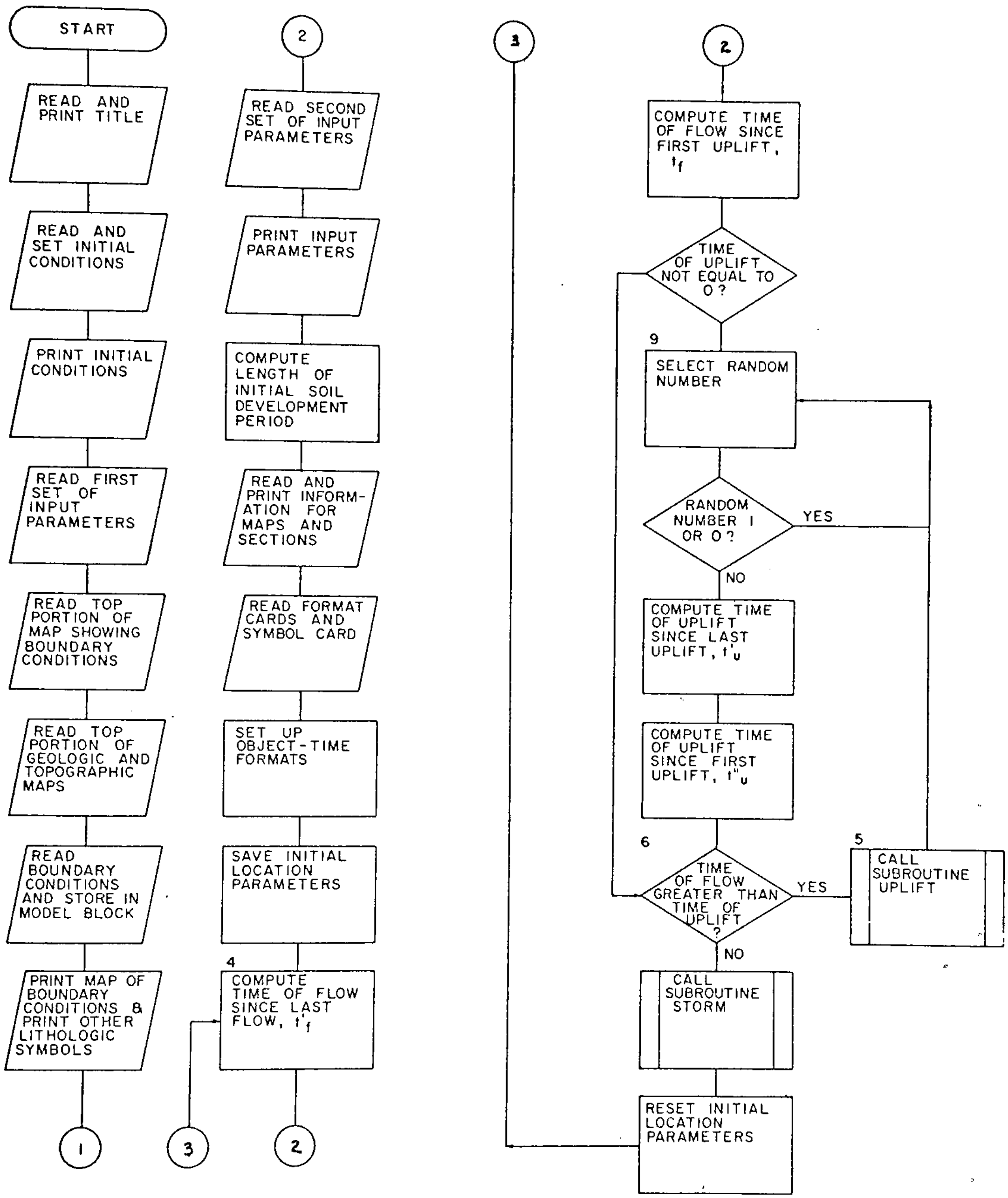


Figure 5.--Flow chart for main program of ALFAN.

information, a list of the initial conditions, a map of the boundary conditions (not to scale), a list of lithologic symbols used in printing the maps and sections other than those included in the map of boundary conditions, a list of the input parameters, and output information for the maps and sections. A typical sample of output data from the main program is shown in figure 6.

Relief Development

Faulting Relations

Relative Uplift. Much of the arid and semiarid portion of the United States lies within the Basin and Range province (Fenneman, 1946), whose major middle and late Cenozoic structures are dominated by normal faults bounding mountain blocks on one or both sides (Hamilton and Myers, 1966, p. 527). Development of the present relief features, then, has been in large part but not exclusively the result of normal faulting. Tectonic activity in the province is still continuing. According to Hamilton and Myers (1966, p. 532), the area is undergoing tension with an east-west component and also right-lateral shear along northwest-trending structures. The result of the total motion is oblique extension. They cite several examples in eastern California and western Nevada in which ranges pulled apart, leaving the intervening basins to move downward relative to the mountains. Thus, alluvial

PROGRAM FOR RANDOM-WALK SIMULATION OF ALLUVIAL-FAN DEPOSITION

INITIAL CONDITIONS

TIME OF FIRST UPLIFT IS 0.0 YEARS

INITIAL ELEVATION OF STREAM CHANNEL AT FAULT IMMEDIATELY FOLLOWING FIRST UPLIFT IS 4.00 FEET

COORDINATES OF INITIAL NODE ARE 1, 22, 2

INITIAL THICKNESS OF WEATHERED LAYER IN BASIN IS 1.0 FEET

BOUNDARY CONDITIONS

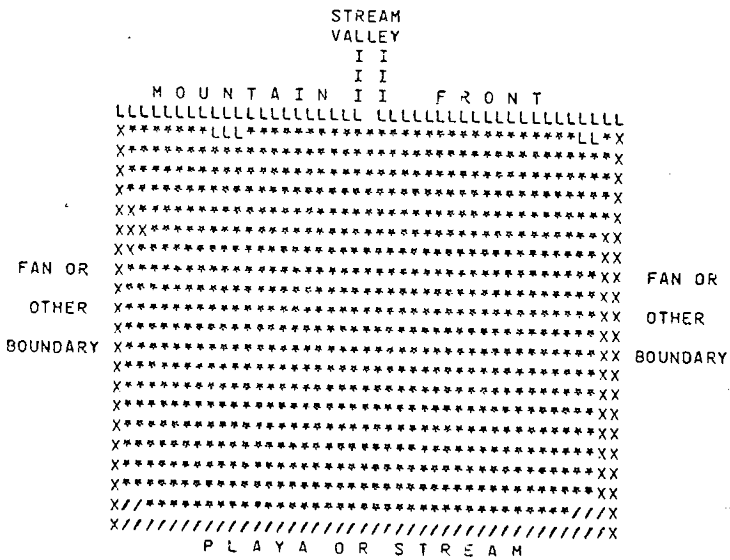


Figure 6.--Sample of output data from main program.

```
OTHER LITHOLOGIC SYMBOLS

        BEDROCK UNDERLYING FAN    ***

        DEBRIS FLOW               -0-

        WATER FLOW

                SILT              ---

                SILT AND SAND     -.-

                SAND              ...

                SAND AND GRAVEL   .0.


INPUT PARAMETERS

        GRID SPACING IS  100. FEET

        MOUTH OF FAN-BUILDING CANYON IS  2150. FEET EAST OF THE WESTERN BORDER OF THE GRID

        MAXIMUM LENGTH OF FAN-BUILDING PERIOD IS  10000.00 YEAR(S)

        MEAN UPLIFT RATE IS  .010 UPLIFTS PER YEAR

        LENGTH OF LOCUS OF POINTS OF MAXIMUM DISPLACEMENT ALONG FAULT IS  4300. FEET

        MEAN PEAK FLOW RATE IS      1000. CUBIC FEET PER SECOND

        CONSTANT RELATING PEAK FLOW RATE TO NUMBER OF STEPS IN RANDOM WALK IS       100.
```

Figure 6.--Sample of output data from main program—Continued

```
MEAN RATE OF FLOW OCCURRENCE IS   .010 FLOWS PER YEAR

ERODIBLE AREA OF BASIN IS    25000. SQUARE FEET

AVERAGE RATE OF DEVELOPMENT OF WEATHERED LAYER IS .0100 FEET PER YEAR

CRITICAL THICKNESS OF WEATHERED LAYER IN BASIN WITH REGARD TO DEBRIS FLOW IS  9.9 FEET

CRITICAL THICKNESS OF WEATHERED LAYER IN BASIN WITH REGARD TO WATER FLOW IS   .1 FEET

MAXIMUM THICKNESS OF WEATHERED LAYER IN BASIN IS 10.0 FEET

AVERAGE RATE OF STREAM BED EROSION WHERE FAULT CROSSES MAIN STREAM CHANNEL IS .0010 FEET PER YEAR

VALUE OF MOMENTUM COEFFICIENT IS   1.5

MEAN THICKNESS OF DEBRIS FLOW DEPOSITS IS  1.0 FEET

MEAN THICKNESS OF WATER FLOW DEPOSITS IS   .1 FEET

LOWER LIMIT OF INITIAL DEPOSITIONAL THICKNESS OF DEBRIS FLOW IS   .50

LOWER LIMIT OF INITIAL DEPOSITIONAL THICKNESS OF WATER FLOW IS   .05

STANDARD DEVIATION OF DEBRIS FLOW BED THICKNESS IS  .5

STANDARD DEVIATION OF WATER FLOW BED THICKNESS IS  .5

COEFFICIENT OF FIXATION IS   10000C.000

MEAN DEPTH OF EROSION IS   .10 FEET
```

Figure 6.--Sample of output data from main program—Continued

```
OUTPUT INFORMATION FOR MAPS AND SECTIONS

          NUMBER OF FLOW EVENTS SPECIFIED IS  32

          NUMBER OF MAPS TO BE PRINTED IS 64

          NUMBER OF TRANSVERSE SECTIONS TO BE PRINTED IS  8

          ROWS TO BE PRINTED ARE      2    3    4    5    6    7    8    9

          NUMBER OF LONGITUDINAL SECTIONS TO BE PRINTED IS 9

          COLUMNS TO BE PRINTED ARE    18   19   20   21   22   23   24   25   26

          MAXIMUM TIME FOR MODEL TO BE RUN IS 350. SECONDS
```

Figure 6.--Sample of output data from main program—Continued

fans may have developed as the result of absolute downward movement of the basin as well as uplift of the mountain block.

Earthquakes. The central problem is to determine the time distribution of relative uplifts. We have shown that, in the arid and semiarid Basin and Range province where many alluvial fans have developed, relative uplift in many cases is the result of normal faulting. However, faulting has been actually observed to occur together with twenty or thirty large earthquakes, and most important earthquakes are believed to have originated in this way (Richter, 1958, p. 5). Both the time distribution and magnitude of earthquakes have been extensively studied in attempts to predict their time of occurrence and intensity (e.g., Lomnitz, 1966; Cornell, 1968; Rikitake, 1969). This suggests, then, that the statistical distribution of earthquakes may furnish some clue as to the time distribution and magnitude of relative uplifts due to faulting.

Effects on Alluvial Fans. As figure 4 clearly demonstrates, alluvial fans may be bounded on the mountainward side either by fault scarps (fig. 4B) or fault-line scarps (fig. 4A). If the magnitude and/or frequency of faulting is sufficiently great, the fan material may abut the fault scarp. On the other hand, if these processes are sufficiently slow compared to erosion of the mountain front, subsequent faulting will dislocate an accumulation of the fan deposits as well as the bedrock (fig. 4B). For the sake of simplicity, this condition is neglected in the model, and the fans are considered to be unfaulted, regardless of the tectonic conditions.

It should be noted that if the increase in relative relief is due primarily to downdropping of the basin block in basins whose drainage is external and therefore subject to a regional base level, such a condition will favor a thicker accumulation of fan sediments than one in which uplift of the mountain block occurred.

Stochastic-Deterministic Model of Relief Development Due to Faulting

Time Distribution of Events. The most commonly used model to represent the time distribution of earthquakes is that based on the Poisson probability law. When applied to a stochastic process the law may be written as:

$$P\left[\{k\}\right] = e^{-\lambda t}\frac{(\lambda t)^k}{k!} \tag{8}$$

where

k = the number of occurrences of an event and is represented by the integers k = 0, 1, 2, . . . ,

λ = mean rate of occurrences of an event, and

t = a period of time (or space).

$P\left[\{k\}\right]$ then represents the probability that exactly k events will occur in a time period of length t.

The Poisson model, however, has not always given a good fit to earthquake data (see for example Knopoff, 1964). This has been attributed by some to the statistical dependency of earthquake data (Knopoff, 1964; Aki, 1956). Lomnitz (1966), however, feels that observed deviations from the Poisson distribution attributed to a dependence in time may in fact be due to spatial inhomogeneity. The Poisson process also has been used as the basis for seismic risk analysis (Cornell, 1968) and seems to be the most useful model presently available.

Our concern here, however, is primarily with the intervals between events in the Poisson process. Accordingly, we set k in equation (8) to zero and obtain:

$$P\left[\{0\}\right] = e^{-\lambda t} \tag{9}$$

which is the probability that exactly no events will occur in a time period of length t. The probability then that the first event will occur in this time interval is $\left[1-e^{-\lambda t}\right]$. Let the random variable T be the time of the first event. Therefore the cumulative distribution of T is:

$$F(t) = P\left[\{T \leq t\}\right] = 1-e^{-\lambda t}, \text{ for } t \geq 0.$$

The probability density function of T is then:

$$f(t) = \frac{dF(t)}{dt} = \lambda e^{-\lambda t}, \text{ for } t \geq 0. \tag{10}$$

This is the negative exponential distribution. The Poisson process, like the Markov process, has no memory. Therefore, the process starts anew after each event. The important point to be noted here is that the result for T verifies the fact that the probability distribution of time between successive events is exponential with parameter λ. The above result was lucidly derived by Hillier and Lieberman (1967, p. 294-295).

The Poisson process model with exponentially distributed interoccurrence times is then used to represent the time distribution of relative uplift events in program ALFAN. The parameter $\lambda = \lambda_u$ represents the mean rate of occurrence of these events, in uplifts per year, and is specified at the beginning of the computer program. Some idea of the values that may be assigned λ_u can be gained by a study made of a site in Turkey (Cornell, 1968, p. 1591). Assuming that all the earthquakes for a period of 1, 953 years occurred along the 650 km of the major fault system in the region, the average number of earthquakes in excess of magnitude 5 is $\lambda_u = 0.10$ earthquakes per year.

Interoccurrence times of the relative uplift events are randomly sampled from the negative exponential distribution by utilizing the random number generator of the computer. As suggested by Hahn and Shapiro (1967, p. 242), a two-parameter form of the negative exponential probability density function is employed:

$$f(t; \lambda_u, \mu) = \lambda_u e^{-\lambda_u (t-\mu)}, \ \mu \leq x < \infty, \ -\infty < \mu < \infty, \ \lambda_u > 0 \quad (11)$$

The first parameter, λ_u, scales the distribution, and the second parameter, μ, defines the distribution origin. If $\mu = 0$, equation (11) reduces to the one-parameter model of equation (10). The equation then programmed is:

$$t'_u = -\frac{1}{\lambda_u} \ln (1 - R_u) \qquad (12)$$

where R_u is a random value from a uniform distribution over the interval (0, 1), t'_u is in years, and λ_u is the parameter λ applied to uplift events. Use of equation (12) in this form, however, will result in either conceptual or computational difficulties. Accordingly, in program ALFAN R_u is restricted to the range $0 < R_u < 1$. Methods for generating exponential variates are also discussed by Naylor and others (1968, p. 81-86) and Pritsker and Kiviat (1969, p. 100).

By way of example, assume that in the region earthquakes equal to or greater than some specified magnitude recur on the average once every 10 years. Then, $E(t) = 10$. But $\lambda_u = 1/E(t) = 0.1$. Suppose the random value, R_u, chosen is 0.50. Then, by equation (12),

$$\begin{aligned} t'_u &= -10 \cdot \ln (1 - 0.50) \\ &= -10 (-0.69) \\ &= 6.9 \text{ years.} \end{aligned}$$

Stationarity of earthquake occurrences, although probably not present under natural conditions, is nevertheless assumed for the sake of simplicity in this model.

Magnitude Distribution of Events. The amount of relative uplift depends not only upon the maximum displacement on the mountain-front fault, but the location of this displacement with respect to the fan. Displacements may occur anywhere along the fault, and in this discussion it is assumed that the probability of a displacement occurring at a given point on the fault is equal throughout the length of the fault. A given fault movement has a finite length L_d and a maximum displacement D, vertical, horizontal, or oblique. It is furthermore assumed that the amount of vertical displacement declines linearly from the point of maximum displacement at the center of the fault movement to zero at either side (fig. 7).

The next problem is to relate the earthquake magnitude, M_e, to the source parameters L_d and D. Press (1967) has suggested the following equation from energy relations on a semi-empirical basis:

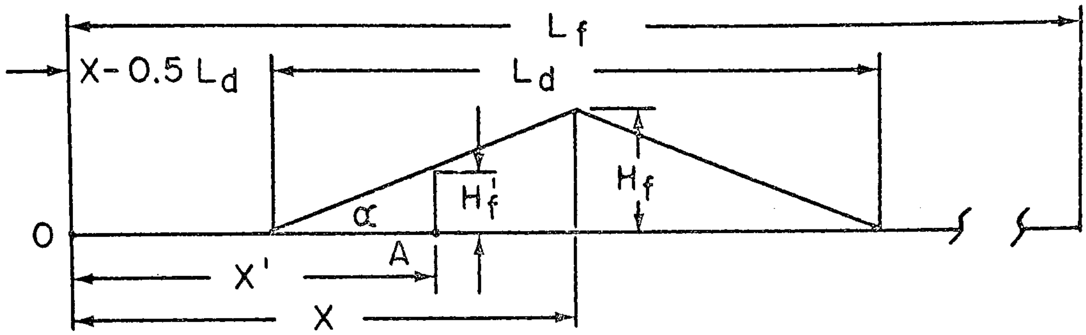
$$M_e = 1.6 \log L_d - 3.5 \qquad (13)$$

where L_d is in units of centimeters. The above is suitable for magnitudes less than 6. For magnitudes greater than 6, Press suggested:

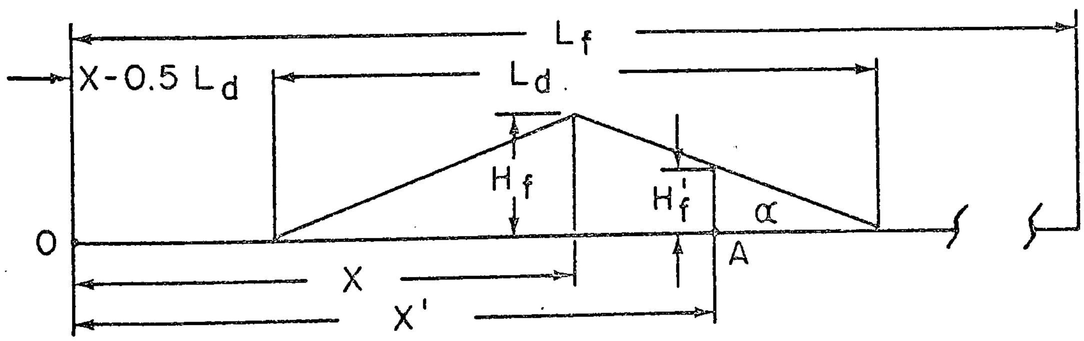
$$M_e = 1.06 \log L_d + 0.23 \qquad (14)$$

where L_d is in units of centimeters.

Chinnery (1969) found a linear relation between magnitude and displacement over the magnitude range of 3.4 to 8.3 of the form:



A. POINT OF MAXIMUM VERTICAL DISPLACEMENT, H_f, EAST OF STREAM CROSSING AT A



B. POINT OF MAXIMUM VERTICAL DISPLACEMENT, H_f, WEST OF STREAM CROSSING AT A

Figure 7.--Assumed relation of the length of movement, L_d, along a fault of length L_f, to the displacement of the fault, H_f, at the stream-channel crossing.

$$M_e = (1.32 \pm 0.16) \log D + (4.27 \pm 0.32) \quad (15)$$

where D is in units of centimeters and the error ranges represent 95 percent confidence limits. Using large magnitudes only, he obtained

$$M_e = (1.04 \pm 0.16) \log D + (4.96 \pm 0.37) \quad (16)$$

where D is in units of centimeters and the error ranges represent 95 percent confidence limits, which he considered likely to be nearer to the correct relationship. Chinnery based his conclusions primarily on data from strike-slip faults because the data from dip-slip faults show more scatter (Chinnery, 1969, p. 1972).

However, we make the assumption here that the results arrived at by Chinnery are equally applicable to dip-slip (or oblique-slip) faults. Inasmuch as faults in the Basin and Range province probably dip an average of about 60^{o}, it is necessary to apply a correction to the displacement data to obtain the relative gain in elevation. If H_f is the maximum vertical displacement, then $D = 1.1547 H_f$. Substituting in equation (15), we have:

$$M_e = 1.32 \log (1.1547 H_f) + 4.27$$

Transposing, and changing the units to feet:

$$H_f = \frac{10^{(M_e - 4.35)/1.32}}{30.48} \quad (17)$$

In the same manner, from equation (16) we obtain:

$$H_f = \frac{10^{(M_e - 5.02)/1.04}}{30.48} \tag{18}$$

We also may convert equations (13) and (14), respectively, to read:

$$L_d = \frac{10^{(M_e + 3.5)/1.6}}{30.48} \tag{19}$$

and

$$L_d = \frac{10^{(M_e - 0.23)/1.06}}{30.48} \tag{20}$$

In ALFAN, equations (17) and (19) are used for earthquake events of magnitude less than 6 and equations (18) and (20) for earthquake events of magnitude 6 or larger.

At this point it should be mentioned that the functional relations between earthquake magnitude, M_e, and the fault parameters D were developed from regression analyses and therefore represent the mean values of a statistical fluctuation. For this reason, if we were to accurately simulate magnitude from these same parameters, we should properly reintroduce the variance inherent in the original data. This is not done in order to simplify the model.

Finally, in order to determine the effect of the faulting on the trunk stream feeding the fan, it is necessary to ascertain the amount of displacement at the point x' where the main channel crosses the fault (fig. 7). The location of x' and the total length, L_f, of the fault bounding the mountain front are specified as initial conditions in program

ALFAN. Because the probability of an earthquake event occurring at any point along the fault is assumed equal, the point of maximum displacement, x, along the fault is given by $x = (4300 - L_f)/2 + x_\ell$, where $x_\ell = L_f R_u$. The amount of vertical displacement at the channel crossing is then

$$H'_f = (x' - x + 0.5\,L_d)H_f/0.5\,L_d, \qquad (x - x') < 0.5\,L_d \tag{21}$$
$$= 0 \qquad \text{otherwise}$$

assuming that the point of maximum displacement, H_f, lies to the east of the stream crossing. If H_f is to the west of the channel crossing $(x' > x)$, then H'_f is calculated from

$$H'_f = (x - x' + 0.5\,L_d)H_f/0.5\,L_d, \qquad (x' - x) < 0.5\,L_d \tag{22}$$
$$= 0 \qquad \text{otherwise.}$$

If $x = x'$,

$$H'_f = H_f. \tag{23}$$

All units are in feet and tenths of a foot. Over a period of time and repeated uplift events,

$$H_T = \sum_{i=1}^{n} H'_{fi} \tag{24}$$

where H_T is the elevation of the fan apex after n uplifts.

By way of an example, suppose that $M_e = 4.3$; applying equations (17) and (19), respectively, we have:

$$H_f = \frac{10^{(4.3 - 4.35)/1.32}}{30.48}$$

$$= 0.03 \text{ feet;}$$

$$L_d = \frac{10^{(4.3 + 3.5)/1.6}}{30.48}$$

$$= 2,400 \text{ feet.}$$

Suppose that the length of the locus of points of maximum displacement, L_f, along the fault is 1,000 feet. Picking a random number R_u = 0.094 from a uniform distribution, we compute

$$x_\ell = L_f R_u$$

$$= 1,000\ (0.094)$$

$$= 94 \text{ feet.}$$

We assume that the length of the locus of points is centered about the canyon mouth, x' = 2,150 feet east of the origin. Therefore, the point of maximum displacement is x = (4,300 - 1,000)/2 + 94 = 1,744 feet east of the western boundary of the model grid.

Because x lies to the west of the channel crossing, we use equation (22) to calculate H'_f:

$$H'_f = (1,744 - 2,150 + 0.5\,(2,400))\,0.03/0.5\,(2,400)$$

$$= 0.02 \text{ feet.}$$

Again, if M_e = 7.1, we apply equations (18) and (20), thus:

$$H_f = \frac{10^{(7.1 - 5.02)/1.04}}{30.48}$$

$$= 3.4 \text{ feet}$$

$$L_d = \frac{10^{(7.1 - 0.23)/1.06}}{30.48}$$

$$= 102,000 \text{ feet.}$$

Suppose the point of maximum displacement is 2,462 feet east of the western boundary; applying equation (21), we have:

$$H'_f = (2,150 - 2,462 + 0.5(102,000))3.4/0.5(102,000)$$

$$= 3.4 \text{ feet.}$$

The magnitude of the parameters is such that there is essentially no difference between H_f and H'_f.

We have utilized a functional relationship $H' = f(L, H)$. But $(L, H) = f(M_e)$; we need therefore to determine the magnitude, M_e. According to Lomnitz (1966, p. 389) and Epstein and Lomnitz (1966, p. 254) the distribution of magnitudes in the time series represented by equation (8) may be formulated by a negative exponential distribution of the type:

$$f(M_e, \beta) = \beta e^{-\beta(M_e - M_0)} \qquad (25)$$

where M_0 is the minimum magnitude of events to be considered, and $f(M_e)$ is the frequency of occurrence of events of magnitude M_e.

In order to compute $f(M_e, \beta)$ from equation (25) it is necessary to assign values to M_0 and β. The value given to M_0 is arbitrary. Lomnitz and Hax (1966) were unable to detect any clustering of earthquake events above magnitude 4.0, thus implying that shocks of larger magnitude from different epicenters can be treated as independent random events. Cornell (1968, p. 1586) suggests that, from an engineering standpoint, events of magnitude less than 4 may be ignored. Accordingly, we set M_0 equal to 4.0.

The value of β may be determined from b in the well-known formula of Gutenberg and Richter (1954, p. 17)

$$\log N = a + b\,(8 - M) \tag{26}$$

where N is the annual frequency of earthquakes, M is the magnitude, and a and b are constants; b is a slope coefficient expressing the rate at which magnitude increases as frequency decreases. For shallow shocks Gutenberg and Richter give $b = 0.90 \pm 0.02$. These parameter values apply within the range M = 6.0 to M = 8.25. Above magnitude 8.25 the number of observed shallow shocks falls off more rapidly than equation (26) indicates. β may then be calculated from (Lomnitz, 1966, p. 390):

$$\beta = b/\log_{10} e \tag{27}$$

$$= 0.90/0.434$$

$$= 2.07.$$

Below M = 6.0 the statistics are reliable only for limited regions, as for example southern California. In the southern California area Gutenberg and Richter (1954, p. 18) determined $b = 0.88 \pm 0.03$, the logarithmic law applying down to magnitude 4. In this case, $\beta = 2.02$.

In order to obtain a random value of the magnitude M' we represent equation (25) on the digital computer as (Hahn and Shapiro, 1967, p. 242):

$$M' = -1/\beta \cdot \ell n(1 - R_u) + M_0 \tag{28}$$

By way of example, assume that a random number, R_u, is drawn and is equal to 0.5. If a trial calculation using equation (28) indicates that the calculated magnitude will be less than 6.0, a β of 2.02 is used, and

$$M' = \frac{1}{2.02}\ell n(1 - 0.5) + 4.0$$

$$= 4.35.$$

We have then created a stochastic model of relative uplift in both time and space. It should be noted that we have assumed, as Rikitake (1969, p. 83, 92) has done, that the time and magnitude distributions are independent of each other. As in the case of the relationship between earthquake magnitude and fault parameters, there is no attempt to reproduce the variance inherent in the original data.

The functional relations just described, with one exception, are used as a basis for constructing computer subroutine UPLIFT (fig. 8), which computes the amount that the basin drainage above the fault is raised relative to the area of fan deposition. The one functional relationship not included in UPLIFT is that which determines the time of the uplift event. This relationship is given by equation (12), and therefore inclusion of equation (12) in the main program (fig. 5) is necessary in order to call subroutine UPLIFT into action at the appropriate time.

A summary of values of the principal variables used in computing the magnitude of each uplift event is given for each event in the

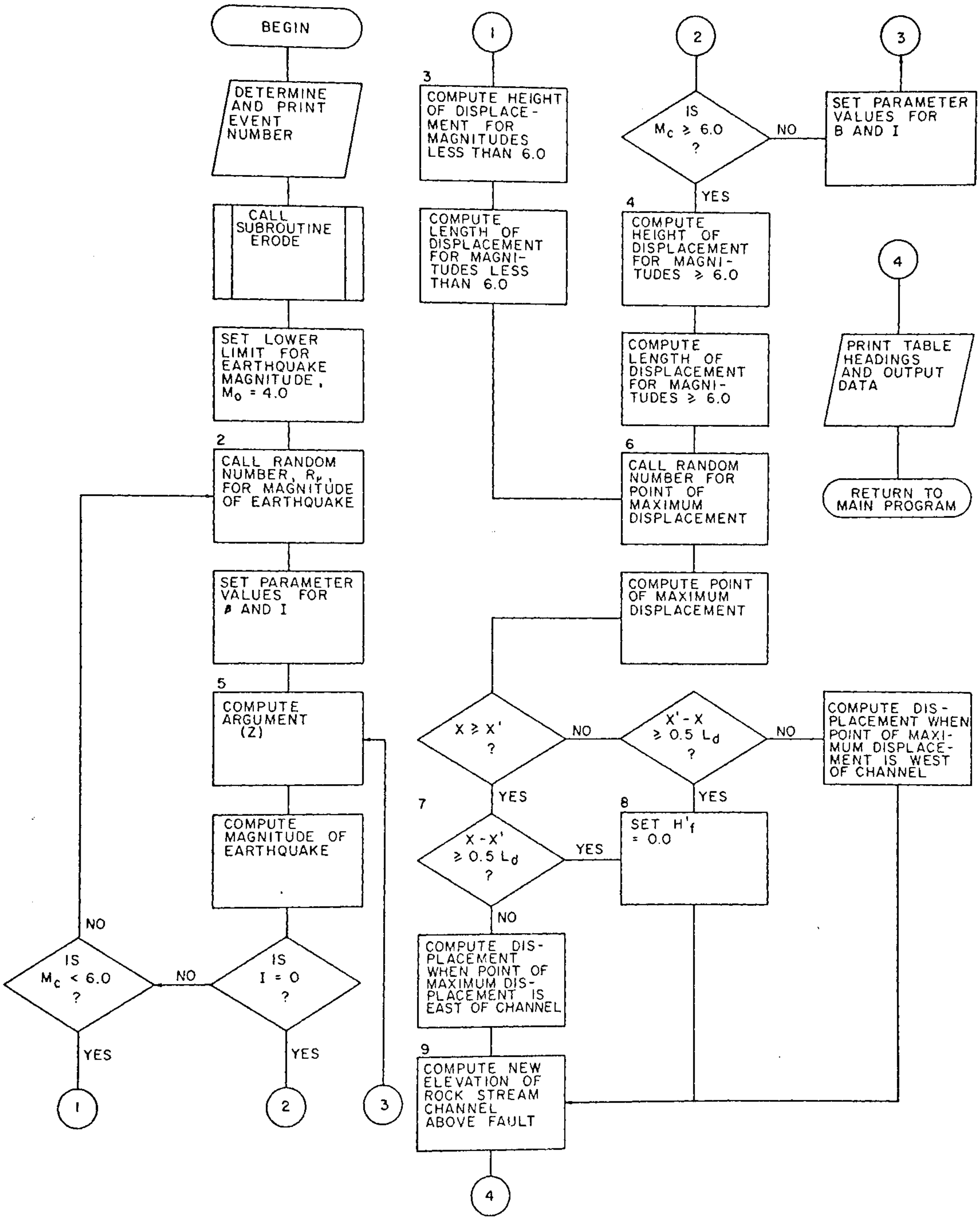


Figure 8.--Flow chart for subroutine UPLIFT.

computer printout. A sample of the computer printout for the numerical example presented earlier in this section is given in figure 9.

Drainage Basin Processes

Accumulation of Immediately Erodible Material

From the standpoint of alluvial-fan deposition, the processes of principal interest in the drainage basin are the rate of accumulation of weathered material and the rate of erosion. Rates of weathering are controlled principally by temperature, quantity of water and its rate of movement, acidity (pH), and the properties of minerals and mineral assemblages. Rates range from less than 1 inch in 5, 000 years to several inches in a year (Leopold, Wolman, and Miller, 1964, p. 116). The rate of weathering considered over a period of time determines the thickness of the weathered layer, provided no erosion takes place. Leopold, Wolman, and Miller suggest that this thickness (depth of the weathered zone) is an exponential function of time. The total rate of accumulation of weathered material over an entire basin will also be a function of time if the basin increases in area with time.

In ALFAN, the depth of this weathered layer is considered to be equal to the thickness of material that is available for erosion and transport to the alluvial fan. Considered over a long period of time, the rate of accumulation of the weathered material will tend to equal the rate of its removal. But rates taken over a short period of time may be

SUMMARY OF UPLIFT EVENT

EVENT NUMBER	TIME, IN YEAR(S) SINCE INITIAL UPLIFT	BETA	MAGNITUDE OF EARTHQUAKE	HEIGHT OF DISPLACEMENT, IN FEET	LENGTH OF DISPLACEMENT, IN FEET
2	50.86	2.02	4.3	.03	2378.

POINT OF MAXIMUM DISPLACEMENT EAST OF THE WESTERN BOUNDARY, IN FEET	DISPLACEMENT AT FAN APEX, IN FEET	NEW ELEVATION OF CHANNEL AT FAN APEX FOLLOWING UPLIFT, IN FEET
2352.	.02	3.80

Figure 9.--Computer printout summarizing uplift event.

very different, as for example during a storm. The rates of erosion in the basin are generally estimated from the rates of deposition on the fan.

Croft (1962, p. 1521-1522) estimated annual sedimentation rates for four drainage basins along the Wasatch Mountain front that were known to have produced mudflows. The annual rates for the Bairs, Farmington, and Parrish watersheds, where vegetation and soil were seriously damaged—presumably by fire or overgrazing—on less than 10 percent of the areas, were 2.1×10^{-2} inches (1.75 feet per 1,000 years) for the period 1912-47, 4.5×10^{-2} inches (3.75 feet per 1,000 years) for the period 1923-47, and 11.7×10^{-2} inches (9.75 feet per 1,000 years) for the period 1930-47, respectively. In contrast, the near-pristine Morris watershed had an annual rate of 4.7×10^{-5} inches (0.0039 foot per 1,000 years) for the period 1935-58. Watershed use, then, had increased the sedimentation rates 450, 1,000, and 2,500 times, respectively. Bull (1964b, p. 37) determined that at least 31 acre-feet of material was deposited on the Arroyo Hondo fan during the 1957-58 season, representing a sediment yield of 1.2 acre-feet or 2,300 tons per square mile of drainage basin. Bull (1964b, p. 37) also estimated the rate of deposition at three places on the Arroyo Hondo fan. Not all parts of the Arroyo Hondo fan (or other alluvial fans) receive deposits at the same time. Deposition occurs downslope from the end of the stream channel, and the rest of the fan does not receive deposits until the stream switches to that part of the fan. Thus, the basic model of deposition on alluvial fans is one of continuous deposition on the fan as a whole and intermittent deposition at specific points on the fan. Locally, gaps in the depositional record of several thousand years are commonplace.

Thus, the mean rate of an alluvial-fan accumulation at a given point is a function of time. The maximum depositional rates occur during those brief intervals when the stream is actively depositing at a given point throughout the time period being considered, and the minimum depositional rate is for a long-term rate of accumulation of fan deposits, which is sufficiently long to include deposition on all parts of the fan. For the Arroyo Hondo fan, a 40-year period of record indicated a depositional rate of 0.7 foot per decade (70 feet per 1,000 years). At a second locality on the fan a radiocarbon date indicates that during the past 1,040 $\pm$ 200 years the mean rate of deposition has been about 1.1 feet per 100 years. For the Arroyo Hondo fan as a whole, the mean rate of deposition during the last 600,000 years has been about 1.0 foot per 1,000 years.

In the Soviet Union, Chebotarev (1966, p. 424) reports that the amount of erosion from watersheds in the Caucasus and central Asia during the period of mudflows is 16-26 mm per km^2 [sic].

Erosional rates on basins are comparable to depositional rates on their fans only if the basin and fans are of equal area. Because this is rarely the case, rates will be lower for the feature of larger area and higher for the feature of smaller area in a basin-fan system. On the Arroyo Ciervo fan, the average rate of deposition for the eight-season period 1956-63 was 25,500 tons per season, which is equivalent to a sediment yield of about 3,200 tons per square mile of drainage basin. If this rate represents the entire Arroyo Ciervo basin, the basin is being eroded at a rate of about 2 feet per 1,000 years. Ruhe (1967, p. 28) estimated a deposition rate of 1 foot per 445 years (2.24 feet per 1,000 years) for Organ sediments in southern New Mexico. Bull (written commun., 1971) reports that the depositional rate on fans in the San Joaquin Valley has ranged from 0.8 foot per 1,000 years to 1.5 feet per 1,000 years during the past 600,000 years. Beaty (1970, p. 57-58) estimated that the Milner Creek fan was built at an average rate of accumulation of 3,200 cubic yards per year. This amounts to an alluviation of about 0.25 to 0.50 foot per 1,000 years, assuming the material were spread evenly over the growing fan. According to Bull (personal commun., 1971), in areas of rapid accumulation of fan sediments, 4,000 to 10,000 flood events are needed to deposit 100 feet of sediments over an entire alluvial fan over a period of 100,000 years (1 foot per 1,000 years). Table 1 summarizes erosional and depositional rates in basins and on fans. The higher rates for the Bairs, Farmington, and Parrish watersheds, as compared to the Morris watershed, are probably due to land usage (Croft, 1962, p. 22-24).

TABLE 1

EROSION AND DEPOSITION RATES FOR SELECTED BASINS AND FANS

Basin or fan	Erosion rate (in feet per 1,000 years)	Deposition rate (in feet per 1,000 years)	Length of record (in years)
Basin			
Bairs	1.75	---	36
Farmington	3.75	---	25
Parrish	9.75	---	18
Morris	.0039	---	24
Arroyo Ciervo	2	---	8
Fan			
Arroyo Hondo	---	1.5	600,000
Organ surface	---	2.24	2,500
San Joaquin Valley	---	0.8 -1.5	600,000
Milner Creek	---	0.25-0.50	700,000

Stream-Channel Erosion

Another process of interest is channel degradation in the basin. Relative rates of channel aggradation and mountain-front uplift are instrumental in determining the general form of the fan and loci of deposition. Information on the rates of valley cutting is not abundant. Leopold, Wolman, and Miller (1964, p. 457) report an annual rate of 0.13 foot for valley cutting of alluvial fills in Tesuque Valley, New Mexico, over a period of 150 years. This rate is comparable in magnitude to rates of erosion observed below dams. These rates would seem to be orders of magnitude higher than long-term average rates.

Mathematical Modeling of Basin Process Rates

The volume of weathered material in the fan basin tends to increase with time as the depth of weathering increases and as the area of the basin increases. The increase in thickness of the weathered layer is assumed to be exponential and is represented in ALFAN by:

$$y_s = m_s (1 - e^{-\eta t}) \qquad (29)$$

where

y_s = thickness of the weathered layer,

m_s = maximum thickness of weathered layer,

ϵ = dimensionless constant equal in numerical value to m_s,

$\eta = \frac{\epsilon c}{m_s}$, in which c = rate of soil development in feet per 1,000 years, and t = a time increment, in thousands of years.

Equation (29) is shown graphically in figure 10. As the figure indicates, the thickness of the weathered layer developed is a function of time and the rate of increase of weathered thickness, and therefore is an important factor in determining the type of flow—debris flow, water flow, or eroding water flow—that will take place on the fan model. The data in table 1 are of some help, at least as far as orders of magnitude are concerned, in assigning values to the parameters in equation (29).

Assuming that m_s = 10 feet, c = 0.01 foot per year, and that the initial thickness of erodible material is 0.0 foot, after 5.78 years the thickness of erodible material that would have accumulated is

$$y_s = 10\left[1 - e^{-0.01(5.78)}\right]$$
$$= 0.56 \text{ foot.}$$

This is a very high value and could represent the weathering of a material like mudstone that slakes rapidly after periods of alternate wetting and drying.

In ALFAN, it is assumed that the fan source basin and adjacent drainage basins meet at sharp divides, so that there is little or no lateral migration of divides, only lowering. Under these conditions, basin area will remain constant with time.

Soil development in ALFAN is modeled by subroutine BASOIL (fig. 11).

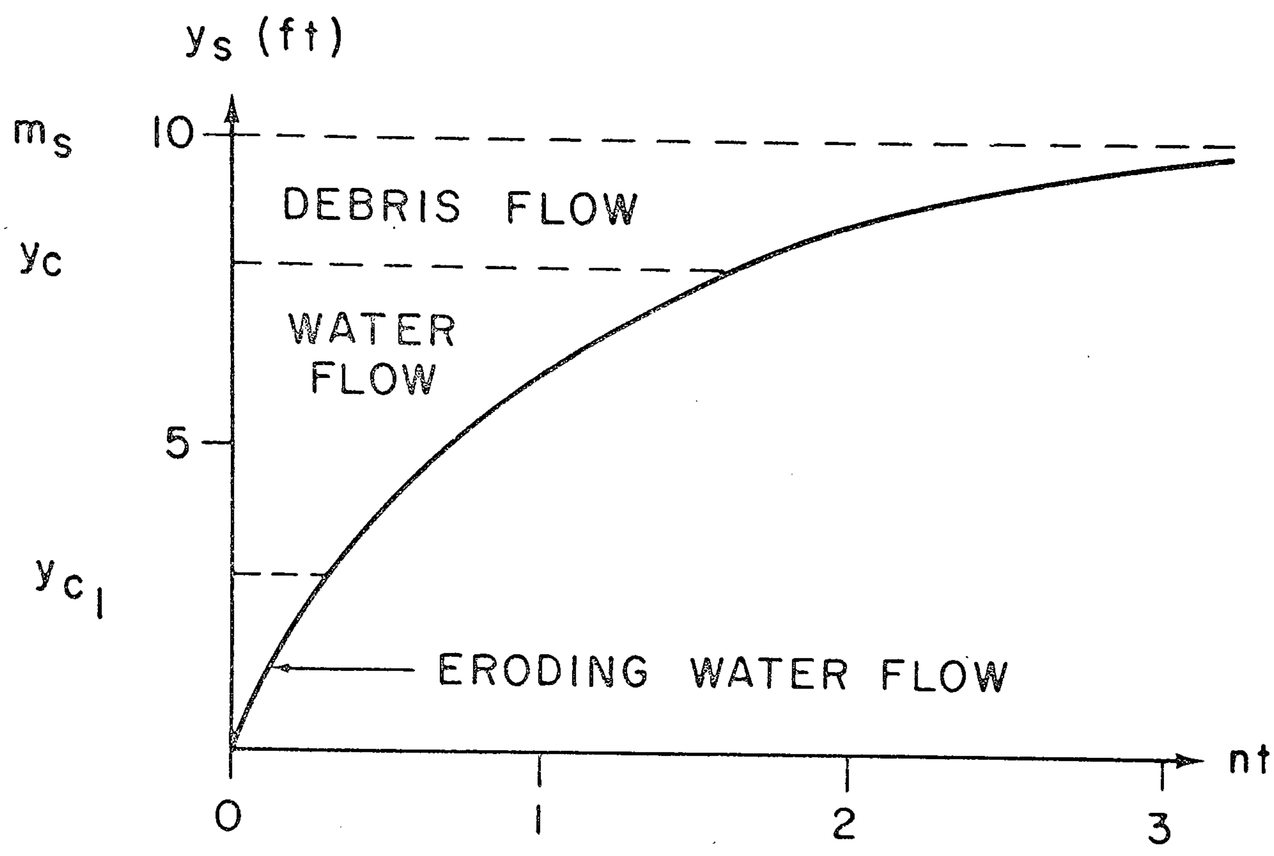


Figure 10. --Graph showing rate of increase of weathered layer in basin, and critical values for flow events in model ALFAN.

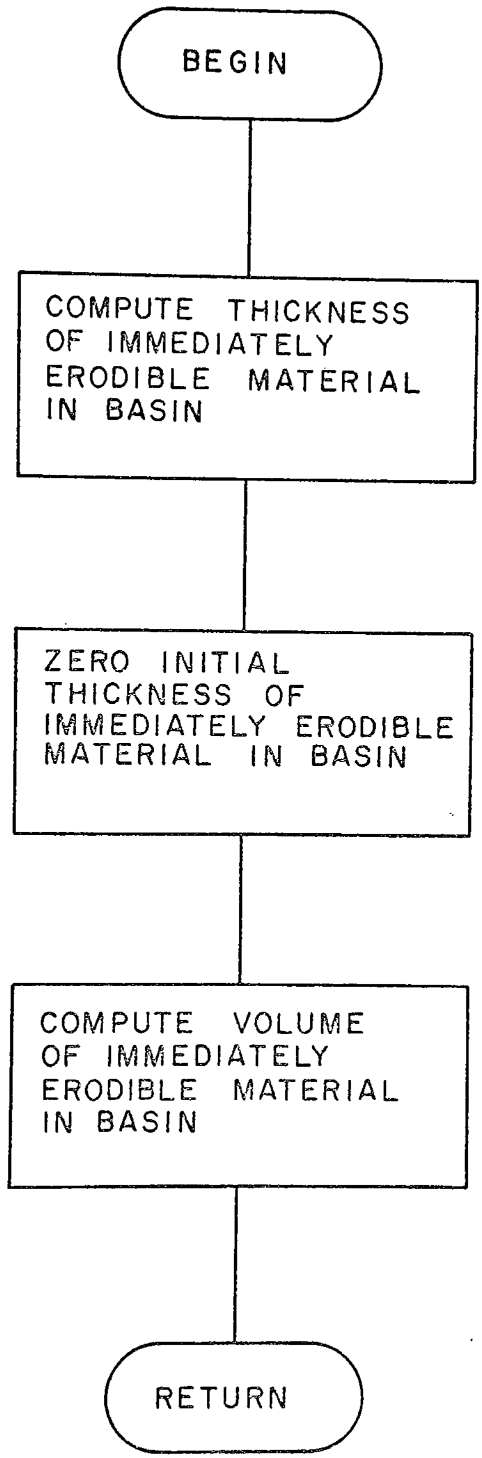


Figure 11.--Flow chart for subroutine BASOIL.

Following each uplift, erosion is assumed to lower the stream channel in the basin. We are particularly interested in the magnitude of this degradation at the point where the mountain boundary fault crosses the main stream channel. Here, erosion is assumed to lower the stream channel according to the exponential relation

$$h = H_0 e^{-kt_i} \tag{30}$$

where h is the elevation of the streambed, in feet, above base level, at a particular time, t_i; H_0 is the elevation of the streambed, in feet, above base level immediately following an uplift at time t_0; and k is a dimensionless parameter which expresses the average rate of decline of the rock channel in the vicinity of the fault crossing.

Suppose that the average channel degradation rate is 0.001 foot per year, H_0 is 128.04 feet, and we wish to determine h at the end of 61.74 years. We have, from equation (30),

$$h = 128.04\, e^{-0.001\,(61.74)}$$

$$= 121.15 \text{ feet.}$$

Channel degradation in ALFAN is modeled by subroutine ERODE, whose flow chart is shown in figure 12.

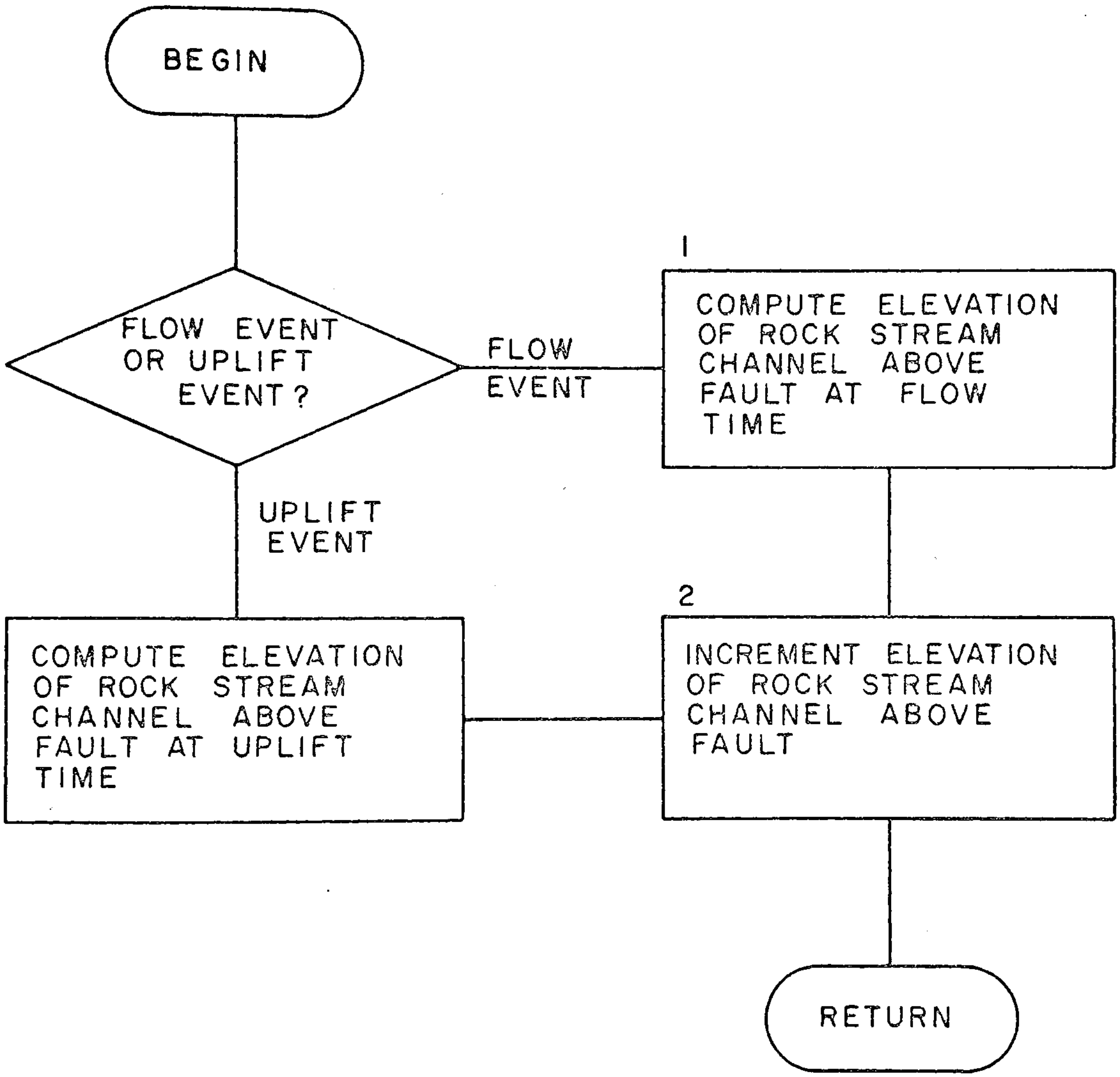


Figure 12.--Flow chart for subroutine ERODE.

Flow Events

Spatial Representation

Description of Grid. Deposits of alluvial-fan material are represented on a rectangular grid at least as large as the alluvial-fan system (fig. 13). The grid is oriented with north at the top. The mountain front is assumed to lie along the north or top part of the grid, and the fan-building stream to flow south, east, or west from near the middle of the mountain front. The significance of points A, B, and C is explained later in the text.

Form of Deposits. Simulated flow events may proceed north, east, south, or west. They follow grid lines at all times, depositing sediment of a given type, character, and thickness at each node. Deposits are assumed to be continuous between adjacent grid intersections (nodes) along the lines of flow, and to extend a distance equal to half the distance between nodes on either side of the line of flow. In section, the deposits are rectangular with the long axis horizontal. Successive deposits lie on top of each other to form a three-dimensional model.

Time Distribution

Frequency and Timing of Debris Flows. The frequency of major debris flows in a given stream system depends largely upon the occurrence of an intense rainfall in the catchment basin and on the rate of accumulation of alluvium and colluvium on its trunk canyon floor

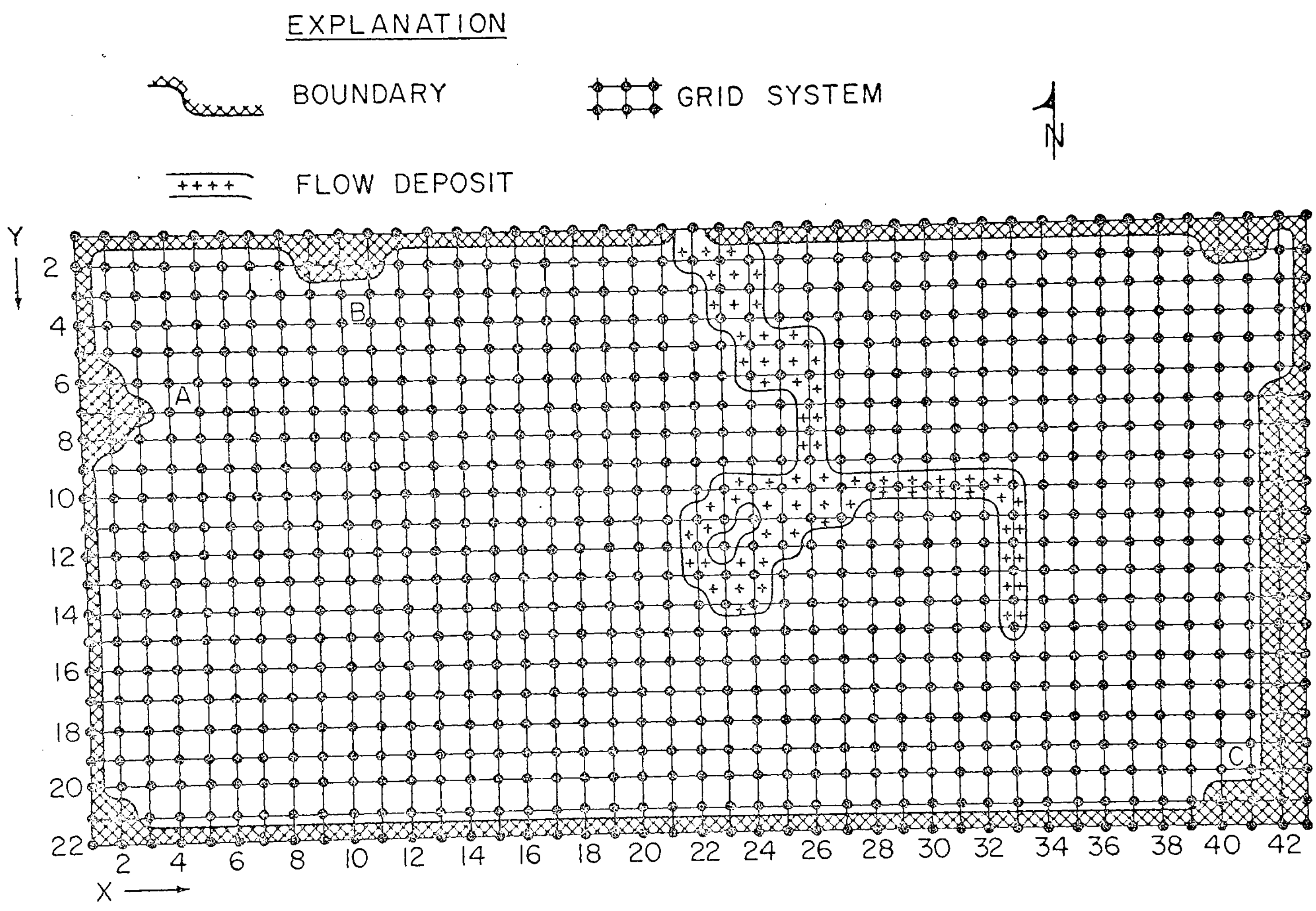


Figure 13.--Map showing grid system, boundaries, and flow deposit.

(Blackwelder, 1928, p. 467; Troxell and others, 1942, p. 373-374; Beaty, 1970, p. 73-74). McGee (1897, p. 108), Blackwelder (1928, p. 469), and Davis (1938, p. 1344) considered that such flow events were separated by decades or by centuries of time. The January 1969 flooding that produced large debris flows near Glendora, California, was estimated by Giessner and Price (1971) to have a recurrence interval greater than 70 and perhaps greater than 100 years. However, Bull (1964b, p. 22) studied alluvial fans in western Fresno County on which mudflows deposited fresh material every year between 1955 and 1960. Woolley (1946, p. 75-76) also recorded two to four mudflows per season on several streams in Davis County, Utah, in the summer of 1930. Nevertheless, Croft (1962, p. 1512-1513) pointed out that the frequency of some present-day debris flows may not represent the frequency of past debris flows because man's use and abuse of the land has accelerated the process of erosion.

Frequency and Timing of Water Flows. Little information is available on the frequency and time of water flows that deposit material on fans. Eckis (1928, p. 125) reports that the runoff from streams in the Cucamonga district, California, is seldom sufficient to carry coarse debris out onto the fans more than once or twice during the winter, and that in dry winters it fails to do so at all. This is also true of the fans in western Fresno County studied by Bull (written commun., 1971).

Mathematical Models. It is evident from the preceding that flow events that either erode or deposit significant quantities of sediment on fans are generally of the nature of extreme hydrologic events. There are no models as such for the time distribution of flow events on fans (Wolman and Miller, 1960, p. 71-72), but models have been developed for infrequent hydrologic events such as floods (Shane and Lynn, 1964; Kirby, 1969; Todorovic and Zelenhasic, 1970), droughts (Szigyarto, 1960), high-intensity rainfall (Thom, 1959), and oceanic storm waves (Borgman, 1963). Nearly all these models are based upon or utilize the fact that many infrequent hydrologic events follow a Poisson process with exponentially distributed interoccurrence (or intercedence) times. We therefore use equations (8) and (10), previously developed in the section dealing with the time distribution of uplift events, to also describe the time distribution of flow events on the fans.

When applied to flow events, equation (10) may be written in the form

$$f(t_f, \lambda_f) = \lambda_f e^{-\lambda_f t} \qquad (31)$$

where λ_f = the mean rate of occurrence of flow events, and

t_f = a period of time.

The return period, $1/\lambda_f$, must be specified initially in the program. As regards mudflows, the return period ranges from at least yearly (Bull, 1964b, p. 22) to a hundred years or more, judging by the intensities of rains producing mudflows (Croft, 1967, p. 6-8). The frequency of debris flows in some areas in recent times, however, is very probably due to man's interference, and is therefore not an indication that such frequencies obtained in the past (Croft, 1967, p. 22-25). On the other hand, little information is available on the frequency of water flows large enough to deposit significant quantities of sediment on fans.

When programmed for the digital computer, equation (31) is written

$$t'_f = -\frac{1}{\lambda_f} \ell n (1 - R_u) \qquad (32)$$

where t'_f is in years, and R_u is a random value from a uniform distribution over the interval (0, 1). As in the case of equation (12), R_u is restricted to the range $0 < R_u < 1$.

The time of flow events in ALFAN is computed by equation (32) in the main program, whose flow chart is given in figure 5. The procedure used is to select a random time for a flow event and also a random time for an uplift event. The two times are compared, and the earlier is chosen. If the event chosen is an uplift event, subroutine STORM is called. The event selected is then immediately replaced with a random value of the <u>same</u> type of event, and the process is repeated.

The primary task of subroutine STORM, whose flow chart is shown in figure 14, is not to compute functional relationships but to call certain subroutines at the proper time. STORM calls the basin

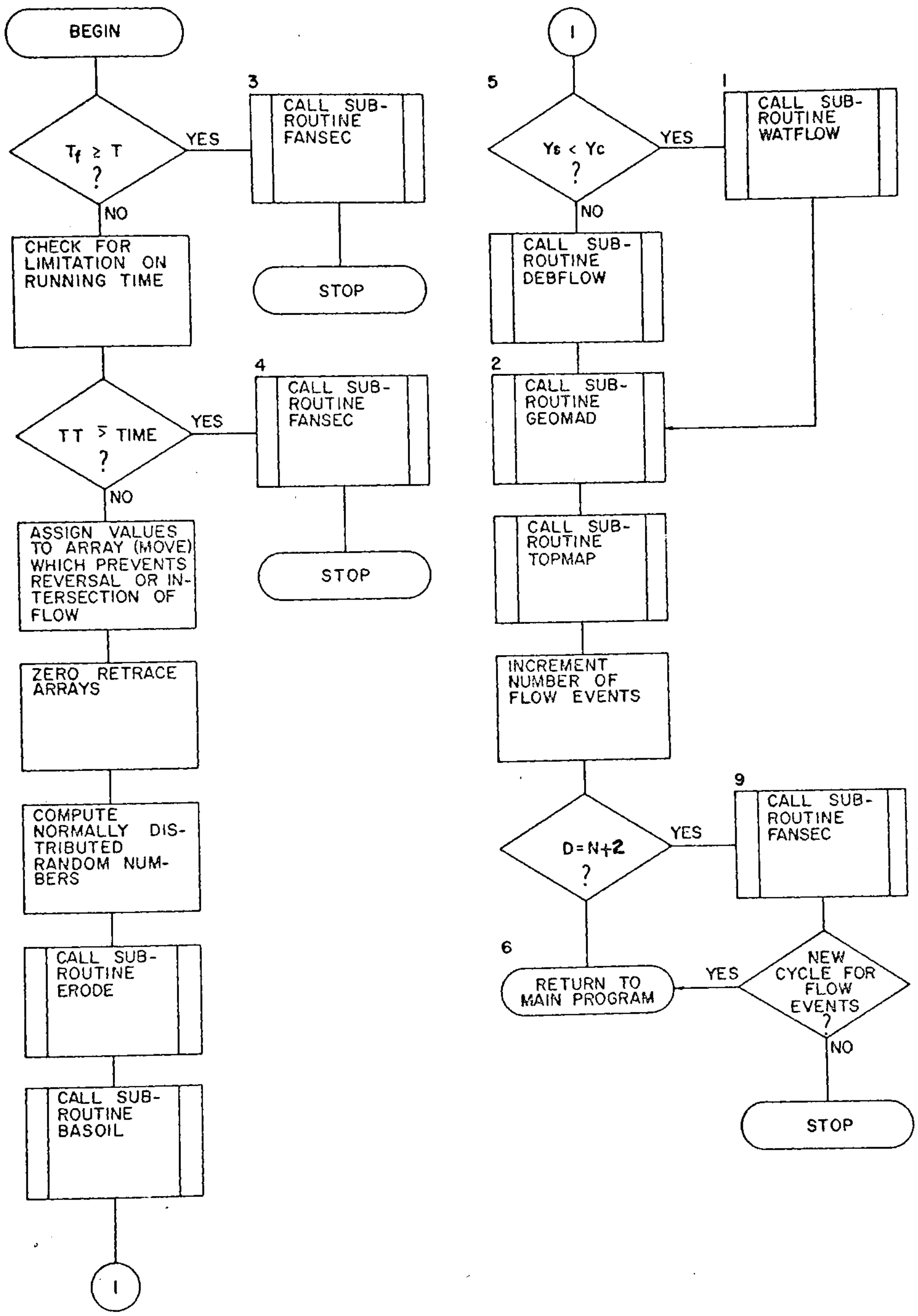


Figure 14.--Flow chart for subroutine STORM.

subroutines BASOIL and ERODE, then decides which depositional subroutine, DEBFLOW or WATFLOW, should be brought into action. When the flow event has been completed, STORM orders subroutine GEOMAP to print a geologic map of the fan surface and TOPMAP to print a map showing elevations on the fan surface. Finally, when all flow events have taken place, or the time period for development of the fan has been reached, or the stipulated running time for the model has been completed, STORM calls subroutine FANSEC, which prints out tabular data for the geologic sections.

Magnitude Distribution

The infrequent flow events modeled in ALFAN are large flow events which may either deposit material on the upper part of the fan or erode material from the upper part of the fan and deposit it on the lower. Which of the two events occurs depends in large part on conditions of accumulation of weathered material in the basin. The rate of accumulation of weathered material is discussed in the section "Accumulation of Immediately Erodible Material"; in this section we are concerned only with the magnitude of storms and water flows which produce significant changes on fans.

Debris Flows. If severe storms occur on basins where much readily erodible material is present, particularly in trunk channels, debris flows may result. On August 13, 1923, debris flows occurred from canyons in the Wasatch Mountains near the towns of Willard and Farmington, respectively 50 and 15 miles north of Salt Lake City, Utah. At Salt Lake City 0.35 inch of rain fell in 5 minutes, and 1.05 inches in half an hour (Pack, 1923, p. 351). The storm lasted 2 hours and the total precipitation was 1.23 inches; during the period of greatest downpour 0.1 inch of water fell in 1 minute. The return period for a storm of this intensity in this area is about 100 years (Hershfield, 1961, p. 21). Croft (1967, p. 25) determined that a reasonably heavy rainfall of 1 to 2 inches coupled with high intensity rates of 4 to 8 inches per hour, plus a good-sized areal coverage, were needed to initiate most debris flows.

Troxell and Peterson (1937, p. 54, 67-68) estimated the maximum discharge of water to be 645 cfs per square mile during two debris flows in Pickens and Verdugo Canyons, California, assuming that the rate of rainfall was 1.5 inches per hour for 15 minutes throughout the drainage area of Pickens Canyon, and that the mean rate of runoff was 1 inch per hour. They also estimated the discharge from 19 square miles of the Verdugo Creek drainage to be about 320 cfs.

Other factors contributing to debris flows are the presence of antecedent moisture in the weathered layer and undercutting of incoherent material that has accumulated on the lower slopes and along the trunk streams.

Water flows. If, on the other hand, severe storms occur on basins where smaller quantities of erodible material are present, water flows may result. If the quantity of erodible material is sufficiently small and the volume of water sufficiently large, stream channels may be deepened enough to produce trenching (see references under temporary entrenchment, Bull, 1964a, p. 121). According to Bull, variation in the intensity and amount of rainfall is the most likely regional cause of fanhead trenching in western Fresno County, California. Two periods of fanhead trenching after 1854 were recorded. One was from about 1875 to 1895, the other from about 1935 to 1945. Many channels were deepened 25 to 40 feet. Rainfall data from five stations in central California show two periods of much greater than average rainfall, which were also periods of high frequency of large daily rainfall. For example, in 1875-95 and 1935-45 the number of days of rainfall of more than 0.50 inch in Sacramento were among the highest on record (Bull, 1964a, p. 122).

Mathematical Models. The magnitudes of flood events have been modeled by Shane and Lynn (1964, p. 9-12) and Todorovic and Zelenhasic (1970, p. 1646-1647) using an exponential distribution of magnitudes. Shane and Lynn employed the density function

$$f(y, \gamma) = 1/\gamma e^{-(y-v)}, \; y > 2, \; \gamma > 0 \qquad (33)$$

where y = peak flow rate magnitude,

v = base flow, and

$\gamma = \bar{y} - v$.

Because the base flow on alluvial fans is of little or no significance, $v = 0$, and γ = the mean peak-flow rate; $f(y, \gamma)$ then becomes a density function of flow events on the fan, and may be written:

$$f(y) = \frac{1}{\gamma} e^{-y/\gamma}, \gamma > 0 \qquad (34)$$

Equation (34) is then represented on the digital computer in the form:

$$y' = -\gamma \ell n(1 - R_u) \qquad (35)$$

where y' = a random value of the mean peak-flow rate, and

R_u = a random value from a uniform distribution over the interval (0, 1). In program ALFAN, R_u is restricted to the range $0 < R_u < 1$.

The assumptions made here are the same as those made by Todorovic and Zelenhasic (1970, p. 1646), viz. that the y_i are independently distributed random variables with distribution function $P(y_i \leq x)$ and that y_i and t_i, the time associated with each flow event, are mutually independent sequences.

The Flow Event as a Markov Process in the Horizontal Plane

Definition and General Description. Flow events in program ALFAN are represented as discrete time, continuous state, stochastic processes. A stochastic process, defined as an indexed collection of random variables X_t, $\{X_t\}$, is said to have the Markovian property if:

$$P\left\{X_{t+1} = j \middle| X_0 = k_0,\ X_1 = k_1, \ldots,\ X_{t-1} = k_{t-1},\ X_t = i\right\}$$

$$= P\left\{X_{t+1} = j \middle| X_t = i\right\} \tag{36}$$

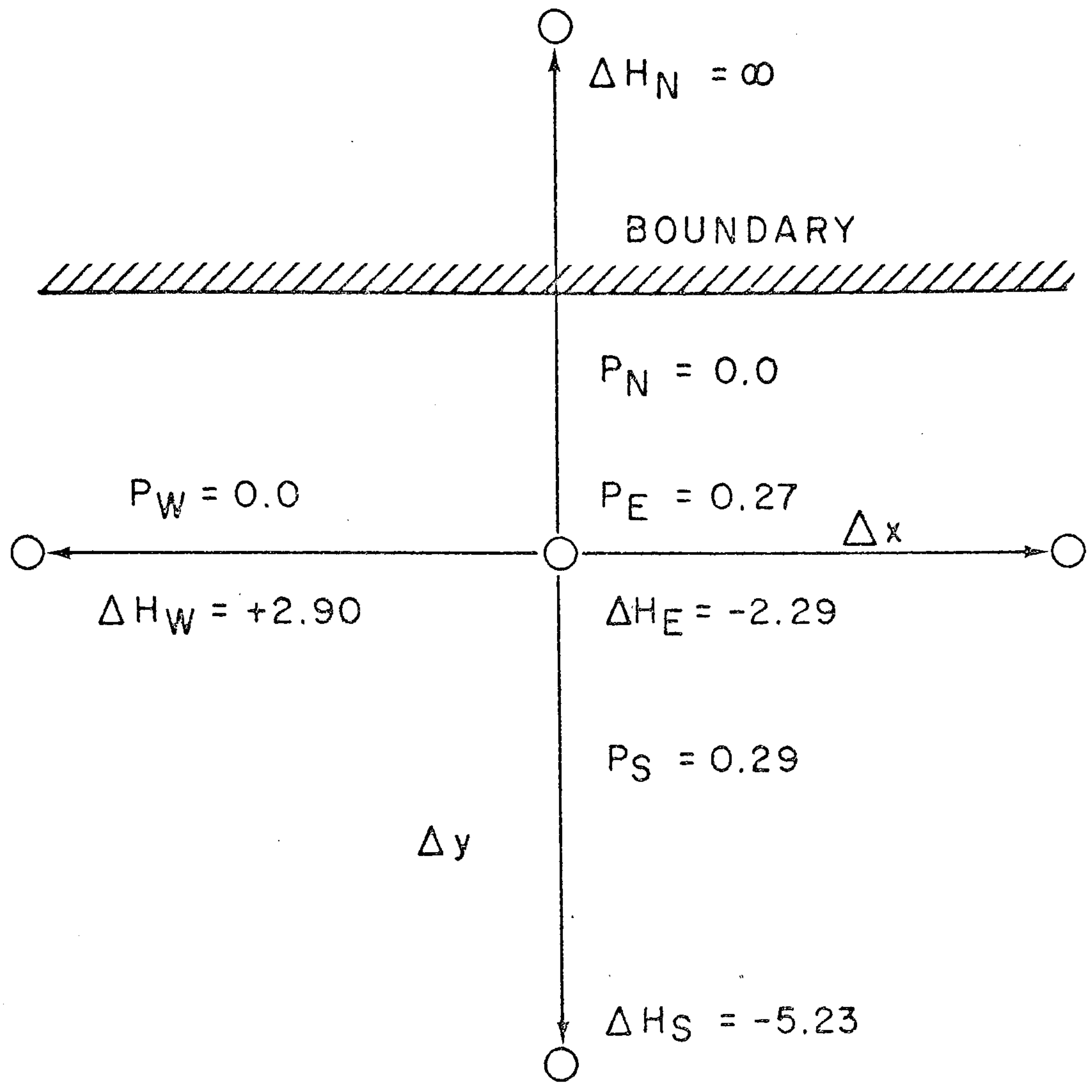
for $t = 0, 1, 2, \ldots$ and every sequence, $i, j, k_0, k_1, \ldots, k_{t-1}$ (Hillier and Lieberman, 1967, p. 403). This Markovian property states that the conditional probability of being in any future state, given any past state and the present state $X_t = i$, is independent of the past state and depends only on the present state of the process. In ALFAN, the condition at every node at a given time $t = 0, 1, 2, \ldots$ for each flow event beginning at $t = 0$ represents a state of the system. This condition is the elevation of the top of the latest deposit at the node.

Transitional Probabilities. The probabilities

$$P_{ij} = P\left\{X_{t+1} = j \middle| X_t = i\right\} \tag{37}$$

are called one-step transitional probabilities, and in ALFAN are the probabilities that a flow event will move to another node lying to the north, east, south, or west. The manner in which the transitional probabilities are computed is illustrated in figure 15. The subscript k indicates the direction of movement—north (N), east (E), south (S), or west (W).

In order to compute the P_k the computer searches each surrounding node. The value of the transitional probability is obtained by



$\Delta x = \Delta y = 100$ FEET

ΔH = DIFFERENCE IN ELEVATION BETWEEN CENTRAL AND OUTLYING NODE

p = PROBABILITY OF MOVEMENT IN THE GIVEN DIRECTION

Figure 15.--Diagram illustrating method of computing transitional probabilities.

first subtracting the elevation of the central node from the elevation of each of the surrounding nodes. If the difference, Δh, is positive for any node, the probability of the flow moving to that node is assigned the value 0. If the result is negative or zero, it is considered possible that flow may move in the direction of that node, and the gradient is computed in that direction. The assumption is then made that the probability that a flow event will move in a given direction is proportional to the gradient in that direction:

$$P_s \propto s \tag{38}$$

where P_s is the probability corresponding to the given slope. Furthermore, it is assumed that if $s = 0$, $P_s = 0.25$, and that if $s = 1$, $P_s = 1.000$. We may then compute P_s from the following relation:

$$P_s = 0.25 + as \tag{39}$$

where a is a constant of proportionality relating $s = \sin\alpha$ to the probability, P. The value of a is 0.75, from whence we obtain:

$$P_s = 0.25 + 0.75\,s \tag{40}$$

The value of the gradient, s, is computed differently for debris flows and water flows. In the case of water flows the gradient is computed from the base of the flow at the central node to the adjacent nodes. Hence, the gradient for water flows is the land-surface gradient. For debris flows, however, the gradient is computed from the top of the debris flow at the center node. Thus, debris flows in ALFAN are able to move upgradient to adjacent nodes, provided the land-surface elevation at the adjacent node is not higher than the elevation at the top of the debris flow.

Using the data given in figure 15, we may compute the transitional probabilities as an example. For the north direction, a boundary is encountered. In ALFAN, this is equivalent to a highly positive gradient, and therefore $P_N = 0.0$. In the east direction

$$\Delta H_E = -2.29 \text{ feet}$$

$$\tan\alpha \approx \sin\alpha = -0.0229$$

$$P_E = 0.25 - 0.75\,(-0.0229)$$

$$= 0.27.$$

In the south direction

$$\Delta H_S = 5.23 \text{ feet}$$

$$\tan\alpha \approx \sin\alpha = -0.0523$$

$$P_S = 0.25 - 0.75\,(-0.0523)$$

$$= 0.29.$$

In the west direction a positive gradient is encountered, and $P_W = 0.0$.

Once a stream flows in a given direction, it has a tendency to continue in the same direction. Thus, if all other factors are equal, the probability that a stream will move straight ahead will be greater than the probability that it will turn to the right or to the left. This accounts for the fact that gradients along radial lines adjacent to the mountain front are steeper than the gradient along the medial radial line (Hooke, 1966). ALFAN, then, "remembers" in which direction the previous step was taken and weights the transitional probability of movement in this direction by the multiplicative variable INERTIA. The value assigned to the parameter INERTIA may be 1.0 or greater. In the programs run for illustration purposes for this paper, INERTIA was given a value of 1.5.

Assume now that the previous direction of flow was to the east. Weighting P_E, we have

$$P_E \times I = F_E$$

$$0.27 \times 1.5 = 0.40$$

where I is the value assigned to INERTIA and F_E is simply a weighted flow value and no longer a probability.

In order to recompute the probabilities we take:

$$\Sigma F = F_N + F_E + F_S + F_W$$

$$= 0.0 + 0.40 + 0.29 + 0.0$$

$$= 0.69$$

and

$$P'_N = F_N/\Sigma F = 0.0$$

$$P'_E = F_E/\Sigma F = 0.58$$

$$P'_S = F_S/\Sigma F = 0.42$$

$$P'_W = F_W/\Sigma F = 0.0.$$

Because we have postulated a uniform distribution, we establish the ranges 0.0 to 0.57 for movement to the east and 0.58 to 1.00 for movement to the south. A random number, R_u, is then selected. We find $R_u = 0.01222$. Therefore the flow moves to the east.

Relation to Random Walks. A random walk is a Markov chain with the property that if the system is in a state i then in a single transition the system either remains at i or moves to one of the states immediately adjacent to i (Hillier and Lieberman, 1967). Each flow event in ALFAN is therefore properly regarded as a random walk in two dimensions. The computer printout for a typical random walk in ALFAN is shown in figure 16. This particular walk governed the deposition of the second debris flow shown in figure 23.

Reflecting Barriers. In random-walk terminology, the boundaries to the north, east, and west of the alluvial-fan system are called reflecting barriers. These barriers may be the mountain front or other alluvial fans at the sides. Let us then represent the grid system shown in figure 13 in terms of x and y coordinates. Suppose point A is the position of a future flow event. If the gradient allows, the flow is free to move north, east, or south; but the flow cannot move west because of the presence of a barrier at $x = 3\frac{1}{2}$, $y = 7$. If a random number selected from the generator of the computer indicates a move in that direction, the flow does not move but remains at $x = 4$, $y = 7$. By the same reasoning, a flow at point B may not move north, or a flow at point C east.

SUMMARY OF DEBRIS FLOW EVENT

EVENT NUMBER	TIME, IN YEAR(S), SINCE INITIAL UPLIFT	VOLUME OF SEDIMENT IN FLOW, IN CUBIC FEET	ELEVATION OF STREAM CHANNEL AT FAULT CROSSING, IN FEET
8	391.95	236863.37	6.49

STEP	SLOPE FROM CENTER NODE				PROBABILITY OF FLOW				RANDOM NUMBER	DIRECTION OF FLOW	CONDITION OF FLOW	NEW NODE	
	NORTH	EAST	SOUTH	WEST	NORTH	EAST	SOUTH	WEST				COORDINATES	ELEVATION
1	--	--	-.0486	--	0.00	0.00	1.00	0.00	.74016	SOUTH	DEPOSIT	2, 22	4.40
2	--	-.0249	-.0400	-.0440	0.00	.28	.43	.29	.85699	WEST	DEPOSIT	2, 21	1.91
3	--	--	-.0172	-.0191	0.00	0.00	.40	.60	.05620	SOUTH	DEPOSIT	3, 21	2.02
4	--	-.0163	-.0202	-.0183	0.00	.28	.43	.29	.46127	SOUTH	DEPOSIT	4, 21	1.74
5	--	-.0154	-.0155	-.0155	0.00	.29	.43	.29	.18021	EAST	DEPOSIT	4, 22	1.85
6	-.0145	-.0030	-.0165	--	.29	.42	.29	0.00	.26997	NORTH	DEPOSIT	3, 22	1.96
7	--	-.0032	--	--	0.00	1.00	0.00	0.00	.36190	EAST	DEPOSIT	3, 23	3.11
8	-.0121	-.0139	-.0157	--	.28	.43	.29	0.00	.11021	NORTH	DEPOSIT	2, 23	3.30
9	--	-.0148	--	--	0.00	1.00	0.00	0.00	.92107	EAST	DEPOSIT	2, 24	3.12
10	--	-.0312	-.0140	--	0.00	.61	.39	0.00	.29057	EAST	DEPOSIT	2, 25	1.22
11	--	-.0122	-.0122	--	0.00	.60	.40	0.00	.81659	SOUTH	DEPOSIT	3, 25	1.13
12	--	-.0113	-.0113	--	0.00	.40	.60	0.00	.75642	SOUTH	DEPOSIT	4, 25	1.04
13	--	-.0104	--	--	0.00	1.00	0.00	0.00	.37578	EAST	DEPOSIT	4, 26	.96
14	-.0096	-.0096	--	--	.40	.60	0.00	0.00	.46507	EAST	DEPOSIT	4, 27	.87
15	-.0087	-.0087	-.0087	--	.29	.43	.29	0.00	.07947	NORTH	DEPOSIT	3, 27	.78
16	-.0078	-.0078	--	-.0078	.43	.29	0.00	.29	.15830	NORTH	DEPOSIT	2, 27	.70
17	--	-.0070	--	-.0070	0.00	.50	0.00	.50	.75709	WEST	DEPOSIT	2, 26	.61
18	--	--	-.0061	--	0.00	0.00	1.00	0.00	.87057	SOUTH	DEPOSIT	3, 26	.52
19	--	-.0070	--	--	0.00	1.00	0.00	0.00	.79544	EAST	DEPOSIT	2, 28	.43
20	--	-.0043	-.0043	--	0.00	.60	.40	0.00	.86507	SOUTH	DEPOSIT	3, 28	.35
21	--	-.0035	-.0035	--	0.00	.40	.60	0.00	.78230	SOUTH	DEPOSIT	4, 28	.26
22	--	-.0026	-.0026	--	0.00	.40	.60	0.00	.89558	SOUTH	DEPOSIT	5, 28	.17
23	--	-.0017	-.0017	-.0017	0.00	.29	.43	.29	.34299	SOUTH	DEPOSIT	6, 28	.09

Figure 16.--Computer printout for a random walk which governs the deposition of a debris flow.

The method for determining the transitional probabilities and the effect of reflecting barriers in ALFAN is shown in the flow chart for subroutine FLOW (fig. 17).

Channel Entrenchment. Channel entrenchment may be classed as temporary or permanent. Temporary entrenchment is "normal" in the sense that it is part of the normal fan-building process in which material must be periodically transported across upper parts of the fan and deposited at points more distant from the source area. Such transportation is accomplished primarily by water flows in entrenched channels (Troxell and Peterson, 1937, p. 173; Buwalda, 1951, p. 1497; Hawley and Wilson, 1965, p. 24; Lustig, 1965, p. 174; Hooke, 1967, p. 456; Beaty, 1968, p. 50; Hooke, 1968, p. 612, 614). Generally speaking, temporarily entrenched channels are shallow enough that overbank deposition, particularly by debris flows, may still occur.

Temporary entrenchment may be caused by (1) alternation of debris flows and water flows (Bluck, 1964, p. 399; Hooke, 1965, p. 138-141, 1967, p. 457); (2) shift of the locus of deposition to a lower area on the fan that has not received sediment for some time (Hooke, 1967, p. 458); (3) runoff from particularly intense storms (Bull, 1964a, p. 122-125, 1968, p. 103; Hooke, 1968, p. 622-623; Beaty, 1970, p. 66); (4) plugging of channel by debris flows, resulting in channel diversion and renewed channel entrenchment on another part of the fan (Beaty,

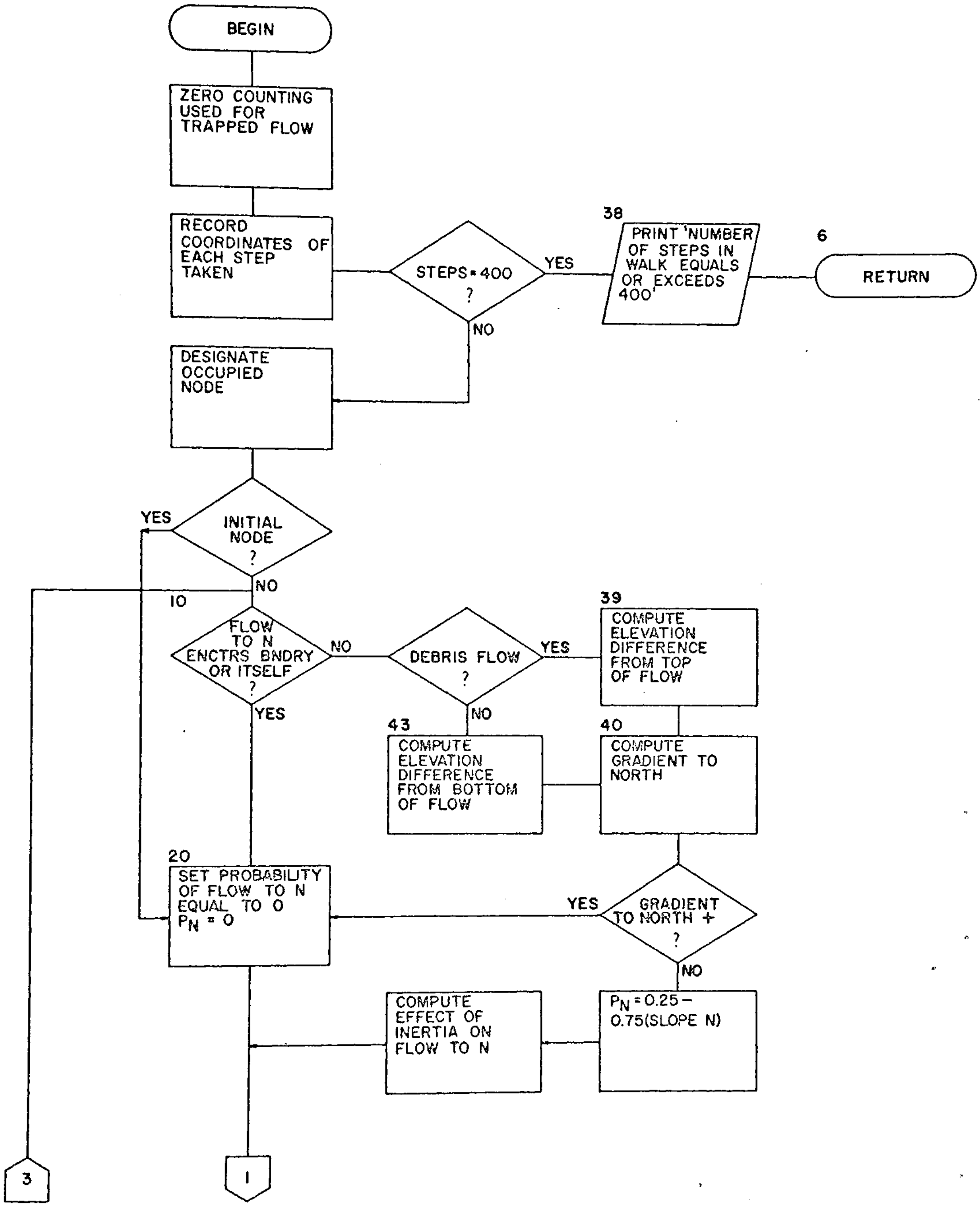


Figure 17.--Flow chart for subroutine FLOW.

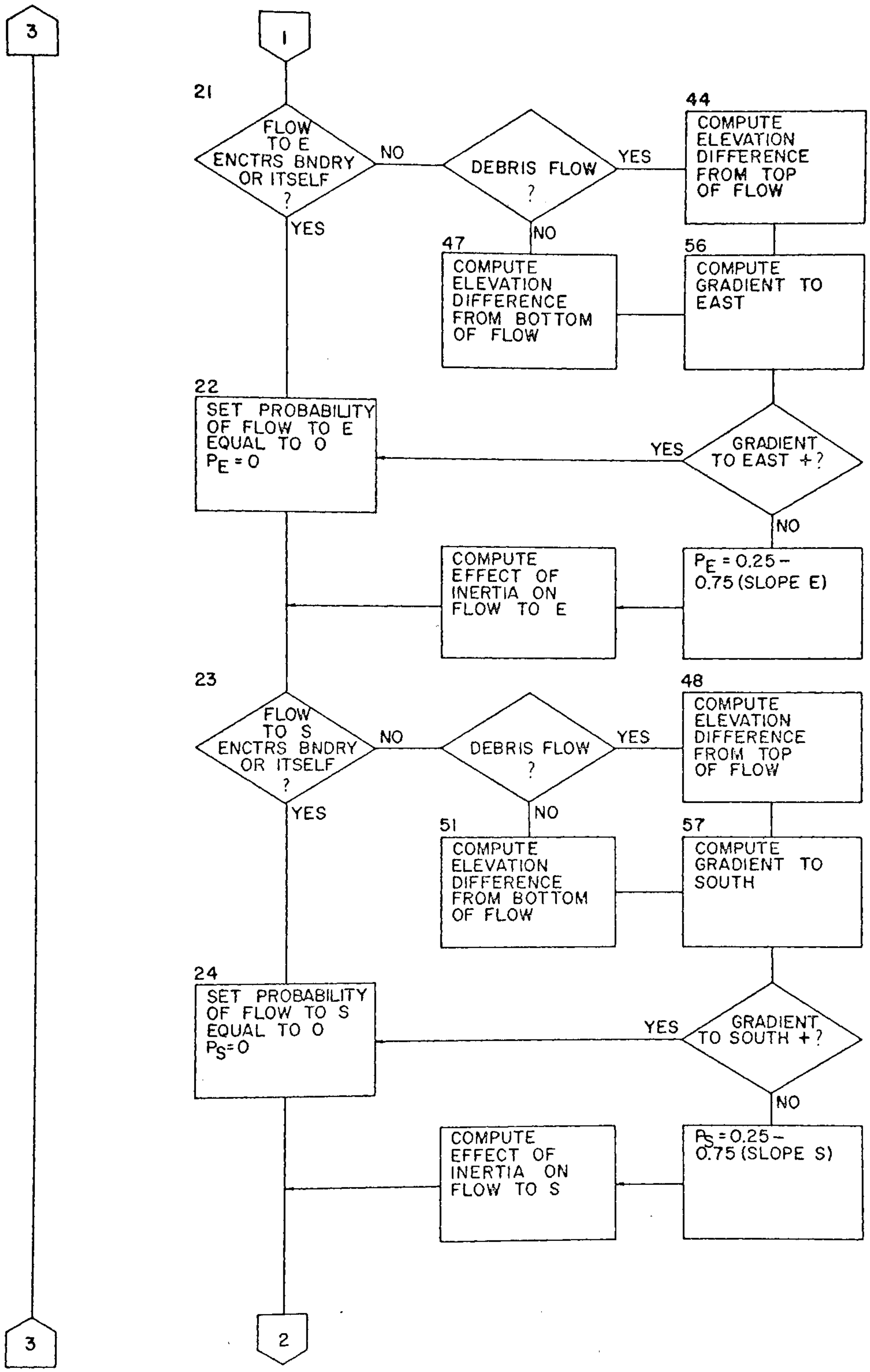


Figure 17.--Flow chart for subroutine FLOW—Continued

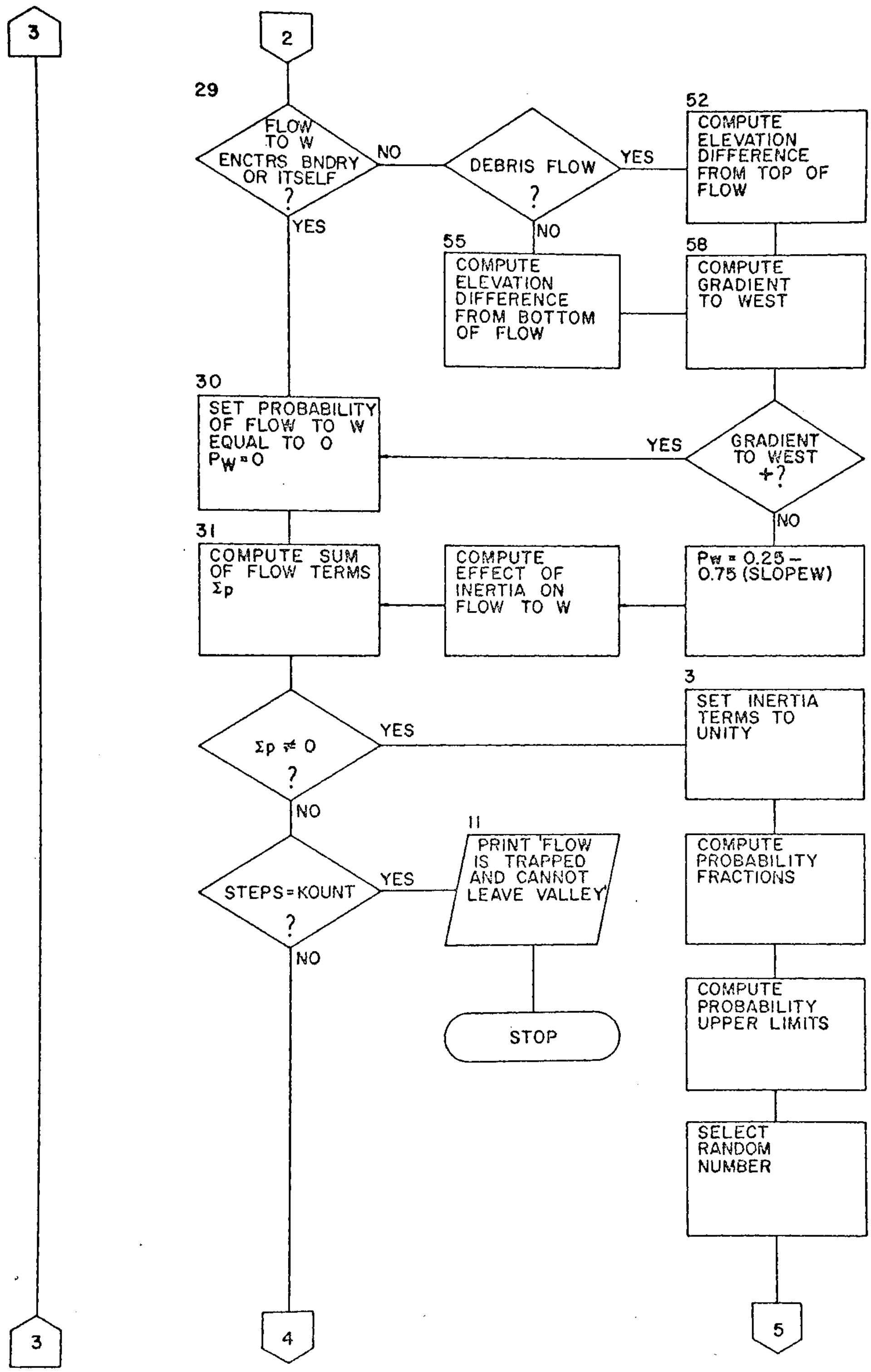


Figure 17. --Flow chart for subroutine FLOW—Continued

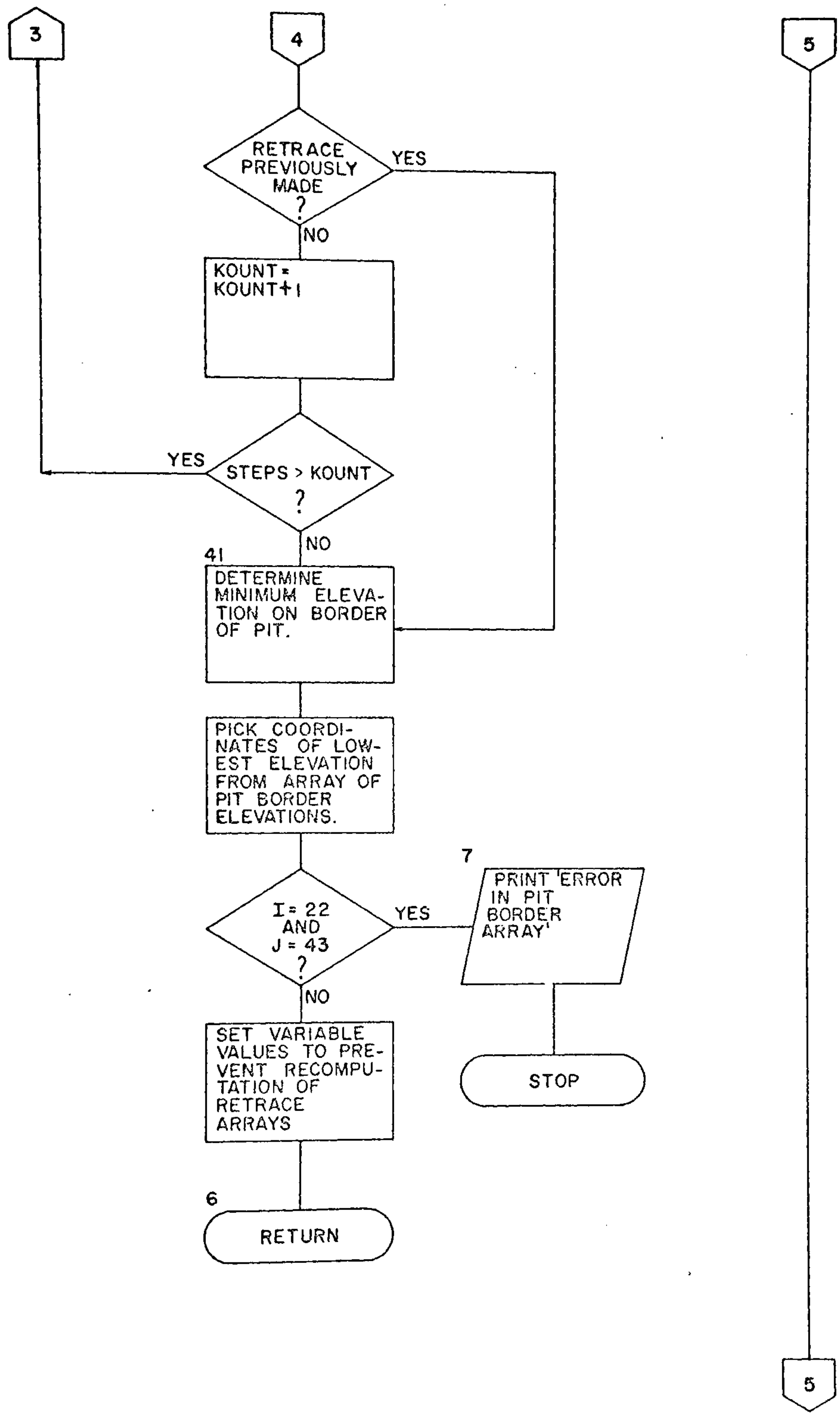


Figure 17.--Flow chart for subroutine FLOW—Continued

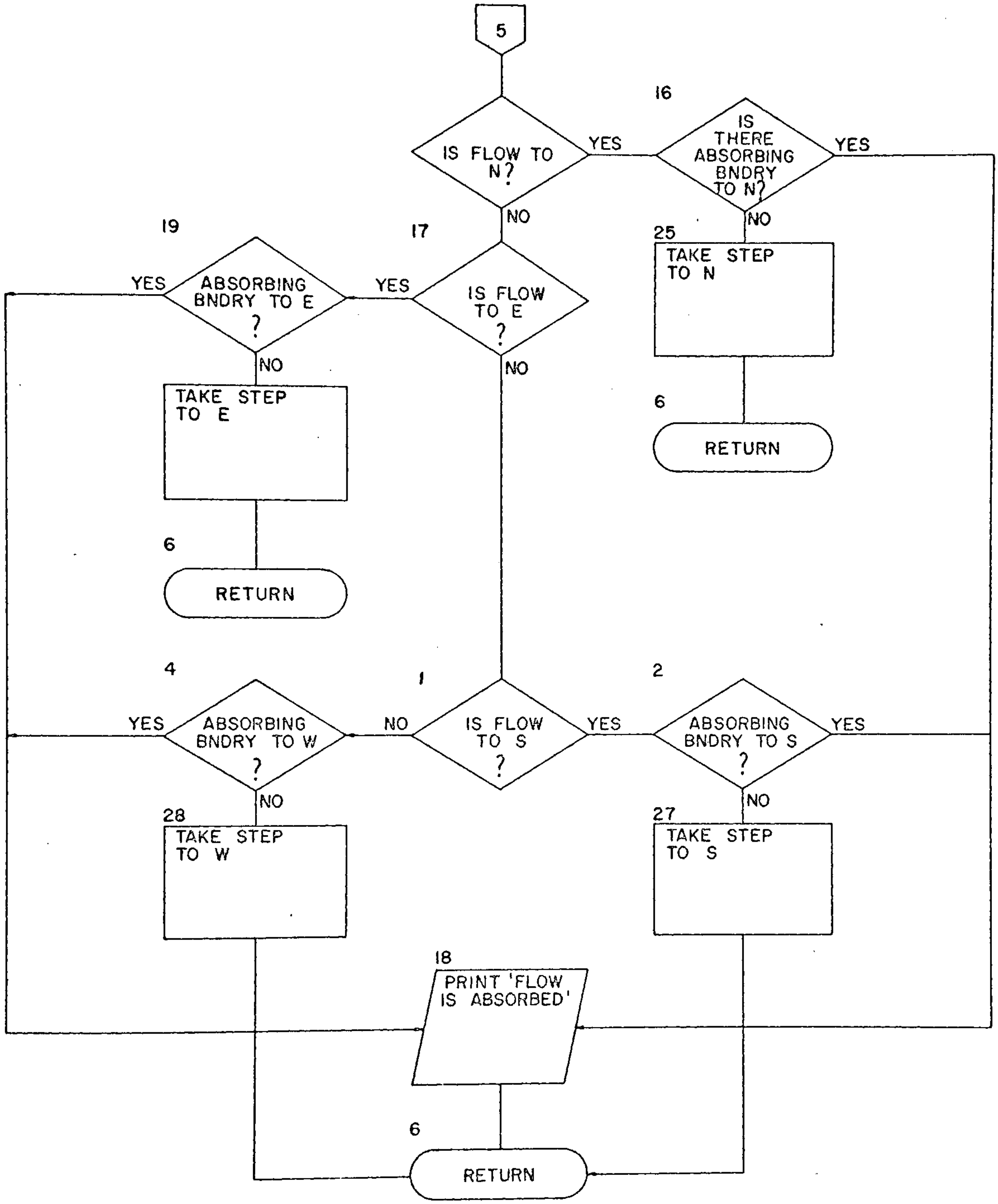


Figure 17.--Flow chart for subroutine FLOW—Continued

1963, p. 527-528; and (5) underloading of the stream during periods of little runoff (Troxell and Peterson, 1937, p. 73).

In ALFAN, temporary entrenchment takes place either (1) when fan material just below the point where the main channel crosses the fault lies at a level higher than the stream channel just above the fault, or (2) when a flow event occurs when little sediment is present in the basin (YSUBS < YSUBC1). In either case, entrenchment in ALFAN is accomplished by calling subroutine EROFLOW, which in turn calls subroutine FLOW. The course of erosion is that of a random walk and is computed by FLOW as a series of steps, each determined by a weighted transitional probability. Erosion in EROFLOW is treated as negative deposition, with the depth of erosion tapered in the direction of flow. The mean depth of entrenchment (ETHICK) is a parameter of the model. Depth of erosion ranges from 2 times ETHICK at the initial point of erosion to 0 at the final point. In case (1), erosion is considered to have taken place during a debris flow or a water flow, and is due in part to the build-up of sediments at the fan apex. In case (2), erosion takes place because the stream is underloaded and not because of any conditions on the fan. Different opinions have been expressed regarding the ability of debris flows, as compared to water flows, to deepen stream channels (Bull, 1968, p. 103). Lustig (1965, p. 165) concluded that debris flows may deepen stream channels. Hooke (1965, p. 138-141), on the other hand, attributes channel incision to subsequent water flows. In ALFAN, flow events are of such small magnitude on the time scale that they are considered to have occurred essentially instantaneously. For this reason, as far as the model is concerned it is immaterial whether channel erosion occurred during a debris flow or shortly thereafter.

The downfan extent of channels is determined by the position of the intersection point, defined by Hooke (1967, p. 450) as the point where the main channel on laboratory fans merged with the surface of the fan (fig. 18). Hooke (1967, p. 457) concluded on the basis of laboratory experiments that the average radial position of the intersection point is governed by the relative importance of debris flows and fluvial processes in transporting material on a fan. In a series of experiments in which water flows alone were used, Hooke found that the average position of the intersection point was about one-fourth of the way down the fan. A second series of experiments employing debris flows followed by water flows indicated that the intersection point could be expected about halfway down the fan. In this case, fluvial deposition predominates near the toe, whereas overbank debris-flow deposition predominates near the fanhead. Hooke (1967, p. 458) also found that no incision, and therefore no intersection point, would occur on laboratory fans built entirely by debris flows with no intervening or subsequent water flows.

Studies have also been made of the length of channels (which end at the intersection point) on natural fans. Buwalda (1951) states that fan channels capable of conveying water flows or debris flows

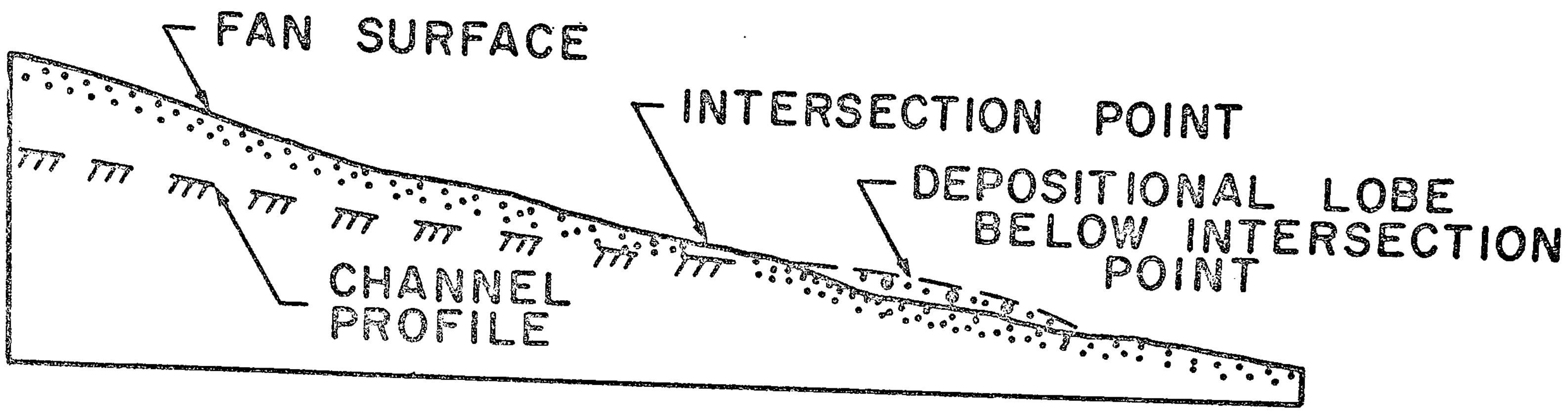


Figure 18. --Definition sketch of intersection point.

From Hooke, 1967, fig. 8.

commonly are entrenched for a quarter or a half of the radial length of the fan. Beaty (1963, p. 523), in his study of alluvial fans along the base of the White Mountains, observed that the depths of active channels were sufficient to contain debris flows for one-third to two-thirds of the radial length of the fans. The flow events recorded by Beaty consist of a debris flow followed by a water flow. Hooke (1967, p. 457) observed that on several segmented fans in the eastern desert regions of California the intersection point was nearer the lower boundary of the segment than might be expected from laboratory observations. He concluded that the intersection-point relationship was complicated by segmentation. Bull (1968, p. 102) reports that fanhead trenches commonly extend half the length of the fan.

The length of the temporarily entrenched channel in ALFAN is in part determined by the parameter CONST, which relates the mean peak-flow rate GAMMA to the length of the channel (CSTEPS) in the model. The topographic map of the fan shown in figure 19 shows depressions, the deepest of which are near the mouth of the canyon. These depressions result chiefly from channeling and subsequent deposition in parts of the channels. The volume of material (VSUBE) removed from the channel is added to that brought down from the source basin (VSUBS) by either debris or water flows and is deposited on the fan, beginning just below the intersection point, unless removed from the fan system by a bypass flow.

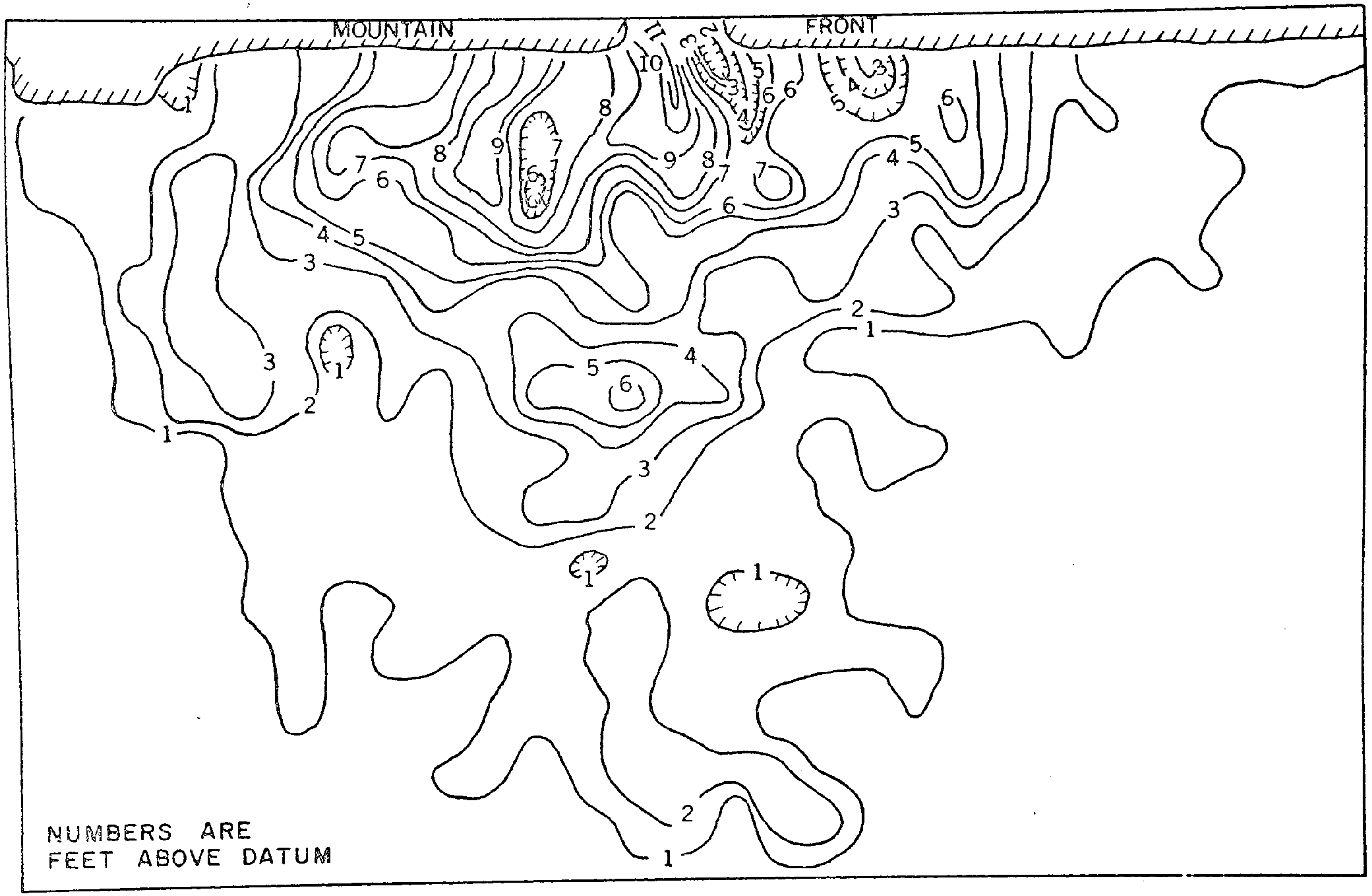


Figure 19. --Topographic map of simulated alluvial-fan deposits after 106 flow events.

In many instances the depth of fanhead channeling is so great that overbank deposition in the adjoining fan surface is impossible. In this case, events largely exogenous to the alluvial-fan system are inferred to have taken place, and permanent entrenchment follows. Such alteration may be due to tectonic movement (Eckis, 1928, p. 237; Bull, 1964a, p. 105-113; Hawley and Wilson, 1965, p. 24; Denny, 1967, p. 84), climatic change (Eckis, 1928, p. 237; Bull, 1964a, p. 103-105, 121; Hooke, 1967, p. 458), long-term reduction in grade of the source-area stream (Eckis, 1928, p. 237; Lobeck, 1939, p. 242; Blissenbach, 1954, p. 179; Hawley and Wilson, 1965, p. 24), capture of the main stream by another stream heading on the fan (Denny, 1965, p. 16, 38, 1967, p. 85-87; Hooke, 1967, p. 458), and lowering of the area trunk stream or migration of the trunk stream into the fan base (Drew, 1873, p. 451-455; Blissenbach, 1954, p. 179-180; Hoppe and Ekman, 1964, p. 340-341).

Because the present model is concerned for the most part with alluvial-fan deposition under stationary conditions, no detailed simulation of permanent trenching is included.

Branching of flows. From the standpoint of branching, two flow environments may be considered: (1) entrenched channels, and (2) the fan surface from slightly above to below the intersection point. Factors determining the extent to which branching occurs in flows in entrenched channels are those characteristic of the channels and those characteristic of the flows. Channel factors are the depth of the channel and the presence of boulders or debris dams blocking the channel. According to Beaty (1968, p. 25-26), the 1958(?) debris flow on the Willow Creek fan spread fresh material on the alluvial fan in the form of an elongated depositional strip flanking a channel which cut to a depth of 10 to 12 feet at the fan apex. The flow split into several lobes where the channel shallows to an average depth of 1 to 3 feet. Studies of the Willow Creek and other fans in the White Mountains area led Beaty (1968, p. 90) to conclude that channels cut to a depth of 10 feet or more near apexes would successfully contain most floods and debris flows, at least on the upper parts of the fan surface. Spreading of debris flows and spilling out of channels of high water floods commonly take place on the middle and lower surfaces of fans where active channels shallow to a depth of 5 feet or less.

Boulders or debris dams may block channels, causing the debris flow to spread laterally (Beaty, 1968, p. 43) or to branch permanently or temporarily into new channels (Beaty, 1963, p. 527, 528). In many cases there is no morphologic reason why spilling out of the moving debris occurred where it did on the fan (Beaty, 1968, p. 43).

Flow factors determining the extent of branching from entrenched channels are (1) the magnitude and (2) the fluidity of the flow. Both water and debris flows may overtop channels if the flows are of sufficient magnitude. However, water flows are more likely to remain in fanhead trenches than debris flows because of their greater fluidity. Even mudflows or debris flows with a relatively high water content tend to follow shallow channels (Blackwelder, 1928, p. 475; Beaty, 1968, p. 25-26). Pack (1923, p. 355), on the other hand, described viscous mudflows which left the channel completely at sharp turns.

At and below the intersection point both water flows and debris flows spread out over the fan surface. Water flows characteristically do so in braided distributary channels (Bull, 1964a, p. 116; Lustig, 1965, p. 172). These channels continually fill with sediment and then shift a short distance to another location. The resulting deposit consists of shallow bars of poorly bedded gravel or crossbedded sand (Bull, 1968, p. 102). Mudflows form sheetlike deposits (Bull, 1964b, p. 23) or wide lobes, as on laboratory fans (Hooke, 1967, p. 450).

In ALFAN, branching occurs as a special case of the random walk when the flow becomes trapped. Trapped flow results from two constraints placed on the random walk: (1) that no flow may cross or intersect itself (Tolman, 1937, p. 369), and (2) that arising from the nature of the transitional probabilities which states that no flow may occur in the direction of a positive gradient. When a flow is trapped, it can proceed no further. In this case, ALFAN checks back along the course of flow, searching each node for another direction of possible movement, and takes the first one it comes to. This results in a branch in the flow, which then proceeds along the new path until the required number of steps in the flow event have been taken. It may happen that ALFAN will check all the way back to the canyon mouth without finding another path of possible movement from the established channel. If no movement can take place in any direction from the previous course of flow, it is then obvious that the flow is in a channel blocked at its lower end, in a hole or depression in the fan surface. In this case, it is assumed that the depression will fill with water and/or sediment to the level of the lowest outlet, where the water will leave the depression and the flow continue as a branch. These processes of retracing the flow route and searching for the lowest outlet may be repeated many times for a single flow event, resulting in many branches. If the branching flows are debris flows or depositing water flows, depressions in the fan surface will be gradually filled. Figure 20 shows the pattern of branching, erosion, and deposition during a water-flow event. The event took place during an early stage of fan development; hence some steps toward the mountain front are present.

The effect of channels on branching is simulated better in some respects than in others by ALFAN. The magnitude of a flow event in ALFAN is reflected in the length of its deposit, not in its depth. Hence ALFAN does not simulate the fact that flows of greater magnitude will more readily overflow channels. ALFAN does, however, simulate the effects of viscosity. Because gradients in the possible flow directions

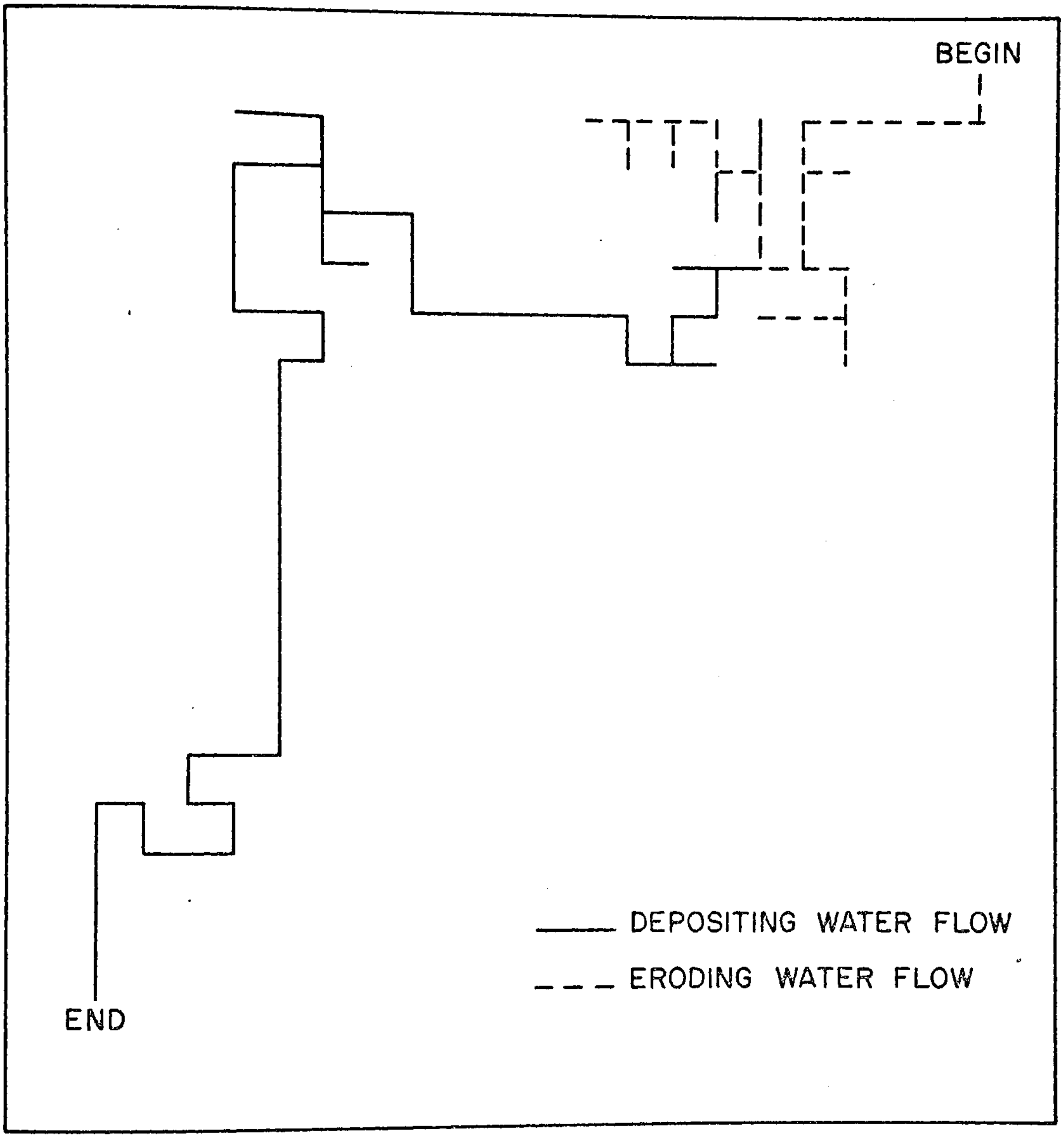


Figure 20.--Random walk of flow event (early stage of fan development).

are measured from the tops of debris flows, the flows are able to move in directions in which there is a small or moderate positive gradient. Thus, debris flows are not necessarily guided by channels. Water flows, however, move only in the direction of negative land-surface gradients, and therefore cannot leave a channel except through its lower end or by filling.

Absorption of Flows. Each flow event is a Markov chain, and each Markov chain in the model must eventually reach an absorbing state. A state i is said to be an absorbing state if the one-step transitional probability P_{ii} equals 1 (Hillier and Lieberman, 1967, p. 409). Thus, if a state is an absorbing state, the process will never leave it once it enters. When a flow event reaches an absorbing state in ALFAN, it ends.

Water flows reach an absorbing state when all the sediment they transport is deposited. The principal causes of deposition are (1) spreading of flow at end of channel and (2) infiltration of stream water into streambeds on the fan surface (Bull, 1964b, p. 17). By the equation of continuity:

$$Q = wdv \tag{41}$$

where Q is the stream discharge, w is the width of the stream channel, d is the mean depth, and v is the mean velocity of flow. When a flow reaches the end of a channel, it may spread out. For a constant Q, an increase in the width of flow on alluvial fans is accompanied by a decrease in both velocity and depth, which in turn results in deposition of sediment.

Actually, the discharge may not remain constant as the flow moves out of a confining channel onto the fan because water may be absorbed through the fan surface. In the equation Q = wdv, a decrease in Q while w is increasing requires an additional decrease in d and v. That deposition on alluvial fans is partly due to loss of stream water by infiltration has been suggested by Trowbridge (1911, p. 738), Eckis (1928, p. 237), Blissenbach (1954, p. 178), Bull (1964b, p. 17), and Hooke (1967, p. 453-456). It is not required that a flow move out of a confining channel for infiltration to take place; the water may also seep through the bottom of a confining channel if the bottom is formed of permeable material.

Modeling of absorption of water flows is based upon the law of conservation of mass. The volume of sediment deposited must equal the total sediment load transported during the flow event. The width of the deposit along each side of the path followed by the flow event, including its branches, is equal to half the grid spacing. The thickness of the deposit laid down by a flow event is assumed to decline from 2 times WTHICK where deposition first takes place to 0 at the flow end. The total length of the deposit is the length of the deposit along the main stem plus all its branches, and it is determined by computing the total number of steps (SUMSTEP) required to deposit the total volume of material brought down from the basin plus any eroded from the stream channel.

It is thus evident that at the end of a flow event deposition will have taken place along the entire channel. This filling presupposes one of the following two conditions: (1) A single storm has occurred, resulting in a flood which has deposited a layer of sediment along the entire channel. (2) What is modeled as a single flow event is actually the result of an entire series of storms which have developed the deposits shown over a period of time and have backfilled the channel.

Schumm (1961, p. 66) has suggested that channel aggradation may be analogous to backfilling of a channel, rather than to a general filling of the channel simultaneously over a long distance. He describes the process as follows:

> Assuming that aggradation begins at one particular point in the channel and then progresses upstream, it is possible to outline the steps in the complete cycle of aggradation and retrenching of that channel. Gradient is decreased by the initial channel deposit, and if it is not swept away by the next flood, this alluvial deposit induces further deposition in the channel. As the channel fills, the zone where major deposition of the coarser fraction of the alluvium occurs, migrates upchannel, and progressively finer sediment is deposited over the originally coarser grained sediment at the site of initial aggradation.

The nature of the aggradation cycle is related to frequency of flow events, which is discussed in the section on time distribution of flow events.

The absorption of debris flows, on the other hand, is determined by the relation given in equation (7) (Hooke, 1967, p. 452). If downslope movement is to occur, equation (7) must be satisfied. When the yield stress, τ_0, falls below the yield strength, τ_c, of the debris, the flow stops. Cessation of the flow may then result from a decrease in fan slope (s becomes smaller), a decrease in flow depth (d becomes smaller), or infiltration (τ_c becomes larger) (Strahler, 1952, p. 929; Hooke, 1967, p. 452). The critical shear stress of a debris flow will also increase if additional dry material is incorporated into the debris flow, thereby increasing the viscosity of the flow (Bull, written commun., 1971).

In ALFAN, the deposition of debris flows is modeled in a manner similar to water flows. Due to their higher viscosity, however, debris flows are generally thicker, and therefore they do not extend so far down the fan as do water flows for the same volume of material.

Features of Deposition

Debris-Flow Deposits

Conditions Favoring Formation. Factors that promote debris flows are abundant rainfall over short periods of time at irregular intervals, steep slopes having insufficient cover to prevent rapid erosion, slope failure, or landsliding, and a source material that provides a matrix of mud. Not all these conditions need to be present for a debris flow to form (Blackwelder, 1928, p. 478; Crawford and Thackwell, 1931, p. 100; Woolley, 1946, p. 20; Bull, 1964b, p. 22, 1968, p. 102). Blockage of flows by landslides or a canyon constricted at its lower end may also contribute to the occurrence of debris flows (Blackwelder, 1928, p. 469; Sharp and Nobles, 1953, p. 559; Croft, 1967, p. 9). From studies of alluvial fans at the base of the White Mountains in California and Nevada, Beaty (1963, p. 525; 1970, p. 73) concluded that unconsolidated alluvial or colluvial accumulations on trunk canyon floors were the primary source of debris, and that the chance concentration of a cell of heavy rain in a drainage basin whose trunk canyon was floored with such material resulted in a debris flow. Croft (1967, p. 8), in his studies of debris flows in northern Utah, estimated that about 80 to 90 percent of the fresh bouldery alluvium came from channel erosion. Beaty (1963, p. 535) observed further that, following a debris flow, a buildup of fresh material must take place on canyon floors before they can again yield large amounts of rubble. During intervals between major rubble flows, while mass movement and other slope processes are transporting debris from canyon walls to floors within the mountains, morphologic changes on fans are minor. Lustig (1965, p. 176-177) has also pointed out that the apex regions of fans, as well as the trunk canyons, may be a source of debris-flow material. The importance of small slope failures as an erosional source of sediment was pointed out by Scott (1971, p. 245), who found that the failures generated many individual debris flows and accounted for surges in the debris flows from larger watersheds.

In ALFAN, a debris flow occurs when a storm event occurs in a basin in which the thickness of weathered material equals or exceeds a certain parameter value (YSUBC). The volume of material brought down on the fan by such a storm event is equal to the thickness of weathered material (YSUBS $\geq$ YSUBC) times the erodible area of the basin (A). Each storm is considered to remove all of the erodible material in the basin. Immediately after each storm, erodible material again begins to accumulate in the basin at the exponential rate described by equation (29) and figure 10. The time required to accumulate enough weathered material for a debris flow to form may range from less than a year in basins underlain by soft materials such as clayey silt to a hundred years or more in basins underlain by more resistant rocks. The depositional features of debris flows in ALFAN are modeled by subroutine DEBFLOW, the flow chart for which is shown in figure 21.

Shape. Debris-flow deposits are characteristically sheetlike deposits with lobate tongues. Margins of the flow are abrupt and well defined (Blackwelder, 1928, p. 470, 472; Chawner, 1935, p. 256; Beaty, 1963, p. 521, 1968, p. 18; Bull, 1968, p. 102). The shapes of typical debris flow in plan view are illustrated in figure 22. These may be compared with simulated debris flows shown in figure 23.

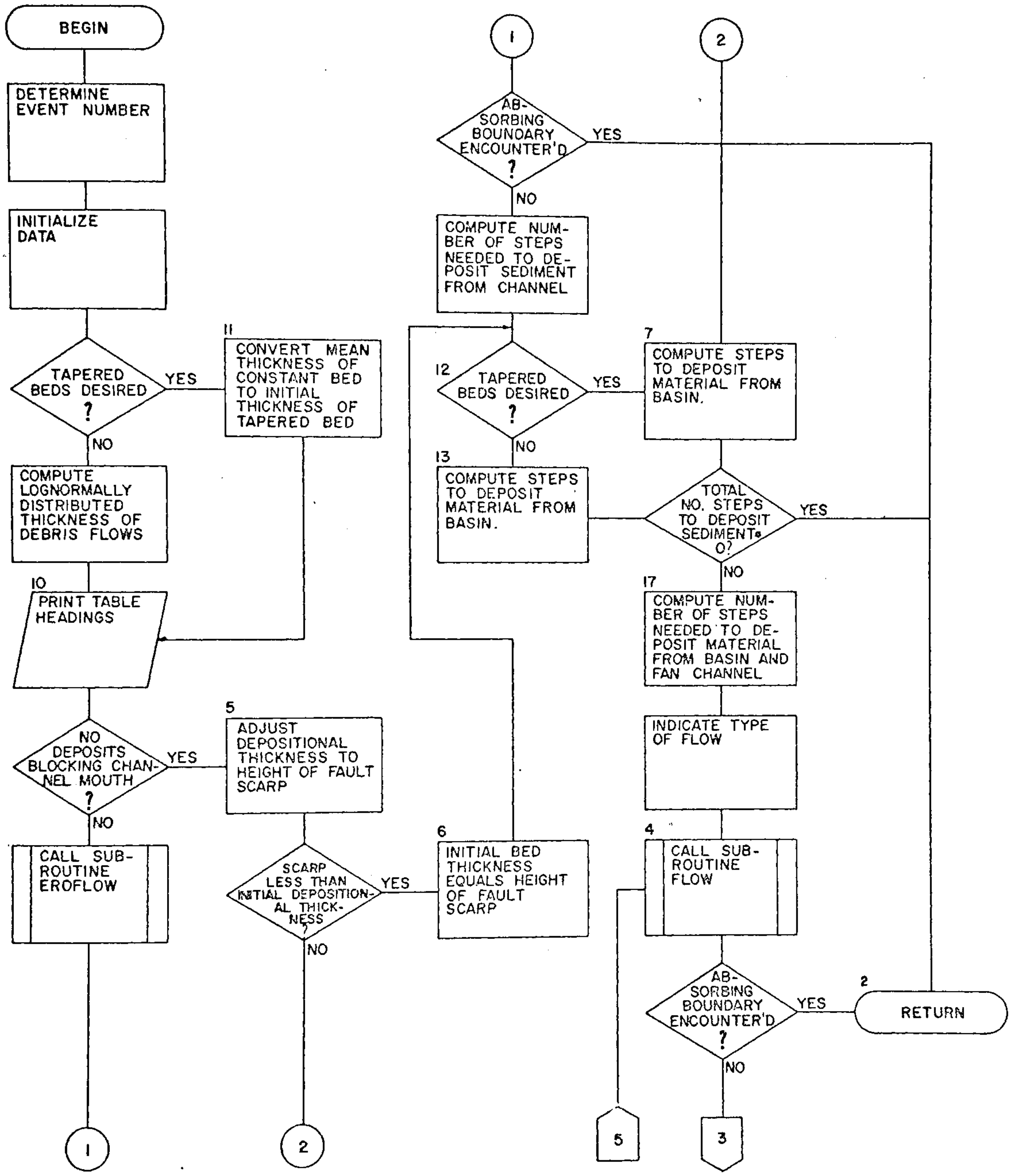


Figure 21.--Flow chart for subroutine DEBFLOW.

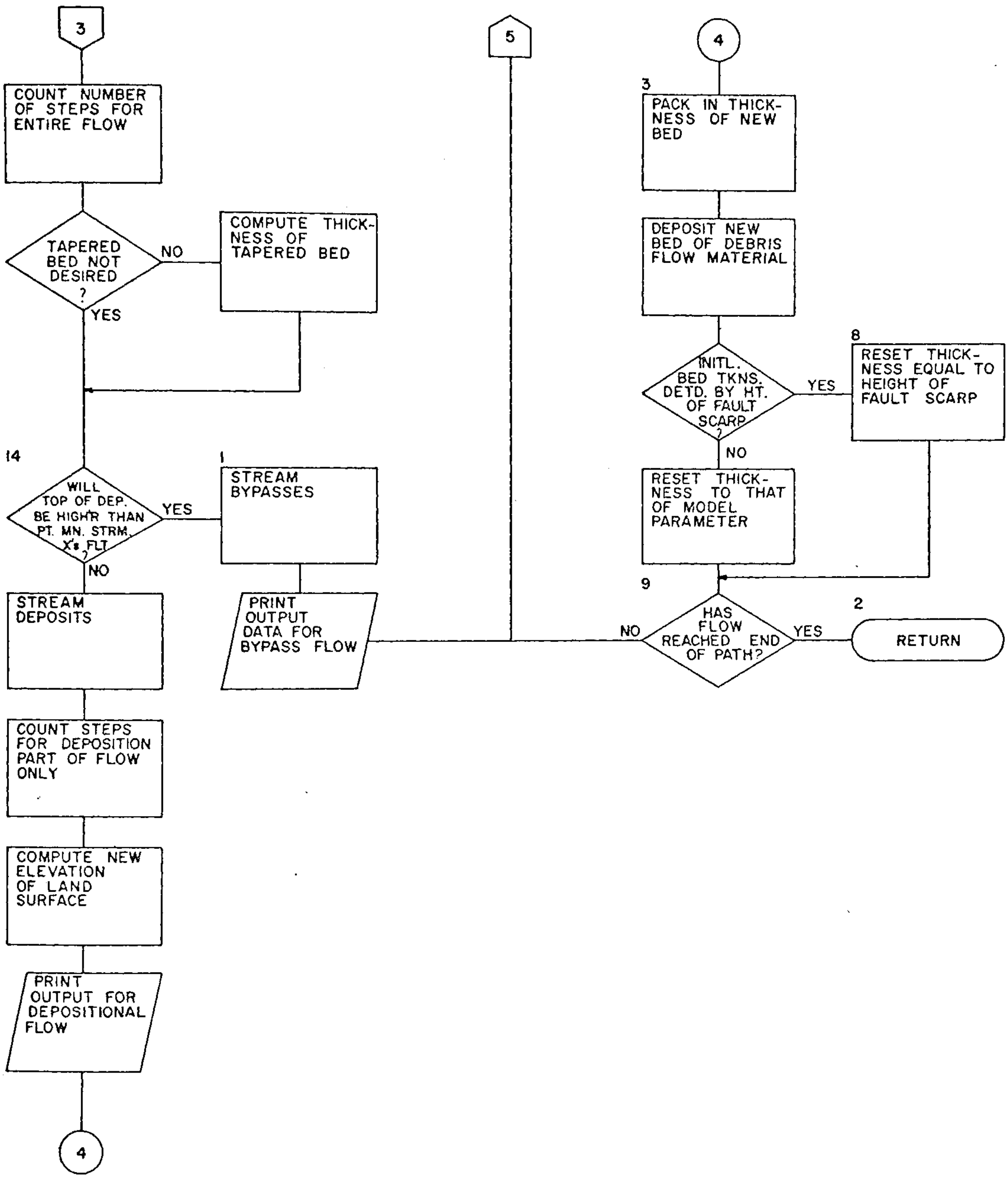


Figure 21. —Continued

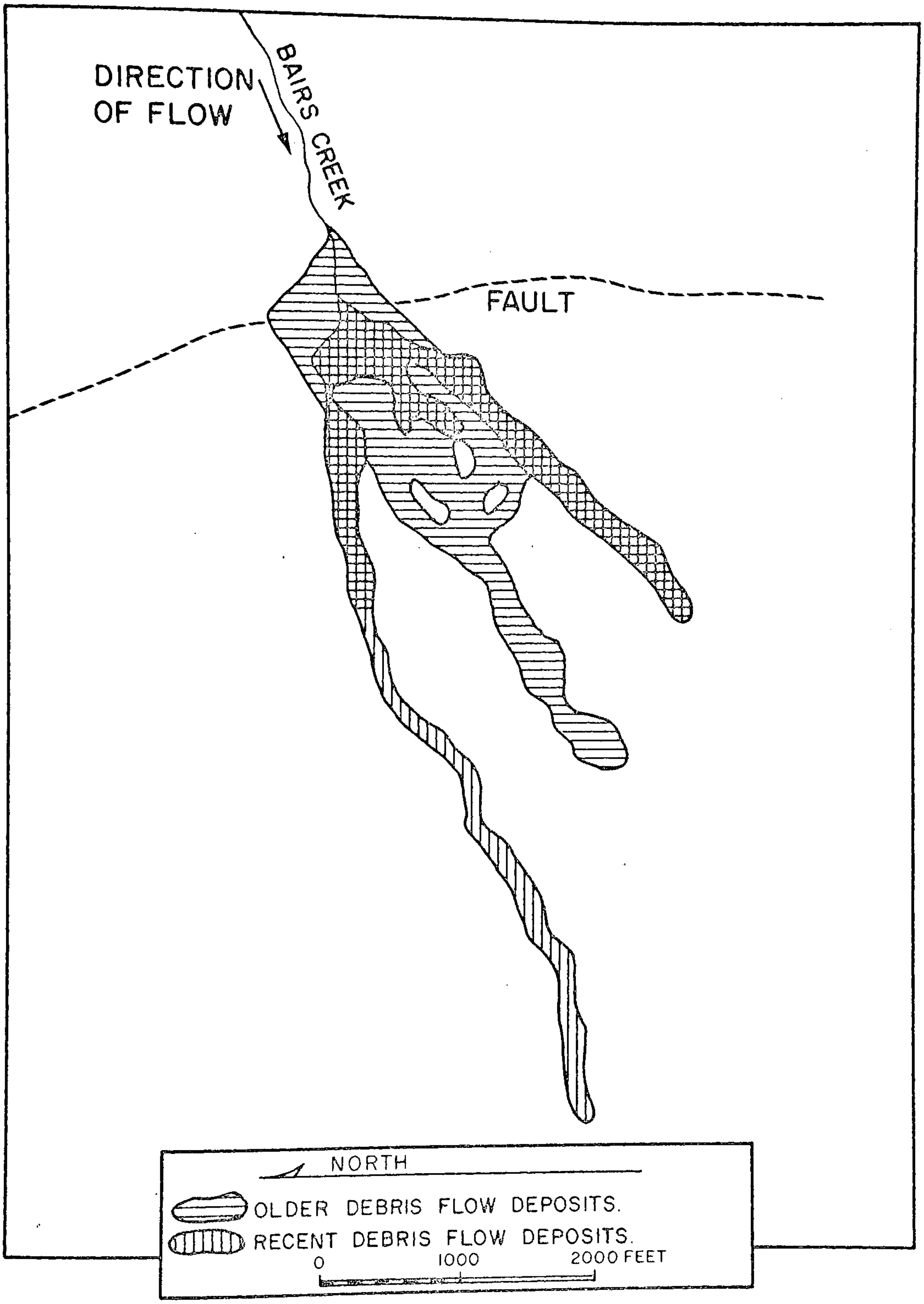


Figure 22.--Map of Bairs Creek debris-flow deposits.

From Croft, 1967, fig. 24.

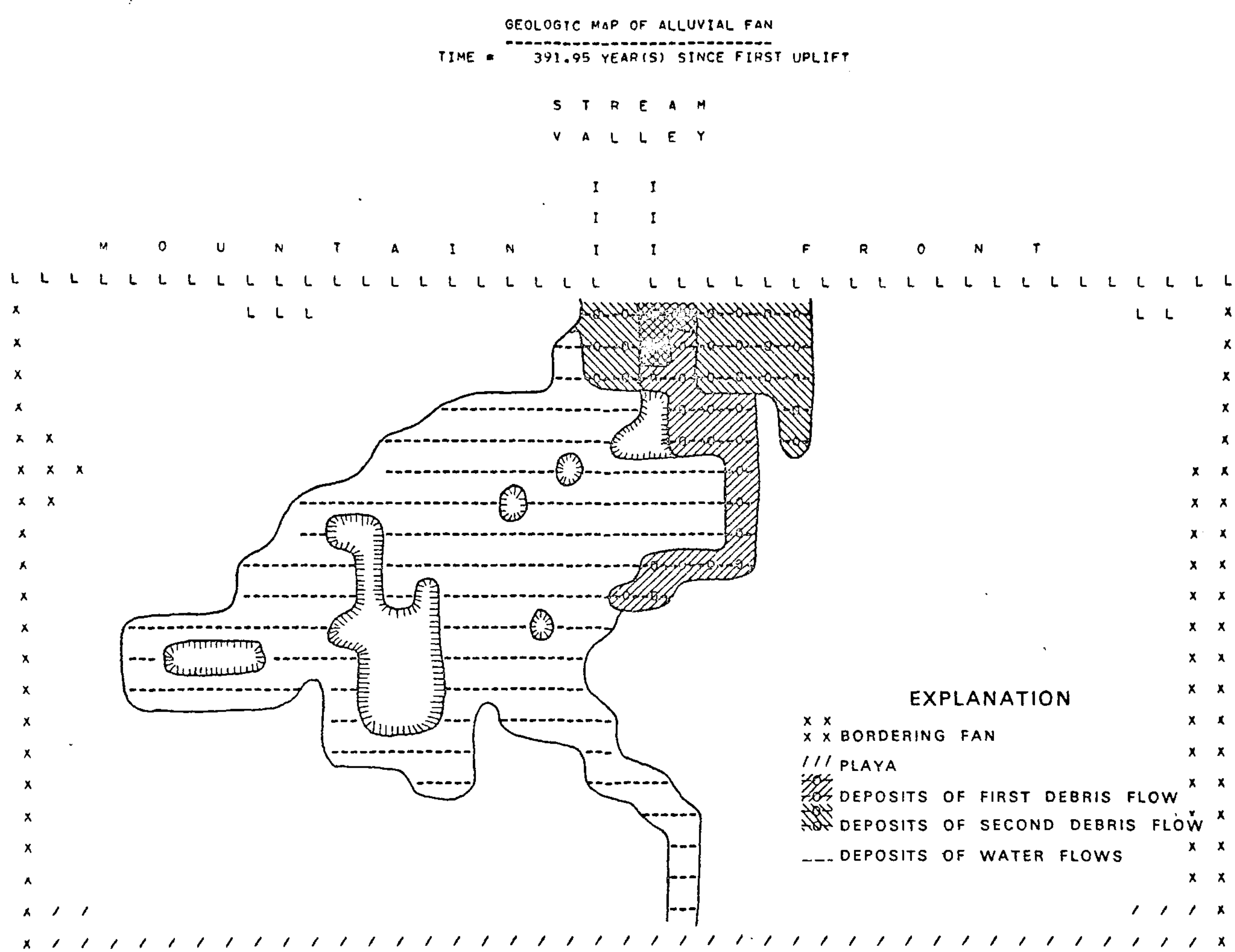


Figure 23.--Computer printout showing shape of simulated debris-flow and water-flow deposits.

Beaty (1963, p. 524) states that debris flows are concave upward in cross section, with well-defined lateral ridges along parts of their margins. Blackwelder (1928, p. 481), on the other hand, found the upper surface of debris flows to be convex and sloping down more steeply at the end, like the end of a glacier. Margins of flows are generally steep (see, for example, Croft, 1967, p. 5). In ALFAN, debris-flow deposits are considered rectangular in section, hence have abrupt margins as commonly described. Debris flows in the model may either lie atop older deposits or occupy channels cut in them.

Size. The areal extent of a debris flow is limited by its volume and yield strength, which is increased by a loss of water to underlying dry material, 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. Debris flows described in the literature range in length from 600 or 700 feet (Beaty, 1963, p. 527) to 15 miles (Beaty, 1968, p. 25). The length of debris flows in ALFAN is governed principally by the volume of sediment brought down to the fan (VSUBS) and by the median thickness (BTHICK) of the flows. Assuming a grid spacing of 100 feet, the model grid is 2,200 feet long from north to south. Hence, when this scale is employed, simulated debris flows cannot be more than a few thousand feet in length.

Widths of debris flows described in the literature range from 20 to 1,000 feet (Sharp and Nobles, 1953, p. 550-551; Beaty, 1963, p. 521, 527). Widths for an individual flow may vary, becoming more narrow when constricted by channels and wider on the fan surface. Debris flows in ALFAN follow paths of constant width, but the effects of branching and doubling back produce patterns of irregular width (fig. 23).

According to Blackwelder (1928, p. 474), debris flows in desert regions range from a thickness of an inch or two to several feet, and most of them are 6 to 20 inches thick. Blissenbach (1954, p. 186) states that individual debris-flow deposits range in thickness from 1 foot on small fans to 15 or 20 feet on large fans. Other authors (Pack, 1923, p. 352, 354; Sharp and Nobles, 1953, p. 552; Beaty, 1963, p. 523, 527; Denny, 1965, p. 22; Hawley and Wilson, 1965, p. 19; Hunt and Mabey, 1966, p. 84-85) report thickness of debris flows ranging from less than a foot to 10 feet. Mean debris-flow thickness in ALFAN is designated by a parameter, BTHICK, which is specified at the beginning of the program.

In the White Mountains of California and Nevada, Beaty (1963, p. 523; 1968, p. 43) found that debris-flow deposits generally decrease in thickness downslope from a depth of 4-10 feet near the apex of the fan to a depth of less than 1 foot near the lower margins of the flow. Thickness of the fresh debris on the Sparkplug Canyon fan (Beaty, 1968,

p. 18) ranged from 4 to 6 feet at the point where spilling from the active channel began to less than 1 foot along the lower margins. The average thickness for the deposit as a whole was 2-1/2 feet. In ALFAN, debris-flow deposits are tapered in the direction of flow from a maximum at the point of initial deposition of 2 times the mean flow thickness to 0 at the end of the flow. Tapering will be uniform only if the modeled flow has no branches.

ALFAN also has provision for assuming a debris flow of uniform thickness. A mean bed thickness (BTHICK) is specified at the beginning of the program, but the thickness of individual flows is drawn from a log-normal distribution. In this case, it is also necessary to specify a value (SIGMAD) for the standard deviation of the bed thickness. However, as the evidence indicates, it is more reasonable to assume that a debris flow thins in the direction of movement than that its thickness remains constant over the whole length of flow.

In not all cases, however, will the initial tapered thickness be represented by 2 times BTHICK or the uniform thickness be represented by a value drawn from a log-normal distribution. In order for deposition to take place, a negative gradient must exist between the base of the main stream just above the fault crossing and the stream just below the fault crossing. The difference in elevation between these two points, if the gradient is negative, is represented by the fault scarp, designated by the variable CLIFF. Now, if the initial thickness of debris-flow deposition is greater than CLIFF and also greater than some specified value DLIMIT, the initial thickness is set equal to CLIFF, and deposition will take place right up to the level of the channel floor above the fault crossing. This procedure has two purposes: (1) to more nearly approach the case in nature, where thinner beds would be deposited as the elevation of the area of initial deposition approaches the elevation of the main stream channel above the fault crossing, and (2) to minimize the condition in which sediment in suspension is not deposited on the fan at all but is carried completely out of the basin-fan system.

Volume of material in debris flows has been reported by a few writers. Troxell and Peterson (1937, p. 55) state that the debris flow in La Canada Valley, California, moved well over 600,000 cubic yards of material from the mountain area onto alluvial fans and the valley floor. Woolley (1946, p. 26) reports that the 1936 debris flow from Willard Canyon, Utah, spread about 65,000 cubic yards of material over some 30 acres of land; in 1923 even more, approximately 100,000 cubic yards, had been added to the fan by a debris flow. Sharp and Nobles (1953, p. 350) mention a flow of 1,200,000 cubic yards. During the 1955-63 period, the yearly volume of deposits laid down on the Arroyo Ciervo fan ranged from 0 to 62 acre-feet (100,000 cubic yards) (Bull, 1964b, p. 38); from 80 to 90 percent of the deposits laid down during this period consisted of debris flows. In ALFAN, the volume of material brought down by a debris flow is equal to the volume of material (VSUBS) removed from the drainage basin after each storm.

Grain Size and Sorting. In order to model deposit lithology, it is necessary to distinguish between debris flows and water flows. Material in debris flows ranges from clay to boulder size and is generally poorly sorted. Bull (1964b, p. 24) found that the sorting coefficient, S_0, of mudflow deposits in western Fresno County had a range of 5.0 to 25, a mean of 5.7, and a median of 8.6. These deposits are poorly sorted. Bull also reports values of S_0 ranging from 2.7 to 5.0 for eleven other mudflows in Utah and California, indicating moderate to poor sorting.

The largest and the mean sizes of particles in debris flows decrease in the downfan direction (Woolley, 1946, p. 77; Beaty, 1963, p. 533; Hawley and Wilson, 1965, p. 19). Bluck (1964, p. 395-397) found an exponential decrease in particle size downfan. Sharp and Nobles (1953, p. 554-555) acutely observed that the decrease in size in the outward direction was limited to the larger fragments, and not the finer constituents. The same effect was noted by Bull (1964b, p. 26), who concluded that debris flows represent a type of mass flowage in which there is sorting of the coarsest fragments but no sorting of the finer grained matrix.

Sorting of the larger fragments of a debris flow takes place transverse to the direction of flow as well as parallel to it. In a debris flow in the Kay Creek area, Utah, rocks were concentrated on the outer margins of the flow, where they formed a crude pair of walls between which the more fluid part of the mud-rock mixture moved (Croft, 1967, p. 2).

Many debris flows are followed by a water flow. The water does not originate by drainage from the debris-flow deposits themselves (Beaty, 1963, p. 523) but is nevertheless associated with the same storm that caused the debris flow. This writer refers to such water flows as the water-flow phase of debris flows. The result of a water-flow phase is to scour a channel in the recently deposited debris flow, and to deposit a layer of water-laid mud downslope from the end of the debris flow (Pack, 1923, p. 353-355; Blackwelder, 1928, p. 160; Beaty, 1963, p. 521, 523-524). The water-flow phase is not, however, modeled in ALFAN.

Stratification. In those fans or parts of fans where most of the individual beds consist of debris-flow layers there is little contrast between these layers of similar composition, and the bedding is therefore poorly defined (Blackwelder, 1928, p. 469; Chawner, 1935, p. 259-260; Sharp and Nobles, 1953, p. 554). However, the bedding of debris flows is remarkably clear in those alluvial-fan deposits where alternating beds of water-laid and debris-flow origin occur (Bull, written commun., 1971). Beaty (1963, p. 527) observed cuts in the White Mountain fans that revealed beds 3 to 6 feet thick which show a progressive thinning downslope. Beaty (1963) felt that the structure of White Mountain fans probably was the same as those of the Colorado Plateau country earlier observed by Dutton (1880, p. 222), who wrote:

> The most perfect stratification is presented when the dissecting cut is made radially. But when a cut transverse to the radius is made . . . , the stratification, though still conspicuous, is much less uniform and harmonious. The cone appears to be built up of long radial or sectoral slabs superposed like a series of shingles or thatches.

Areas of Deposition on the Fan. Because of their high viscosity, debris flows do not flow as far down the fan as do water flows (Bull, 1968, p. 102). Hooke (1967, p. 452-453) concludes that much fanhead deposition probably is 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 will interfinger in the midfan region with water-sorted material deposited near the toe. Blackwelder (1928, p. 475-476) also observed that debris flows typically do not extend to the lower edge of the fan.

In ALFAN, debris flows tend to be clustered in the upper part of the deposits developed by the random walks. This clustering is shown in figure 24, which presents the pattern of deposits resulting from 34 walks, 14 of which simulated debris flows, 17 water flows, and 3 eroding water flows. Because real debris flows are more viscous than water flows, they are markedly thicker. It therefore follows that

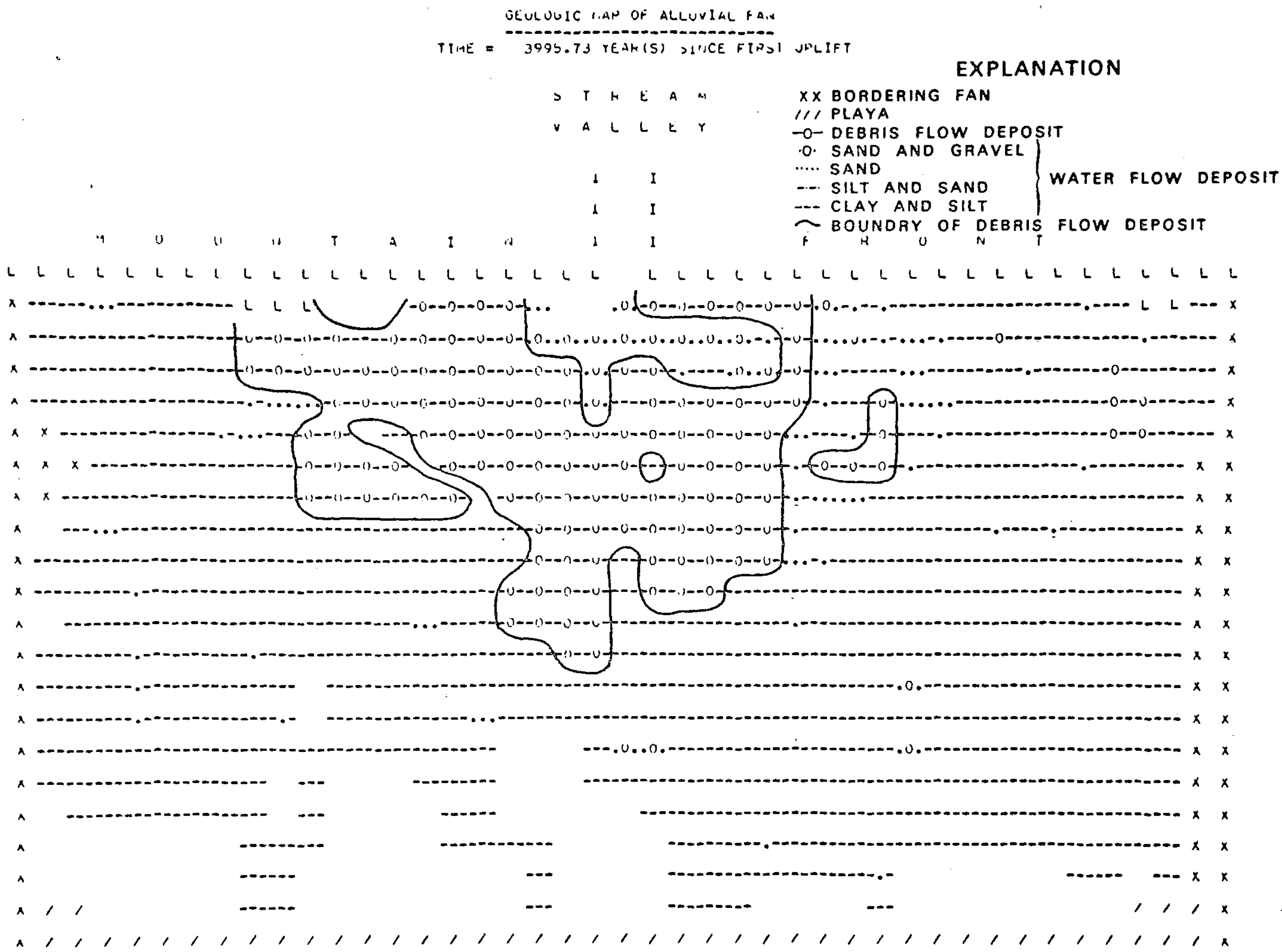


Figure 24.--Computer printout showing relative extent of simulated debris flows and water flows after 34 random walks.

if the flows are thicker, their downfan extent must be less. This is generally true in spite of the greater volume of material in debris flows than in water flows.

Water-Flow Deposits

Conditions Favoring Formation. From his study of alluvial fans in the desert regions of California, Hooke (1967, p. 453) concluded that water-flow deposits occur on fans whose source areas have little fine material. Both the Gorak Shep fan, whose source basin is underlain by resistant carbonate rocks, and the Shadow Rock fan, whose source area is underlain by resistant quartzite, have practically no recognizable debris-flow deposits. Hence, lithology of the source basin is the controlling factor in determining whether flows will be of the water or debris type. Bull (1964b, p. 26) found that deposition of well-sorted sand and silt on fans in western Fresno County was from flows that contain much less clay than mudflows and have sufficient water to winnow the finer material from the sand.

In ALFAN, the relative proportion of water-flow material in the fan may be controlled by varying the parameter YSUBC (y_c) between its lower limit of 0 and its upper limit, which is given by the parameter MSUBS (m_s). A value of YSUBC near 0 may represent a basin in which easily erodible fine material accumulates; a value of YSUBC near MSUBS may indicate a basin in which the weathered material is not readily erodible, even if a relatively large thickness should accumulate. The relative proportion of water flows may also be controlled by varying the parameter C (c), which determines the rate of increase of the weathered layer. Smaller values of c will mean that a longer period of time will be required, and hence a smaller probability will ensue, for reaching a sufficient thickness of weathered material YSUBC for a debris flow rather than a water flow to occur.

The thickness and lithology of water flows in ALFAN are computed in subroutine WATFLOW, the flow chart for which is shown in figure 25.

Shape. In western Fresno County, Bull (1964b, p. 26-27) found that two types of water-laid sediments occur on alluvial fans. Most of the water-laid sediments consist of sheets of sand and silt deposited by a network of braided streams. The second type consists of sand and gravel deposited in the stream-channel beds of the fanhead trenches and in the larger distributary channels farther downslope. In the stage of deposition, the surface of an alluvial fan shows a system of radiating channels focused in the main stream at the apex of the fan (Blissenbach, 1954, p. 178-179; Tolman, 1937, p. 369). Figure 26 shows the shape of the Arroyo Hondo fan deposits for the 1958 season. The shape is distorted in places, particularly next to the manmade dike at the downslope edge of the deposits. This may be compared with the shape of water-flow deposits simulated by ALFAN (fig. 23). The

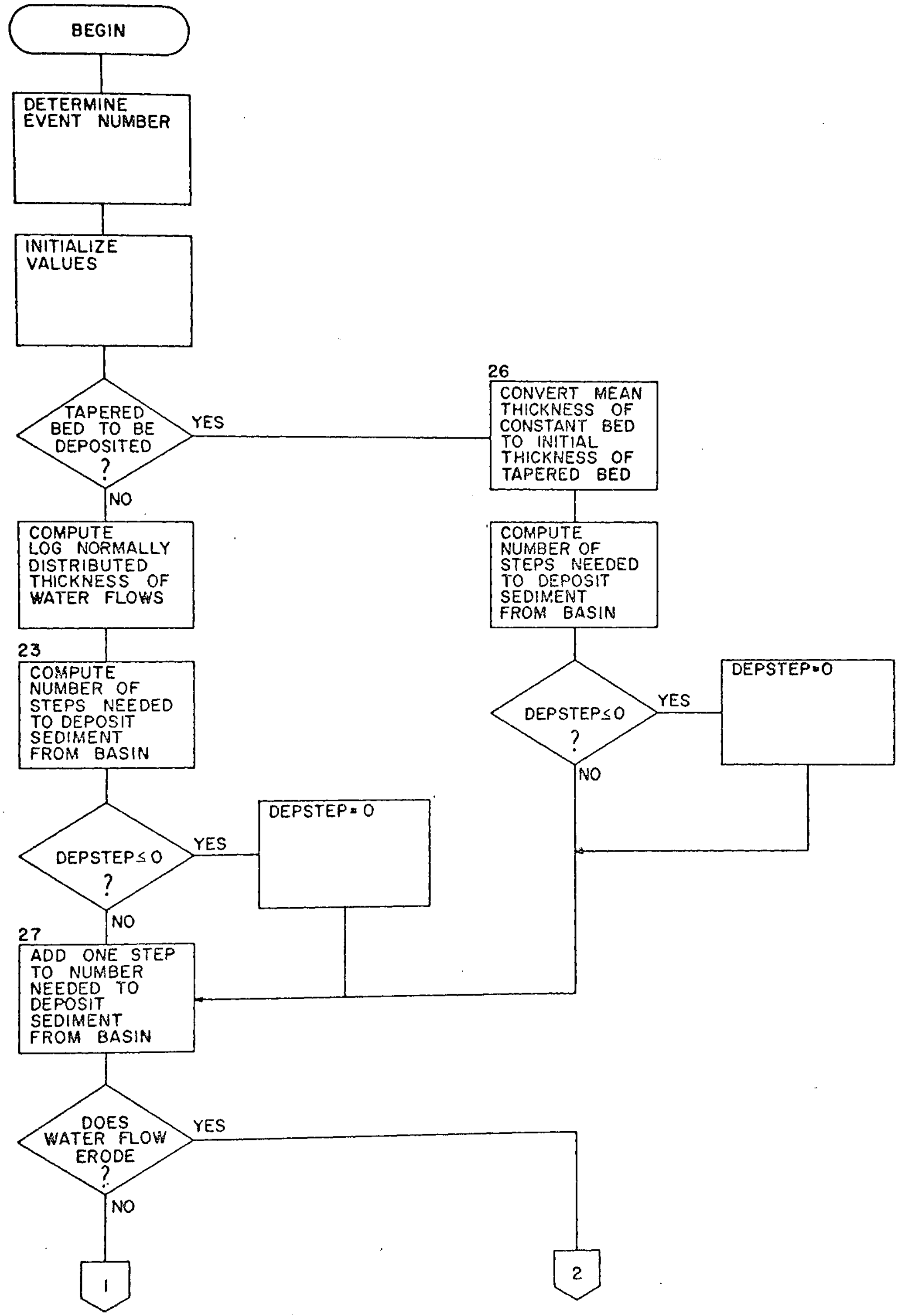


Figure 25.--Flow chart for subroutine WATFLOW.

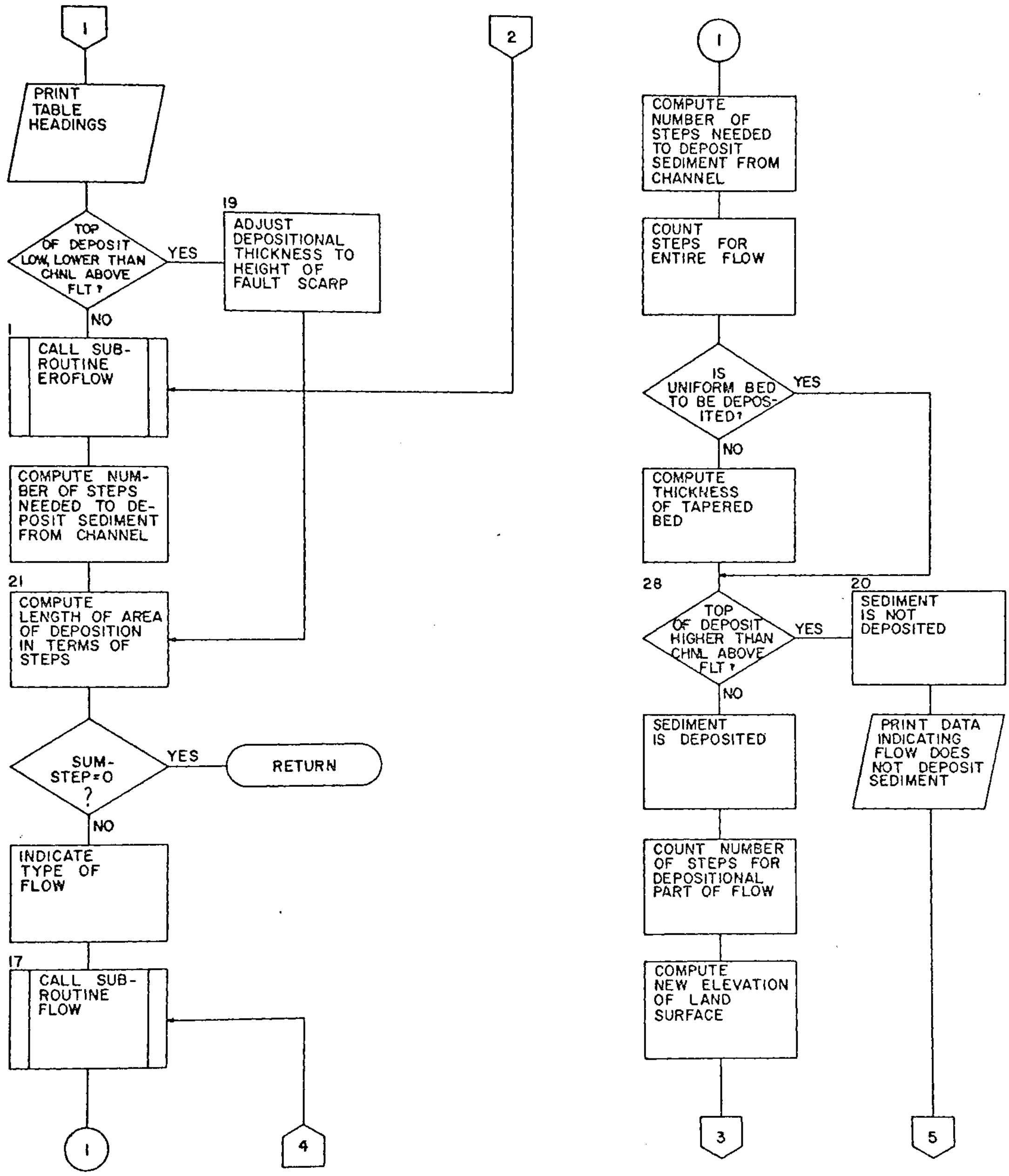


Figure 25. —Continued

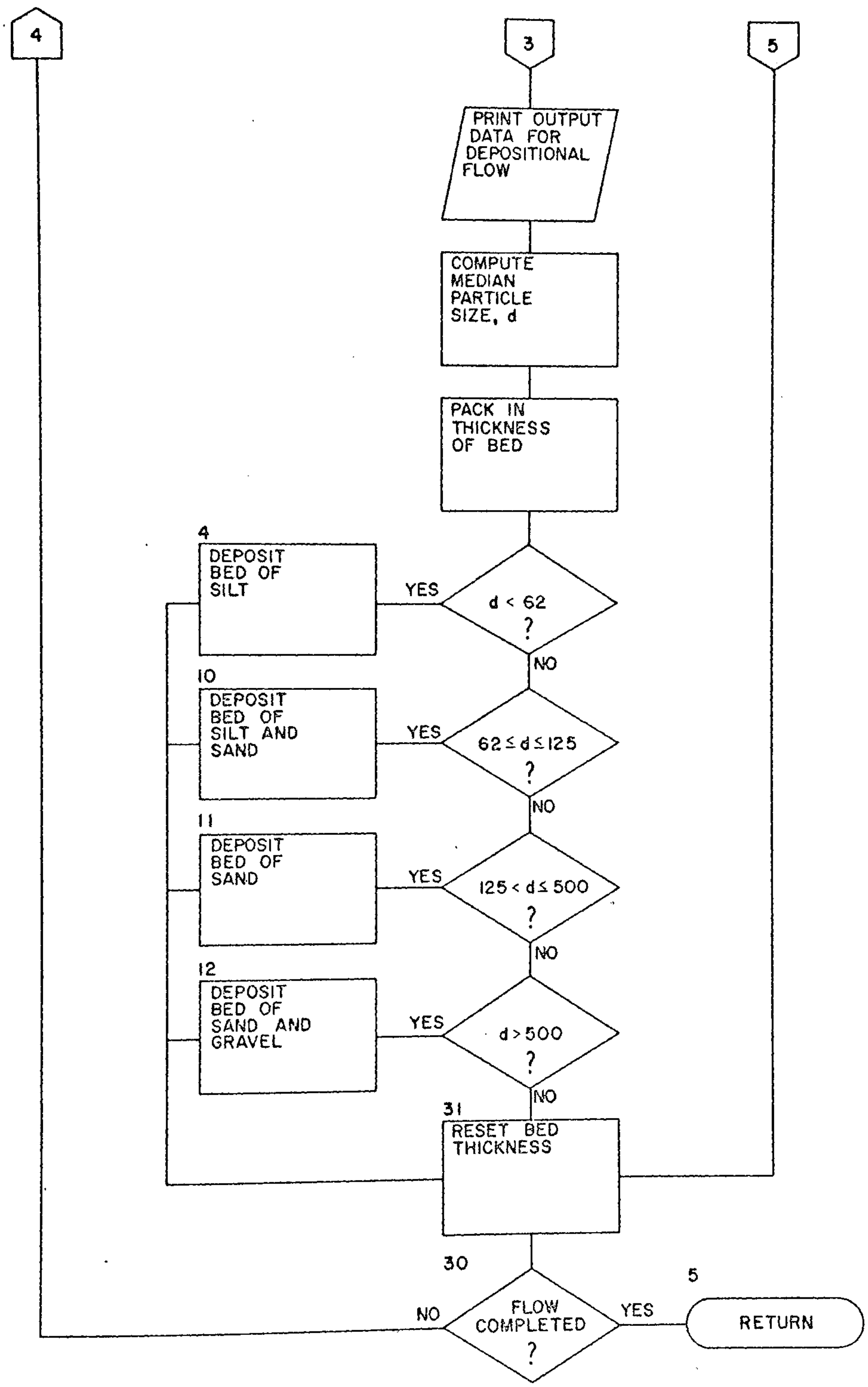


Figure 25. —Continued

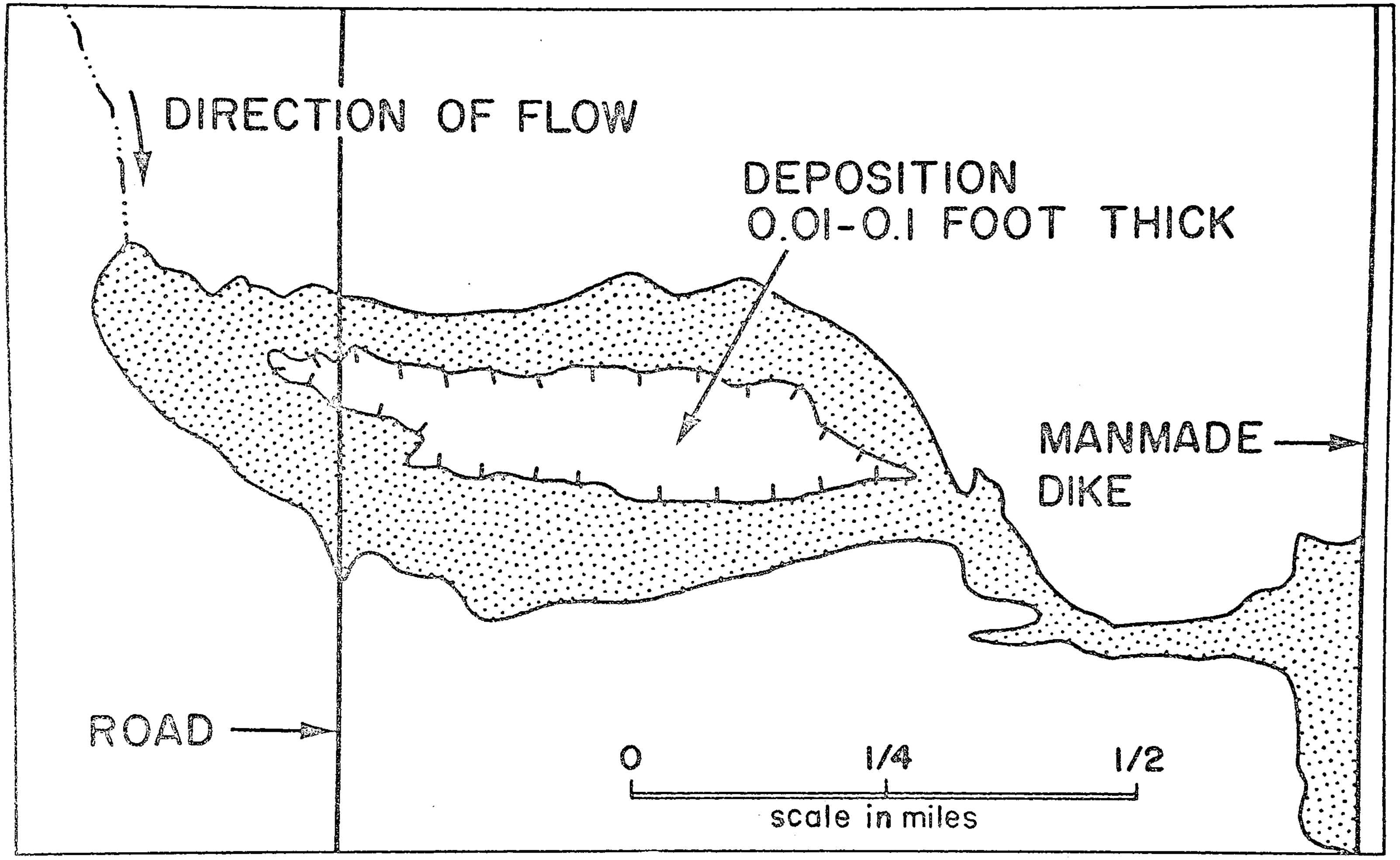


Figure 26.--Map showing shape of Arroyo Hondo fan water-flow deposits.

From Bull, 1964b, fig. 14.

irregularity of the water-laid deposits in ALFAN is controlled partly by the randomness of the walk and partly by the presence of contiguous flows.

According to Blissenbach (1954, p. 187), water-laid deposits are rudely lenticular in section. Channel deposits in semiarid valleys, described by Schumm (1960, p. 180-181), are distinctly rectangular in section. However, as Schumm (1960, p. 183) points out, channel-fill deposits are only a part of the fluvial sedimentary complex. After a channel has been filled, sediment-laden water spreads over the flood plain. Sections of valleys in which the channel has been completely filled and where flood-plain aggradation is important are broadly convex.

In ALFAN no distinction is made between the deposits of braided streams and streams confined within channels. The individual channels and bars of a braided stream are all considered part of a larger channel deposit extending the entire width of the braided area. It is of interest to note that Howard, Keetch, and Vincent (1970) have devised a random-walk simulation model of individual channels in a braided stream. All channels in ALFAN are considered of constant width and rectangular section. Overbank deposits as such are not modeled.

Size. The width and depth of channels and channel deposits on alluvial fans vary greatly. On the Shadow Rock fan Denny (1965, p. 11) mapped channels ranging from 50 to several hundred feet in width. On the Hanaupah Canyon fan the main wash leaves the mountains as a channel nearly 1,000 feet wide (Denny, 1965, p. 33).

In ALFAN, the width of a water-flow deposit which does not occupy laterally adjacent nodes and which is the result of a single flow event is controlled entirely by the grid spacing. In the examples shown in figures 13, 19, 23, and 24, the grid spacing is 100 feet. Because deposits in a given flow event are considered to extend half the grid spacing distance on either side of each node, the width of the deposits is therefore also 100 feet.

According to Blissenbach (1954, p. 186), most deposits laid down by streams on alluvial fans are in layers 1 inch to 1 foot in thickness. Successive stream deposits may attain a vertical extent of several tens of feet. In ALFAN, the mean thickness of water-flow deposits is designated by the parameter WTHICK. Deposits are assumed to taper linearly in the direction of flow, so that the thickness at the initial point of deposition is 2 times WTHICK and the thickness at the final point of deposition is 0 foot.

Grain Size and Sorting. Water-flow deposits are generally moderately to well-sorted silty to gravelly sand, although boulders may also be present (Bull, 1964b, p. 30). A general downstream decrease in grain size of water-flow deposits is shown better on some fans than on others. Bluck (1964, p. 182) obtained an exponential decrease of maximum particle size downstream in an alluvial-fan water-laid deposit in southern Nevada. Bull (1964b, p. 28) sampled a 1-mile reach of braided stream deposits on a fan in western Fresno County but did not find a significant downslope trend in grain size. Allen (1965, p. 159) plotted data obtained by Eckis (1928, p. 233) from three fans in the Cucamonga district, but only one of the curves showed an exponential decrease of maximum particle size with distance in the downfan direction. Denny and Drewes (1965, p. 626) plotted estimated mean size of particles from three fans in the Ash Meadows quadrangle versus distance from the apex of the fan, on semilogarithmic paper. The materials deposited were apparently water laid. The data show considerable scatter, but samples from a fan northwest of Shadow Mountain do have a linear trend. Denny (1965, p. 42) made a similar analysis of samples from fans in the Death Valley region and found considerable variability. He concluded that the change in size of bed material downward does not seem to follow any general law. For example, east of the Panamint range, changes in the size of bed material from one sample site to another were considerably greater than any overall decrease in size from headwaters to the toe of the fan.

Scheidegger (1970, p. 220-227) reviews various quantitative approaches to the problem of representing the downstream decrease of pebble size. The first of these approaches is based on Sternberg's formula, which attributes the downstream reduction in grain size to abrasion. Sternberg's equation may be written

$$Y = Y_o e^{-aL} \tag{42}$$

where Y is the mean pebble size at any point L along the stream, Y_o is the initial size at L = 0, and a is a constant that is proportional to the rate of decrease.

In an attempt to relate bed slope and pebble size in streams, Scheidegger (1970, p. 223) then presents a relation developed by Lokhtin:

$$C_F = d/S \tag{43}$$

where d is the diameter of the pebbles, S the corresponding slope, and C_F is a coefficient of fixation which is characteristic of individual streams. Equation (43) may then be combined with an equation developed by Shulits (1941, p. 623):

$$S = S_o e^{-aL} \tag{44}$$

where S_o is the slope at an upstream initial point where the distance, L, equals 0. We then obtain

$$d = C_F S_o e^{-aL}. \tag{45}$$

Scheidegger presents a similar form as a result essentially the same as Sternberg's equation (42) but with a different physical basis. However, since Shulits bases his exponential relation (equation 44) on an analogy with Sternberg's law, the coincidence of equations (42) and (45) is not surprising. Scheidegger (1970, p. 224) next derives an expression for the reduction of pebble size due to selective transportation rather than abrasion. Basing his analysis on the work of Sundborg (1957, p. 249-251), he obtains the following relation predicated on certain simplifying assumptions:

$$w \propto (1/L) \tag{46}$$

where w is the settling velocity. Written in terms of particle diameter, d, the above becomes, for Stokes law

$$d \propto (1/L)^{1/2}. \tag{47}$$

From the standpoint of water-flow deposition on alluvial fans, we are more interested in particles of sand size or larger, which generally follow the impact law (Rubey, 1933, p. 327-331). In the case of coarse sand or larger particles, w, the settling velocity, can be expressed as

$$w \propto d^{1/2} \tag{48}$$

rather than

$$w \propto d^2 \tag{49}$$

as in Stokes law.

Applying the impact law to equation (46), we obtain

$$d \propto (1/L)^2. \tag{50}$$

For sand sizes in general, however, Maddock (written commun., 1971) suggests

$$w \propto d, \tag{51}$$

in which case

$$d \propto 1/L. \tag{52}$$

There seems to be no entirely satisfactory way of expressing the change in median grain size downstream in alluvial-fan water-flow deposits. The actual relations are far more complex than those presented by Scheidegger (see, for example, Maddock, 1970), and, indeed, too complex to be embodied in the present model. In ALFAN, relation (43), developed by Lokhtin, is used, principally for two reasons. First, because it is simple, and second, because equations such as equations (42), (44), and (45) assume a particular form, an exponential profile, for stream channels. As the patient reader who reaches the sections "Fan Profiles" and "Channel Profiles" will discover, there is no basis for assuming an exponential profile, or for that matter any particular profile, for stream channels on fans.

The median grain size of water-flow deposits in ALFAN, then, is determined by first calculating the slope between each node along the walk. The median grain size of material deposited at the lower node is computed from the relation:

$$d = C_f s. \tag{53}$$

For graphical printout of maps and lithologic sections on the computer, four lithological facies of the water-flow deposits are distinguished: (1) sand and gravel, (2) sand, (3) sand and silt, and (4) silt and clay. Using the Wentworth (1922) grade scale and data tabulated by Bull (1964b, p. 66-67) as a guide, median grain-size limits in microns for each of these facies are developed as follows:

$$\text{Sand and gravel} > 500\mu$$

$$500\mu \geq \text{sand} > 125\mu$$

$$125\mu \geq \text{sand and silt} > 62\mu$$

$$62\mu \geq \text{silt and clay}$$

Suppose, for example, that a water flow moves from node 2, 22 at an elevation of 2.40 feet to node 2, 23 at an elevation of 2.11 feet. This indicates a drop of 0.29 foot in 100 feet, or a gradient of -0.0029. By equation (53), assuming C_f is 1 x 10^5:

$$d = 10^5 \times 2.9 \times 10^{-3}$$

$$= 290 \text{ microns.}$$

Because 290 microns falls within the range of 500-125 microns, the material "deposited" at this node, as given on the geologic map and in the geologic section, is sand. In ALFAN, the lithology and thickness of water-flow deposits are computed by WATFLOW (fig. 25).

Areas of Deposition on the Fan. Near the toe of a fan most deposition is probably not by debris flows but by running water, although the material may have been eroded from debris-flow deposits higher on the fan (Hooke, 1967, p. 452). This condition is shown in figure 24.

Erosional Events

Erosion of alluvial fans has been discussed by Drew (1873, p. 451-455), Denny (1965, p. 16-21; 1967, p. 90-93), Hunt and Mabey (1966, p. 90-92), Lustig (1967, p. 96), Hooke (1968, p. 617), and Beaty (1970, p. 71-73). In ALFAN erosion is treated as negative deposition. Two types of erosion may be distinguished in ALFAN. In the first type, material is removed from the fan and transported outside of the fan system. In the second, material is removed and redeposited elsewhere on the fan. In ALFAN, material is lost from the system when it reaches an absorbing boundary, modeled in the examples given here on the southern border of the map as a playa or through-flowing stream. Either debris flows or water flows may pass material out of the system in this manner, particularly if the flow is in a bypass condition. In this case little or no deposition may take place on the fan, and hence a relatively large quantity of material may leave the fan system.

The second type of erosion takes place either (1) when fan material just below the point where the main channel crosses the fault lies at a level higher than the stream channel just above the fault, or (2) when a flow event occurs when little sediment is present in the basin. This type of erosion is discussed in "Channel Entrenchment."

Erosion in ALFAN is modeled by subroutine EROFLOW, which is called into action whenever either of the above two conditions is present. The amount of erosion in ALFAN is governed by the magnitude of the peak-flow rate, which is selected randomly from an exponential distribution (see section on magnitude distribution of flow events). A paramater, CONST, is used to scale the peak-flow rate to the distance over which erosion takes place in the model. The manner in which EROFLOW erodes different thicknesses of strata over varying distances is shown graphically in the flow chart (fig. 27).

Facies of Alluvial Fans

Both water flows and debris flows usually are deposited as long narrow tongues extending radially downslope from the fan apex. These deposits tend to diverge and branch in the downfan direction. As a result, the internal structure of most fans consists of beds that can be traced for considerable distances along a radial line. However, cross-fan sections reveal beds that are apparently of small extent and interrupted by cut and fill structures resulting from periodic stream-channel entrenchment and backfilling (Bull, 1968, p. 102; Tolman, 1937, p. 369).

Fans may also exhibit a radial inhomogeneity (Tolman, 1937, p. 369). In northeastern California, Pyle observed that the upper parts of the fans consisted of permeable bouldery deposits. The middle parts of the fans consisted largely of sand and gravel, while the lowermost

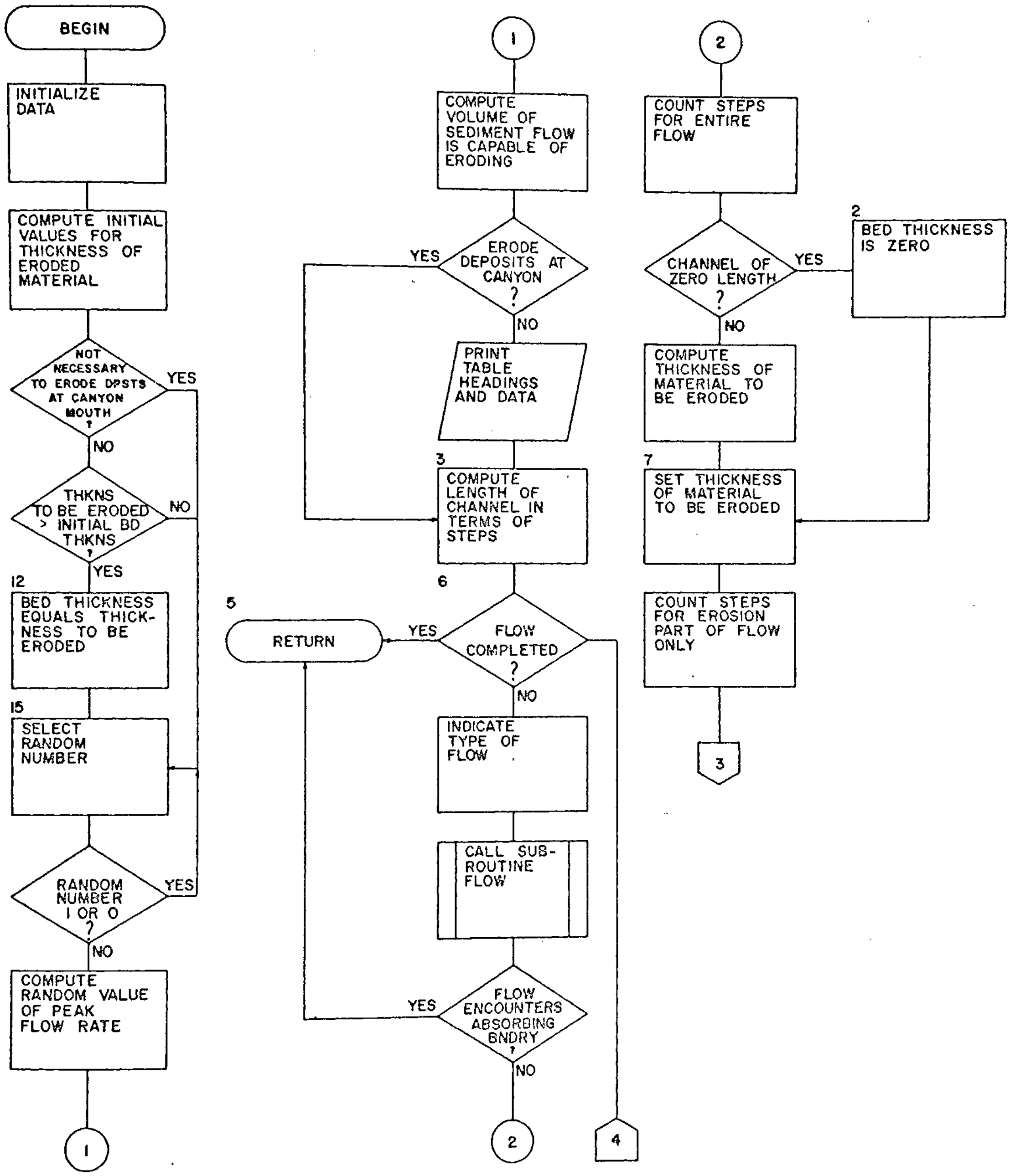


Figure 27.--Flow chart for subroutine EROFLOW.

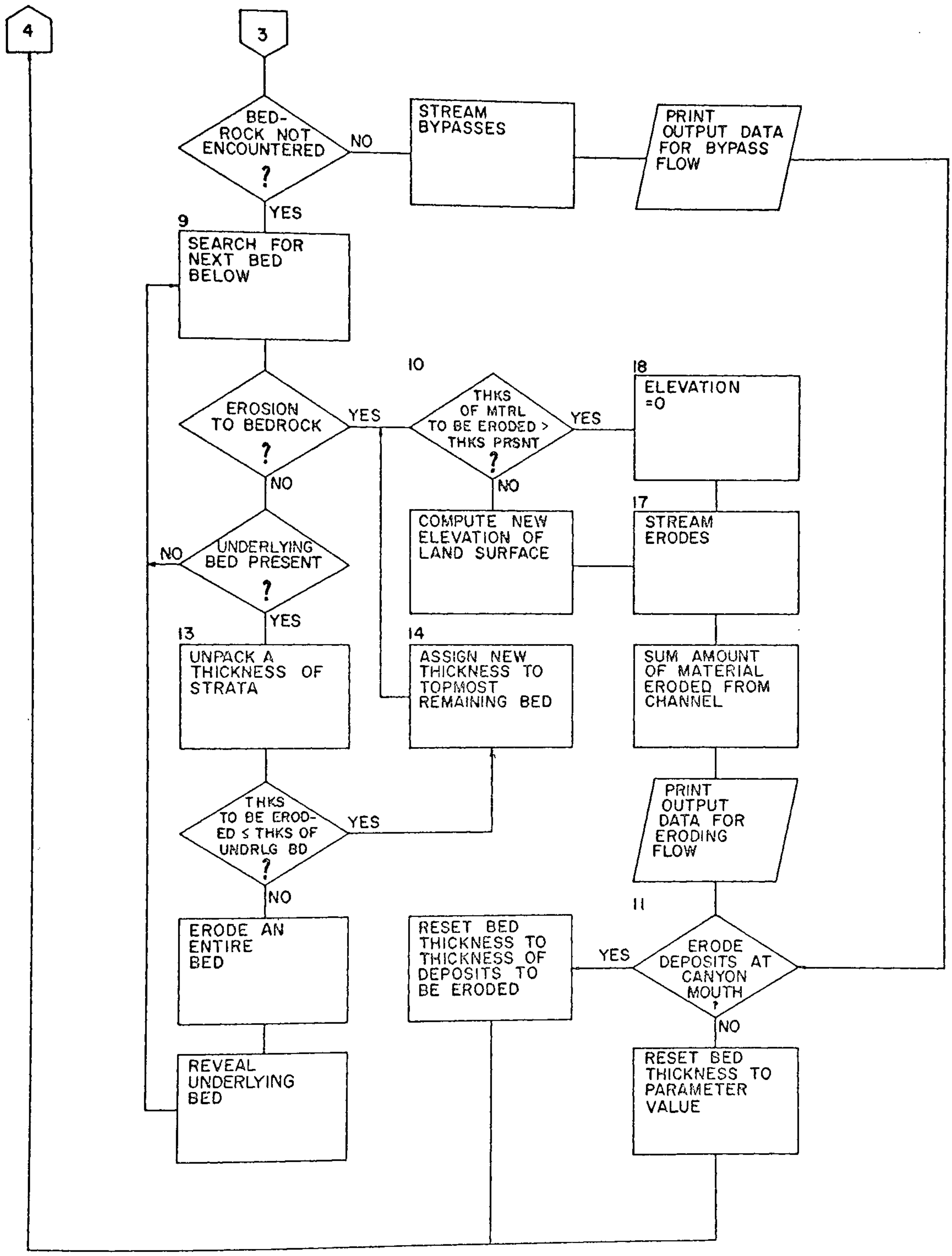


Figure 27. —Continued

part consisted of sand and silt (California Department of Water Resources, 1963, p. 64-65). In a dissected alluvial-fan basin fill north of Los Angeles, Crowell (1954) observed that the uppermost part of a fan deposit consisted of an unbedded to poorly bedded cobble and boulder conglomerate with a matrix of sand- to clay-sized material, apparently of debris-flow origin. Outward from the source area, the sediments graded into fluvial-bedded conglomerate, well-bedded sandstone with shale, and finally into shale.

No attempt was made in this paper to trace individual beds in order to determine their continuity in the radial versus cross-fan direction, but such a project would be worthwhile in future studies. Plots of radial sections (figs. 29, 30, 32, and 33) do, however, show a marked radial homogeneity, which is shown especially well in the sections through the fan built of water-flow deposits (fig. 33). Here, sand and gravel dominate the fan deposits in the apical region, while silt and clay form the lower slopes near the toe. Figure 34 is an example of the computer printouts from which these sections were constructed. Figures 28 and 31 show the location of the plotted sections in plan view.

Alluvial-Fan Morphology

Fan Shape

General. Alluvial fans have been described as having the shape of a cone or half cone, with its apex at the canyon mouth (Drew, 1873,

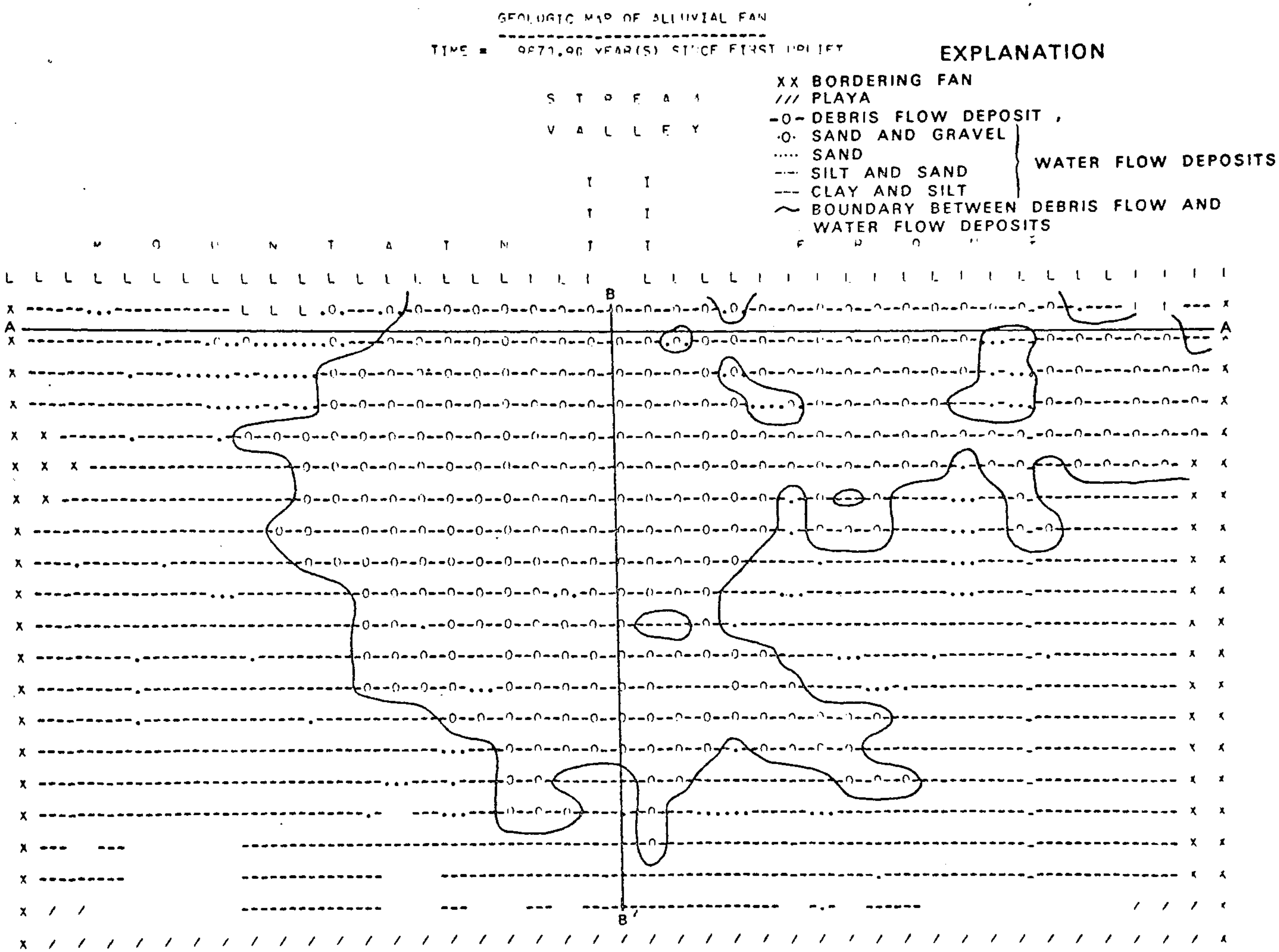


Figure 28. --Computer printout of simulated fan consisting largely of debris-flow deposits, resulting from 106 flow events.

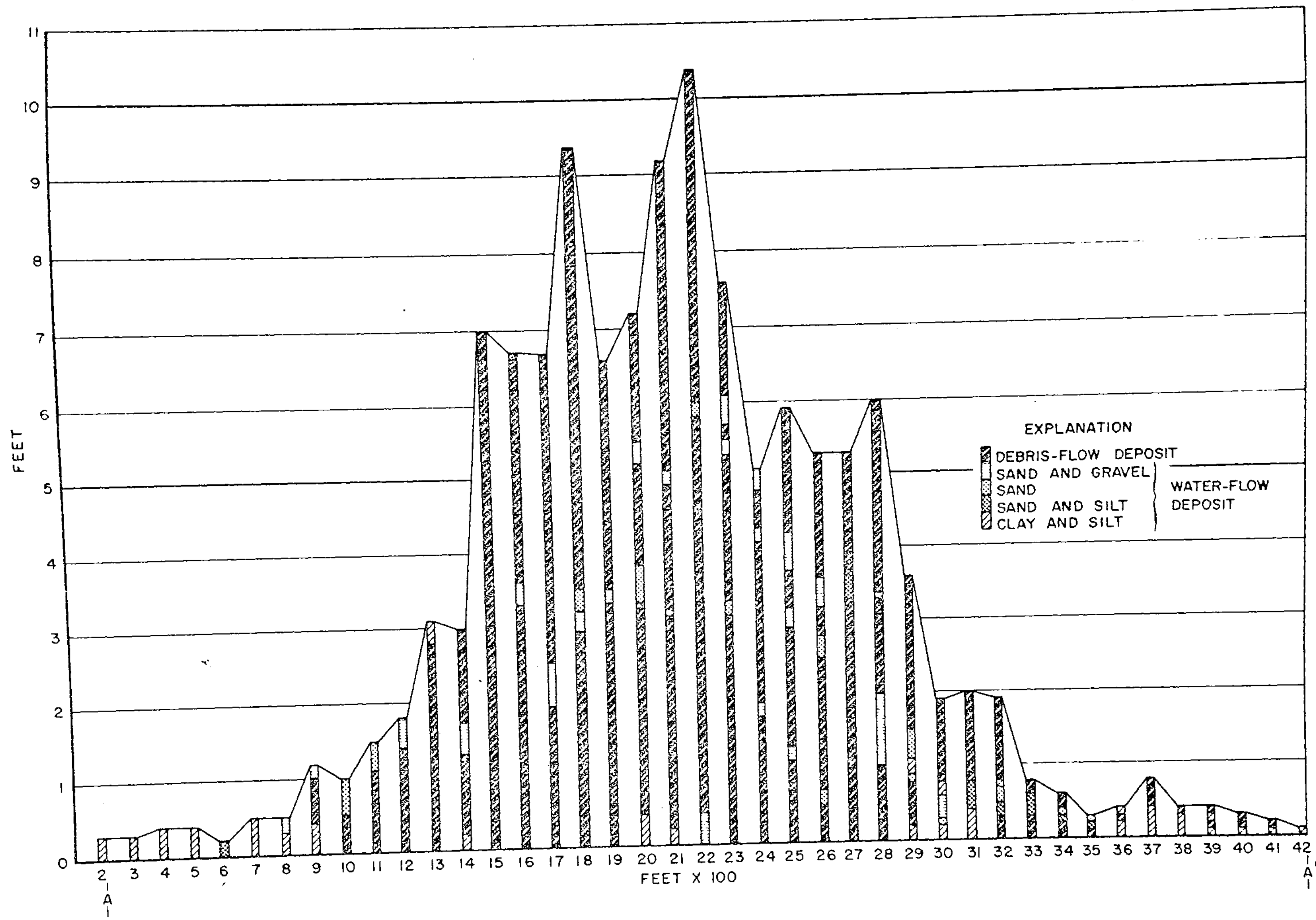


Figure 29. --Radial section through simulated fan consisting largely of debris-flow deposits. Section parallel to mountain front.

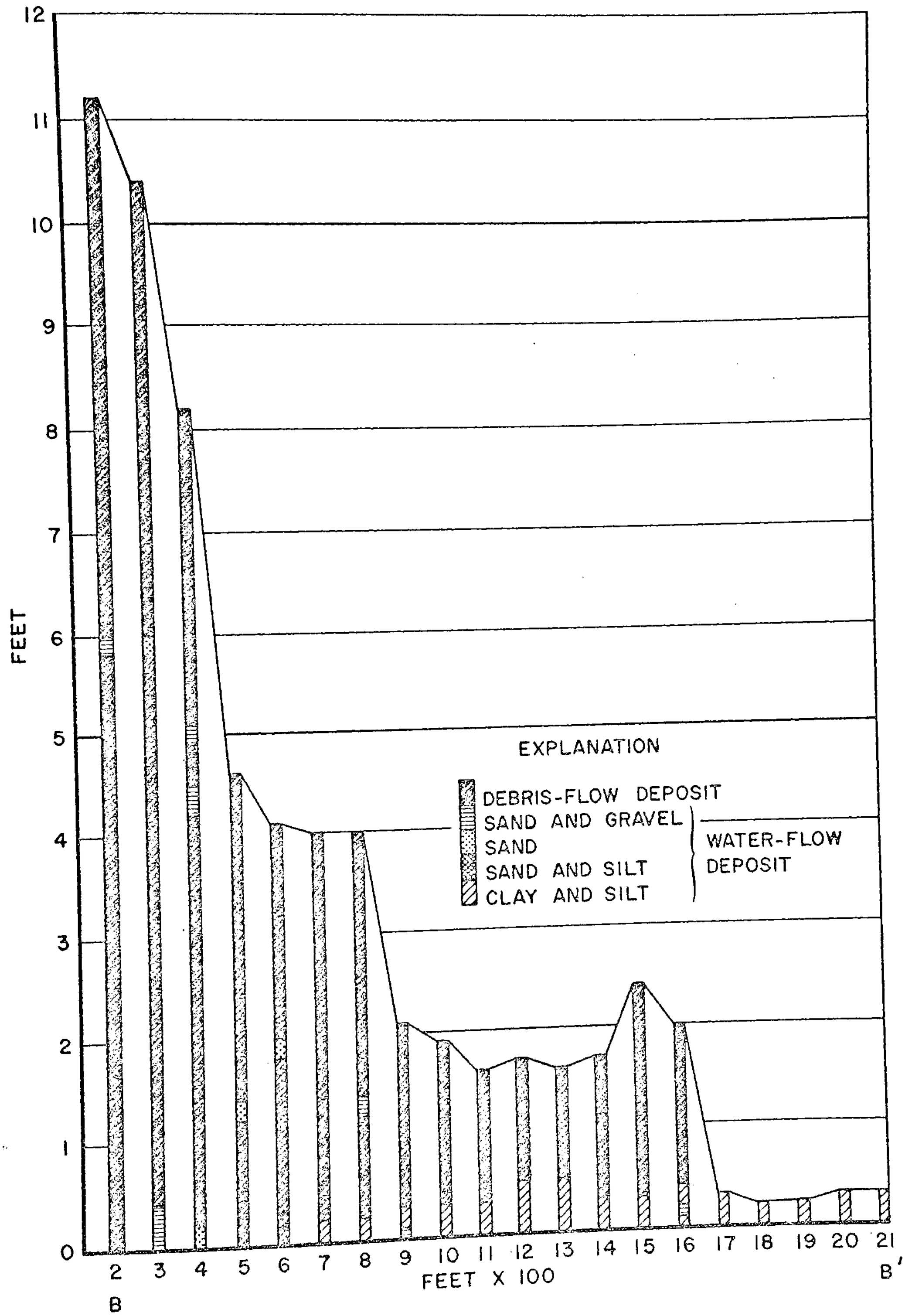


Figure 30. --Radial section through simulated fan consisting largely of debris-flow deposits. Section perpendicular to mountain front.

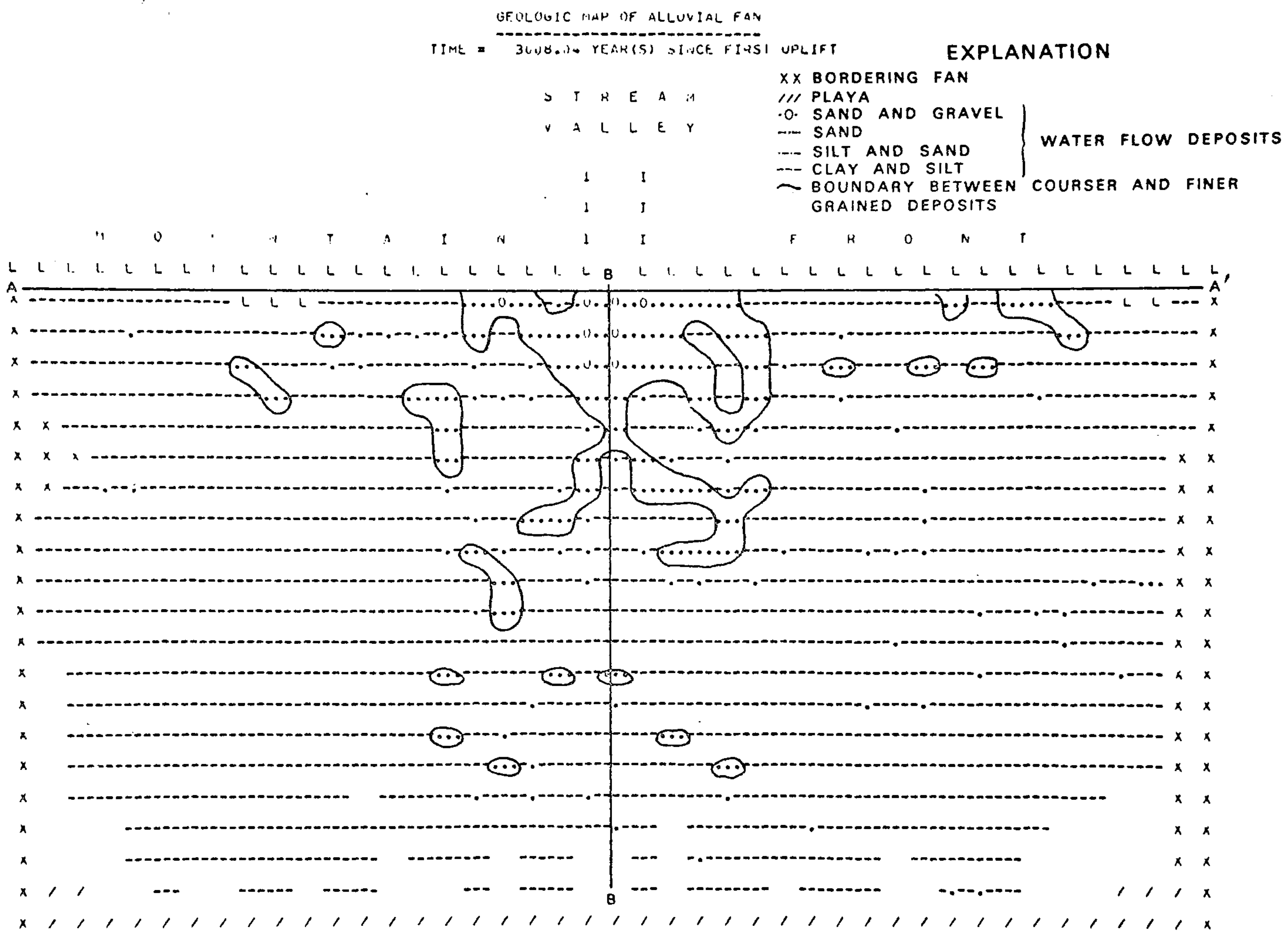


Figure 31. --Computer printout of simulated fan consisting of water-flow deposits.

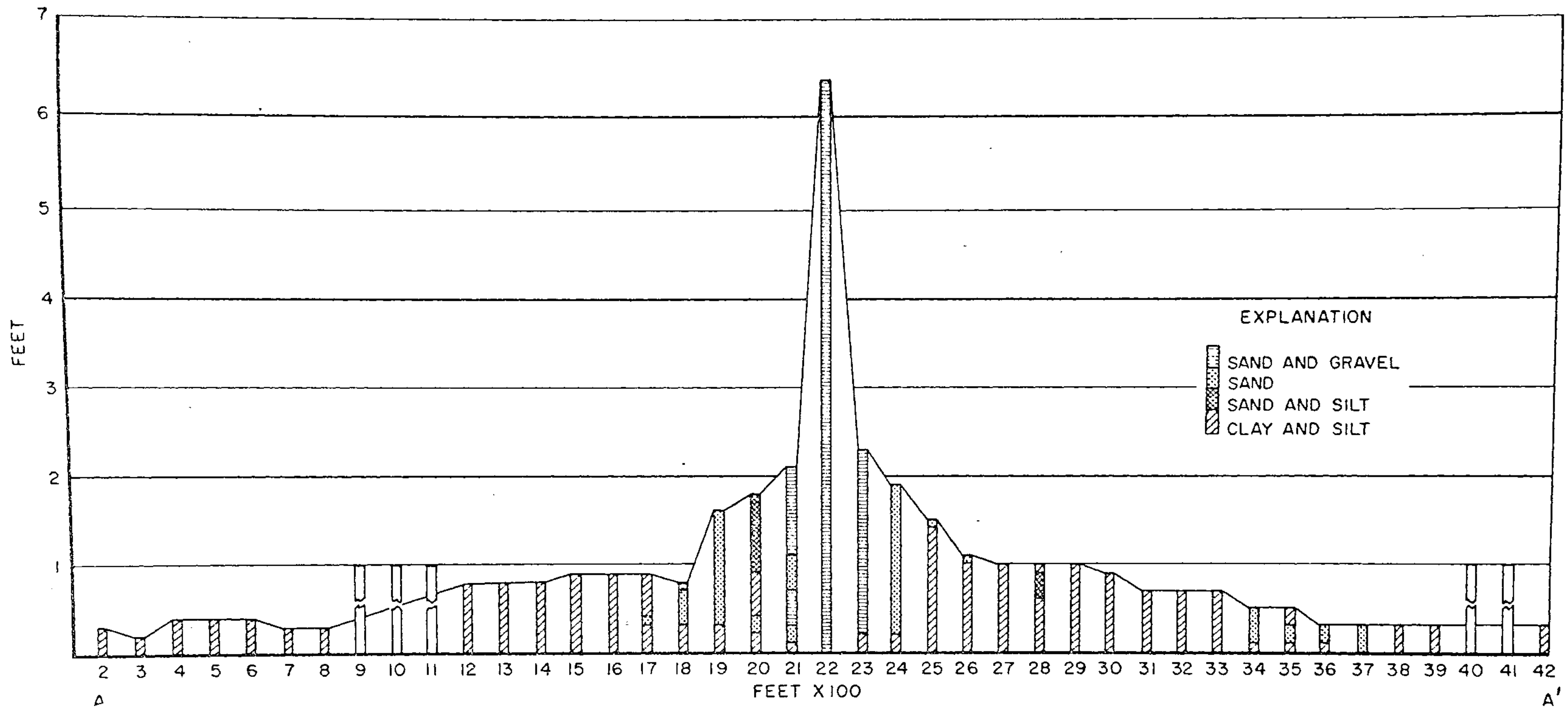


Figure 32.--Radial section through simulated fan consisting of water-flow deposits. Section parallel to mountain front.

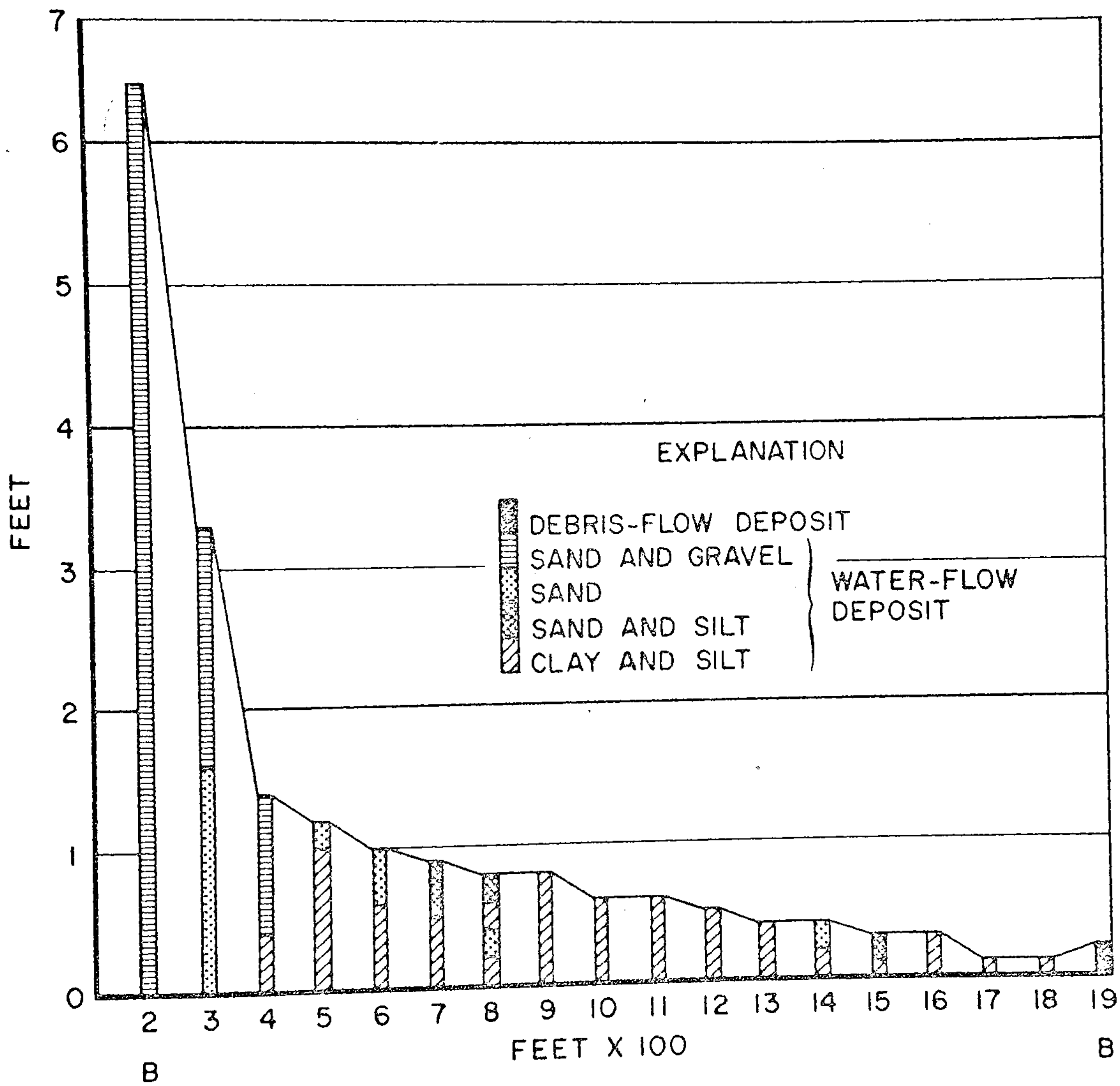


Figure 33.--Radial section through simulated fan consisting of water-flow deposits. Section perpendicular to mountain front.

DATA FOR GEOLOGIC SECTIONS

ROW 3 EAST PART

BED	COLUMN	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43
15	LITHOLOGY																					
	FT. THICK																					
14	LITHOLOGY						-0-															
	FT. THICK						1.4															
13	LITHOLOGY	-0-		-0-	-0-		-0-															
	FT. THICK	1.5		1.8	1.7		1.1															
12	LITHOLOGY	.0.	.0.	.0.	.0.		.0.															
	FT. THICK	.1	.1	.2	.2		.1															
11	LITHOLOGY	.0.	.0.	.0.	.0.		-0-	-0-														
	FT. THICK	.1	.0	.0	.0		1.3	1.2														
10	LITHOLOGY	.0.	.0.	.0.	.0.		.0.	-0-														
	FT. THICK	.2	.2	.2	.2		.1	.9														
9	LITHOLOGY	-0-	.0.	.0.	...		.0.	...		-0-												
	FT. THICK	.2	.1	.1	.0		.2	.2		1.0												
8	LITHOLOGY	...	-0-	-0-	-0-	-0-	.0.	...	-0-	-0-												
	FT. THICK	.0	.5	.5	.4	1.7	.1	.1	1.0	.3												
7	LITHOLOGY	...	.0.	.0.	...	-.-	.0.	...	.0.	-.-	-0-											
	FT. THICK	.2	.0	.1	.1	.1	.2	.1	.2	.2	.9											
6	LITHOLOGY	-0-	.0.	.0.	...	-.-	.0.	---	---	-.-	-0-					-0-						
	FT. THICK	.2	.2	.2	.2	.1	.2	.2	.2	.2	.2					.3						
5	LITHOLOGY	-0-	-0-	-0-	-0-	-.-	.0.	...	.0.	---	---	-0-	-0-		---	---	-0-	-0-				
	FT. THICK	1.8	.4	.1	.4	.2	.0	.0	.1	.1	.1	.2	.2		.1	.1	.1	.1				
4	LITHOLOGY	...	-0-	-0-	-0-	-0-	.0.	...	.0.	---	...	-.-	...	...	-0-	---	---	---	-0-			
	FT. THICK	.2	1.8	1.5	1.4	1.2	.1	.1	.2	.2	.2	.2	.1	.1	.1	.1	.1	.1	.1			
3	LITHOLOGY	-0-	.0.	.0.	...	-0-	-0-	-0-	...	---	-.-	-.-	-.-	-.-	---	---	---	-0-	-0-	-0-		
	FT. THICK	1.5	.2	.2	.2	1.3	.7	.6	.1	.0	.2	.2	.1	.1	.1	.1	.0	.1	.1	.1		
2	LITHOLOGY	-0-	-0-	-0-	-0-	-0-	-0-	---	---	---	-0-	-0-	-0-	-0-	---	---	---	---	-.-	---	---	
	FT. THICK	1.6	1.7	1.1	.5	.8	.3	.2	.2	.2	.3	.3	.2	.1	.0	.0	.1	.1	.1	.1	.1	
1	LITHOLOGY	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
	FT. THICK																					

SYMBOLS SHOWN WITH .0 THICKNESS REPRESENT DEPOSITS BETWEEN 0.0 AND 0.05 FEET IN THICKNESS

Figure 34.--Computer printout of data used in constructing geologic sections.

p. 447; Dutton, 1880, p. 220-221). However, when alluvial fans coalesce, they may completely lack the characteristic conical shape (Hawley and Wilson, 1965, p. 24).

Mathematical. Fan shape has been described quantitatively in three dimensions by Troeh (1965), Murata (1966), and Ruhe (1967). The equation derived by Troeh (1965) may be used for four basic types of landforms, simply by changing signs. When written in the form

$$Z = P - SR + LR^2 \tag{54}$$

the equation can be used to describe the concave-convex curvature typical of alluvial fans. Z is the altitude of any point on the surface of the fan, P is the altitude of the apex, S is the slope of the theoretical fan at P, L is half the rate of change of slope along a radial line, and R is the radial distance from P.

Murata (1966) assumed that a fan is part of a circular cone intersecting a gently sloping inclined plane. The intersection is an ellipse. These conditions have, in fact, been found in nature.

Ruhe (1964) used profiles of radii expressed in feet per mile and the radii of curvature of specific contours to express quantitatively alluvial-fan morphology.

In model ALFAN, the shapes of simulated alluvial fans are shown in figures 19 and 35. The simulated fan shown in figure 19 is the product of 106 flow events, 47 of which were debris flows, 46 water

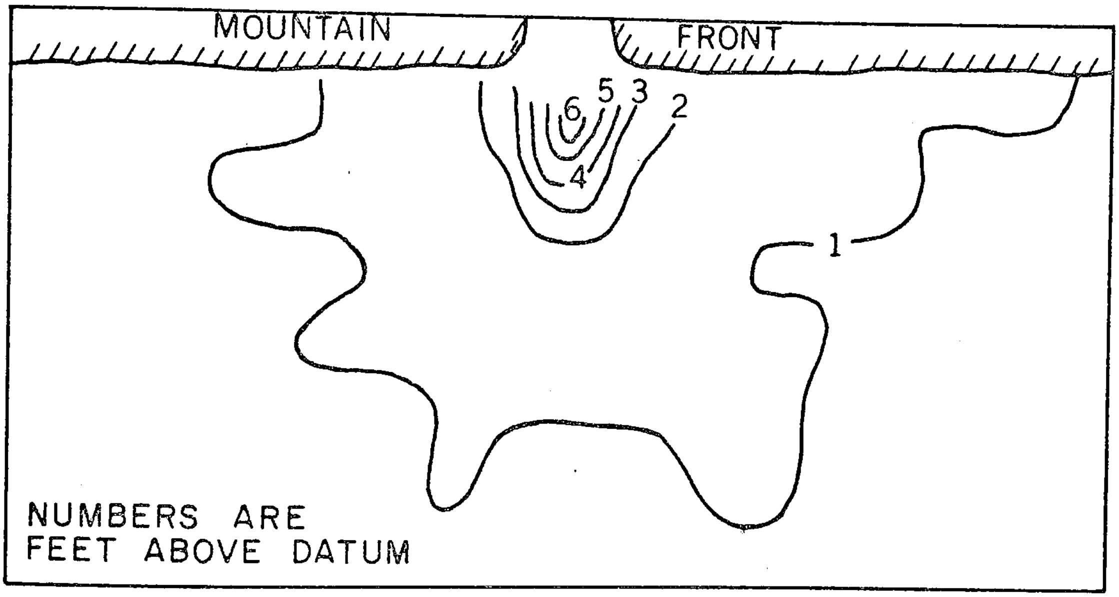


Figure 35. --Topographic map of simulated fan consisting of water-flow deposits.

flows, and 14 eroding water flows. Although only about half of the flow events were debris flows, their deposits dominate the fan, largely because debris-flow deposits are generally thicker than water-flow deposits. The general form of the deposits is that of a fan, although the surface of the fan is irregular and edges of the deposit are ragged. The unevenness of the surface is also reflected in the fan sections shown in figures 29 and 30. This irregularity is believed to be primarily due to (1) the presence of eroding water flows which carve the surface of the fan, (2) the nature of the algorithm which determines the direction of movement of the debris flows, (3) the thickness of the debris flows, and (4) the relatively small number of flow events when compared to a natural fan. As mentioned in the section on transitional probabilities, the algorithm guiding debris flows allows them to climb gentle slopes; hence they are not so effective in filling depressions in the fan surface as are water flows.

The simulated fan shown in figure 35, on the other hand, is built of only 32 water flows, yet it is much smoother. During the construction of the fan, the uplift rate of the mountain block was sufficiently greater than the depositional rate that the main stream channel did not erode below the level of the fan, and the critical value for eroding water flows was so low (0.05) that none occurred. Therefore, no erosion took place to carve the surface of the fan. The raggedness of the edges of the fan, shown in figure 35, probably is due to the relatively small number of flow events. The computer printout giving the elevations upon which this contour map is based is shown in figure 36.

Fan Size

Factors Affecting Fan Size. Overall fan size is controlled mainly by drainage-basin features, such as size, slope, rainfall, and erodibility of the exposed rocks. Tectonic history, the amount of available space on which the fan can be deposited, and the presence of through-flowing streams also determine fan size. Of these features, drainage-basin size is probably the single most important in determining fan area. A general relation can be expressed by the equation

$$A_f = cA_d^{\,n} \tag{55}$$

in which A_f is the fan area and A_d is the drainage-basin area. The exponent n is nearly constant from basin to basin, and is commonly about 0.90 (Hooke, 1968, p. 619). The coefficient c, on the other hand, may have a more than ten-fold variation because of the effect of variables other than drainage-basin area on fan size (Bull, 1968, p. 104). If a given time period is stipulated, the size of the fan developed in ALFAN will be principally a function of (1) the size of the erodible area (A), which is assumed constant over time, (2) storm frequency, reflected as mean rate of flow occurrence, in flows per year (LAMBDAF), and (3)

```
                         ELEVATIONS ON SURFACE OF ALLUVIAL FAN
                         -------------------------------------
                       TIME =   3008.04 YEAR(S) SINCE FIRST UPLIFT

                                    S  T  R  E  A  M
                                    V  A  L  L  E  Y

                                          I   I
                                          I . I
      M   O   U   N   T   A   I   N       I   I             F   R   O   N   T
L L L L L L L L L L L L L L L L L L L L L 13. L L L L L L L L L L L L L L L L L L L L
X .3 .2 .4 .4 .4 .3 .3 L  L  L  .8 .9 .8 .9 .9 .9 .81.61.82.16.42.31.91.51.11.01.01.0 .9 .7 .7 .7 .5 .5 .3 .3 .3 .3 L  L  .3 X
X .3 .2 .4 .3 .4 .4 .4 .4 .5 .3 .6 .5 .6 .6 .51.11.31.41.51.93.31.91.71.31.11.0 .9 .6 .8 .7 .7 .7 .7 .7 .7 .7 .5 .3 .3 .3 .3 X
X .3 .4 .4 .4 .3 .3 .3 .3 .5 .5 .5 .4 .4 .6 .5 .8 .91.01.21.11.41.21.5 .9 .9 .8 .7 .5 .6 .6 .7 .5 .5 .5 .5 .6 .4 .4 .3 .3 .3 X
X .3 .4 .4 .4 .3 .3 .3 .3 .3 .2 .2 .3 .4 .4 .4 .71.01.11.21.11.21.11.51.2 .9 .6 .7 .5 .5 .6 .7 .4 .4 .4 .4 .5 .5 .4 .3 .3 .3 X
X X .3 .4 .4 .2 .2 .2 .2 .2 .2 .2 .3 .4 .5 .5 .9 .9 .71.01.01.01.01.11.1 .8 .7 .7 .7 .7 .7 .6 .3 .3 .3 .3 .5 .5 .4 .3 .3 .3 X
X X X .3 .4 .1 .2 .2 .2 .2 .2 .2 .3 .4 .4 .4 .8 .8 .71.0 .8 .9 .91.01.1 .8 .6 .7 .6 .6 .6 .5 .3 .3 .3 .3 .5 .5 .4 .3 .3 .3 X
X X .2 .2 .2 .1 .2 .2 .2 .2 .2 .2 .3 .5 .5 .5 .5 .8 .7 .9 .6 .8 .7 .6 .8 .7 .5 .5 .6 .6 .6 .5 .4 .4 .5 .5 .5 .3 .4 .3 .3 X  X
X .1 .2 .2 .2 .1 .2 .2 .2 .2 .2 .3 .3 .4 .3 .6 .6 .8 .5 .7 .7 .8 .7 .6 .8 .5 .5 .5 .5 .6 .6 .5 .3 .4 .4 .4 .4 .4 .4 .3 .2 X  X
X .1 .2 .2 .2 .1 .2 .2 .2 .2 .3 .3 .4 .4 .4 .4 .3 .5 .5 .6 .6 .6 .6 .5 .7 .5 .4 .4 .4 .4 .5 .4 .3 .4 .3 .4 .3 .4 .4 .2 .2 X  X
X .1 .2 .2 .2 .1 .1 .1 .1 .1 .3 .1 .1 .2 .2 .3 .4 .4 .5 .5 .4 .6 .6 .5 .6 .6 .5 .4 .4 .4 .3 .4 .4 .4 .3 .4 .4 .4 .3 .1 .1 X  X
X .1 .1 .1 .2 .1 .1 .1 .1 .1 .3 .1 .1 .2 .2 .3 .3 .3 .5 .5 .4 .5 .6 .5 .5 .5 .5 .4 .4 .4 .3 .3 .3 .3 .2 .2 .3 .3 .3 .1 .1 X  X
X .1 .1 .1 .1 .1 .1 .1 .1 .3 .3 .2 .2 .2 .2 .3 .3 .3 .5 .5 .3 .4 .6 .5 .5 .5 .4 .4 .4 .3 .3 .2 .3 .3 .2 .1 .3 .2 .3 .1 .1 X  X
X    .1 .1 .0 .0 .1 .1 .1 .3 .3 .1 .2 .2 .2 .2 .3 .3 .5 .4 .3 .4 .6 .5 .5 .5 .4 .4 .3 .3 .3 .2 .1 .3 .2 .1 .3 .2 .2 .2 .0 X  X
X    .1 .1 .1 .1 .1 .1 .1 .1 .3 .1 .2 .2 .2 .1 .3 .2 .4 .3 .3 .3 .4 .5 .5 .5 .4 .4 .3 .3 .2 .2 .1 .2 .2 .2 .2 .2 .1 .1 .1 X  X
X    .1 .1 .1 .1 .1 .1 .1 .1 .3 .2 .1 .1 .1 .2 .3 .3 .4 .3 .3 .3 .3 .3 .5 .4 .3 .3 .3 .2 .2 .2 .1 .2 .2 .2 .2 .2 .1 .1 .1 X  X
X    .1 .1 .1 .1 .1 .0 .0 .2 .2 .2 .1 .1 .1 .1 .2 .1 .3 .3 .3 .1 .1 .3 .4 .2 .2 .3 .3 .2 .1 .1 .1 .1 .2 .2 .2 .2 .1 .1 .1 X  X
X    .1 .1 .1 .1 .1 .2 .2 .2 .1 .2    .1 .1 .1 .2 .1 .2 .3 .2 .1 .1 .3 .4 .3 .3 .3 .2 .2 .1 .1 .1 .1 .2 .1 .1 .1 .1       X  X
X          .0 .0 .1 .1 .1 .2 .1 .1 .1 .1 .2 .2 .2 .1 .1 .2 .2 .2 .2    .3 .3 .3 .3 .2 .1 .1 .1 .1 .1 .2 .1 .1             X  X
X          .0 .0 .1 .1 .1 .1 .1 .1 .1    .2 .2 .2    .1 .2       .2    .1 .3 .3 .1 .2 .1 .1    .1 .1 .2 .1                X  X
X / /         .0       .1 .1    .1 .0          .2    .1 .2       .1    .1 .2 .3    .1 .1 .1          .1 .1          / / / X
X / / / / / / / / / / / / / / / / / / / / / / / / / / / / / / / / / / / / / / / / / / X
```

Figure 36.--Computer printout of elevations on surface of simulated fan.

erodibility, expressed as the average rate of soil accumulation in feet per year (C).

The effect of tectonic activity on the size of the fans on opposite sides of Death Valley was noted by both Hooke (1965, p. 119) and Denny (1965, p. 38). Eastward tilting of the valley has caused the west-side fans to be extended and the east-side fans to be buried by the playa. ALFAN does not contain provisions for studying the effects of tilting. In the model, tectonic activity is limited to faulting assumed to take place immediately above the fan apex. As long as the rate of uplift minus the rate of downcutting of the stream channel upstream from the fan apex exceeds the rate of deposition at the fan apex in the model, sediments will be laid down initially at the fan apex and will extend away from the apex in diminishing thickness. However, if the elevation of the stream channel immediately above the fault (HSUBT) lies at the same elevation, or nearly so, only thin beds if any can be deposited near the apex. Because the model is subject to the constraint that no deposition on the fan may take place if the top of the material to be deposited will lie at a higher elevation than HSUBT, deposition will occur only farther downfan or not at all. In the latter case, material may bypass the fan system altogether.

As pointed out by Hawley and Wilson (1965, p. 29) and Bull (1968, p. 104), the size of fans is in part determined by the available space in which the fans can be deposited. The amount of space in which the fan modeled by ALFAN may develop is determined by the distance between adjacent grid lines and the boundary conditions stipulated. Larger fans may be modeled by assigning greater grid-spacing distances, but this will be done at the expense of the resolution of fan features.

If a fan is crossed or bounded by a through-flowing stream, material may be removed from the fan area instead of being added to the fan (Hawley and Wilson, 1965, p. 29), thus limiting the size of the fan. ALFAN is assumed to be bounded on the south by a playa or through-flowing stream. If a flow event reaches this southern boundary, it is absorbed. The quantity of sediment in the flow that has not yet been deposited is then assumed to be added to the playa or carried away by a through-flowing stream. In either case, this amount of material is lost from the system.

Range of Values. Fans in the American West range in radius from a few hundred yards to as much as 40 miles (Blissenbach, 1954, p. 177; McKee, 1957, p. 1728; Allen, 1965, p. 158). Many fans in this area are several miles in length (Dutton, 1880, p. 221; Denny, 1965, p. 33; Allen, 1965, p. 158). In other parts of the world, much larger fans are present. The Kosi River fan in Bihar province, India, for example, is more than 100 miles wide (Maddock, personal commun., 1971). The size of a fan modeled in ALFAN depends largely upon the scale used. If a grid spacing of 100 feet is employed, the maximum radius of the simulated fan will be 2,000 feet.

Contemporary alluvial fans may be 2,000 feet or more in thickness. In general, the thickness of alluvial-fan deposits is greatest at the apex of a fan (Scott, 1932, p. 269). The thickness of fan deposits in ALFAN depends largely upon the number of flow events that have taken place and on the thickness assigned to each debris-flow or water-flow deposit. If an average thickness of 1.0 foot is assumed for debris-flow deposits, and if it is further postulated that the rate of uplift exceeds the rate of fan building and that no erosion takes place, then the maximum possible thickness of debris-flow deposits developed after 100 flow events would be 200 feet at the apex.

Other measures of fan size are area and volume. Fans may commonly range from less than a square mile to hundreds of square miles. Beaty (1970, p. 50) estimated the volume of the Milner Creek fan, whose shape resembles one-quarter of a low cone with a radius of 4,800 yards and a height of 370 yards, as 2-1/4 billion cubic yards. One must be careful, however, in estimating fan volumes from fan areas. Volumes of sediment removed from or deposited on equal planimetric areas may differ if the slopes in the areas are not the same. Also, the volumes of sediment in alluvial fans may differ because buried basements vary in their angle of tilt (Lustig, 1965, p. 134). In ALFAN, individual water-flow deposits are in general considered thinner than debris-flow deposits. For this reason, the areas of water-flow deposits shown on the geologic maps of the fans will be larger in proportion to their volume for equal numbers of debris-flow and water-flow events.

Fan Slope

Factors Affecting Fan Slope. Factors related to fan slope are debris caliber, stream discharge, basin size, basin relief, basin lithology, channel slope, and tectonics. In general, fan slopes associated with coarser material, such as debris-flow or sieve deposits, or sand and gravel, are steeper than the fan slopes containing only fine material (Tolman, 1937, p. 365, 536; Russell, 1954, p. 370; Longwell and Flint, 1962, p. 173; Lustig, 1965, p. 134; Hooke, 1966, p. 97, 1968, p. 621; Bull, 1968, p. 105). This relationship was used in ALFAN as a simple means of obtaining the average size of water-flow sediments deposited on the fan. Hooke (1968, p. 622-623) also pointed out that larger discharges generally have higher flow velocities and higher bed shear stresses, and thus are able to transport on a lower slope the same material transported by smaller discharges on a higher slope. Stream discharge is of course related to basin size, which has given rise to the observation by Drew (1873, p. 448) and Bull (1964a, p. 94; 1968, p. 105) that fan slope decreases with increasing fan and drainage-basin size. Fan slope may also be related to basin relief under some conditions, as demonstrated by Melton (1965, p. 1, 24, 30). However, in general, fan slope is related to channel slope; steep fans form at the mouths of canyons having steep longitudinal profiles, and gently sloping fans form at the mouths of valleys having gentle longitudinal profiles (Balchin and Pye, 1956; Bull, 1964a, p. 94, 100; Beaty, 1968, p. 84; Hooke, 1968, p. 627). Slope is also influenced by source-area lithology (Hooke, 1968, p. 625-626). In western Fresno County, Bull (1964a, p. 94) found that fans in the size range 1-100 square miles that are derived from mudstone and shale basins are 35-75 percent steeper than fans of similar area that are derived from sandstone basins. Finally, the slope of fans may be influenced by infiltration and by tectonics. Hooke (1966, p. 97) concluded that fans characterized by very high infiltration rates are steeper than fans on which infiltration plays a minor role. Bull (1964a, p. 94) pointed out that the relations between fan slope, fan area, drainage-basin area, and lithology may be different for areas in which downcutting of stream channels exceeded uplift than for areas in which uplift exceeded channel downcutting.

Range of Values. Fans generally slope most steeply in the apical region near the mountain front, and least steeply near the toe. Few fans slope more than 10° at the apex, and the majority less than 6° (McKee, 1957, p. 1728). Near the toe, slopes may be 1° or 2°, or less. Slopes on the fan modeled by ALFAN are very low, ranging from 1° to 2° near the apex to 0° near the toe.

Fan Profiles

Radial Profiles. The radial profiles of unsegmented fans may be concave, straight, or convex. Concave-upwards profiles in fans are reported by Dutton (1880, p. 221), Eckis (1928, p. 234), Blissenbach (1954, p. 176), Balchin and Pye (1956, p. 171), and Denny (1965, p. 25, 32, 56, 1967, p. 87). Drew (1873, p. 447) and Hawley and Wilson (1965, p. 25) have described fans with straight profiles. The writer knows of no specific fans with convex profiles, but Hawley and Wilson (1965, p. 25) report that they exist.

Bull (1964a, p. 94, 96) found that the slopes of fans in western Fresno County do not decrease gradually away from the mountain front, as do most fan slopes, but have distinct breaks in slope which give their radial profiles a segmented appearance. The fan segments generally have a constant slope and appear as straight lines on a radial profile. Two fans in the area, however, each have a segment that is concave in addition to their straight-line segments. Hooke (1967, p. 441) also reported that two fans he studied in eastern California had segmented profiles. It is also of interest to note that Bull (1964a, p. 96) plotted the profile of the San Antonio Canyon fan on the same radial line as did Krumbein (1937, fig. 5; see following section) and obtained three segments, the upper and lower of which were straight, but the middle concave.

The probable cause of fan segmentation in western Fresno County is intermittent uplift. Bull (1964a, p. 89, 105) recognized two principal cases: (1) The rate of uplift exceeds the rate of stream downcutting. The result is progressively steeper stream slopes and fan segmentation in which the highest segment is the yougest. (2) The rate of stream downcutting exceeds the rate of uplift. The result is progressively greater stream gradients and fan segmentation in which the lowest segment is the youngest. The surface form of the segment itself is also determined by the conditions of uplift (Bull, 1964a, p. 110). A fan segment that appears as a straight line on a radial profile may be the result of rapid uplift of the drainage basin followed by a time of little or no uplift during which the stream channel and fan obtain a common slope. A fan segment that appears concave may represent the case in which a fan surface has not had sufficient time to develop a relatively constant slope after a period of rapid uplift, or it also could be the result of gradual continuing uplift. During a period of continuous uplift the stream gradient would gradually steepen and the depositional slope of the fan also would become progressively steeper.

Mathematical Representation. Alluvial-fan profiles have been described mathematically by Krumbein (1937, p. 586-589) and Ruhe (1967, p. 20-21, 25). Krumbein fitted an exponential equation of the form

$$y = 2,280\,e^{-0.12x}$$

to an alluvial fan in the Cucamonga quadrangle, California. The constant a (0.12 in the above equation), referred to as a profile coefficient, is also a coefficient of sediment thickness because, with reference to the surface of deposition, the profile of the alluvial fan is an expression of the thickness of the deposited material at any point, assuming that the base of the fan deposit is a horizontal plane. Ruhe found that all fan profiles along the Organ-San Augustin-San Andres mountain front in southern New Mexico could be described by two longitudinally merging curves. Above 4,800 feet altitude, the profiles are best fitted by a hyperbolic function $Y' = a + bX$, where Y' is the reciprocal of altitude in feet and X is the distance in miles along each traverse. From 4,300 to 4,800 feet, curves are expressed by the equation $\log Y = a + bX$, where Y is altitude in feet and X is distance in miles.

Inasmuch as fan surfaces are built by streams, fan profiles should be similar to stream profiles. Although slope is related to particle size, Denny (1965, p. 23-24, 55-56) found a poor relation in the fan washes of the Death Valley region, probably because many factors other than particle size affect the slope.

Profiles of the two fans simulated by ALFAN appear to be approximately exponential in nature, with the steepest part of the profile at the apex and the lowest at the toe (figs. 30 and 33).

Channel Profiles

The profiles of channels of ephemeral streams on fans may be concave upward, straight, or convex upward. According to Longwell and Flint (1962, p. 173), the combination of erosion upstream from the fan and deposition on the fan, together with changes in channel cross section, results in a continuous concave-up profile whose form depends chiefly on discharge and the diameter of particles in the bedrock. Leopold, Wolman, and Miller (1964, p. 279) found that rivers having no increase in discharge over long reaches through desert or arid areas have a concavity which is related to the length of the reach downstream from the last major tributary. Concavity is zero or the profile is straight when specific discharge equals some particular value. However, in arid regions loss of water to the stream channel will result in an increase of sediment concentration, which in turn may produce deposition. In the reaches where this occurs, the stream profile may be convex (Schumm, 1961, p. 31, 67; Longwell and Flint, 1962, p. 173; Morisawa, 1968, p. 98-99, 101).

The Problem of Validation

According to Naylor and others (1968, p. 310), the problem of verifying simulation models remains today the most elusive of all the unresolved problems associated with computer simulation techniques. They further state that:

> To verify or validate any kind of model means to prove the model to be true. But to prove that a model is "true" implies (1) that we have established a set of criteria for differentiating between those models which are "true" and those which are not "true" and (2) that we have the ability to readily apply these criteria to any given model. Yet the concept of "truth" has successfully eluded philosophers and theologians since the history of mankind. To decide upon a particular set of criteria that must be satisfied before we can have "truth" suggests that we must choose a subset of rules (truth rules) from an infinite set of rules handed down by philosophers, theologians, and metaphysicians. When placed in this perspective, the problem of verification is completely overwhelming because it may well be argued that man is incapable of recognizing "truth" at all, even if "truth" exists.

However, it is nevertheless "true" that simulation models based on hypothetical functional relationships and data not subjected to empirical verification have little more than pedagogical value.

Van Horn (1969, p. 233) agrees that a simulation model cannot be proved to be true, but he defines validation instead as "the process of building an acceptable level of confidence that an inference about a simulated process is a correct or valid inference for the entire process." The objective then is to validate a specific set of inferences derived from use of the model and not necessarily the mechanism (model) itself. The more positive results we obtain from testing the model inferences, the greater confidence we have in these inferences, and the better our validation is.

After examining philosophical views on validation Naylor and Finger (1967) suggest a three-stage approach, which Van Horn (1969, p. 235-236) has generalized as follows:

1. Construct a set of hypotheses and postulates for the process using all available information—observations, general knowledge, relevant theory, and intuition.

2. Attempt to verify the assumptions of the model by subjecting them to empirical testing.

3. Compare the input-output transformations generated by the model to those generated by the real world.

In the first stage, confidence in the model is increased when the process is easy to measure or observe, or if an extensive body of research is available, or if a strong theoretical base exists, such as in the case of the mathematics of stochastic processes, of which the Markov process is an example.

The second stage includes not only the verification of assumptions, but of exogenous variables, functional relationships, and distributions as well. Statistical tests are of great use here. This stage corresponds to step 4 in the flow chart for planning simulation experiments (fig. 1).

The third stage, comparison of input-output transformations, is the one we are primarily concerned with in this section. The flow chart in figure 1 gives this stage in step 6. Basically, we wish to compare the output of the simulator with that of the actual process, using similar or identical inputs. In program ALFAN input data is transformed into maps showing the geology and morphology of an alluvial fan, and geologic sections showing the internal stratigraphy of the fan. If boundary conditions and other exogenous variables similar to those in the real world are programmed into the model, the output should be a fan with a shape like that of the real fan but a stratigraphy that is only statistically similar. Goodness of fit tests could be used to compare the fan surfaces, while tests of Markov dependence and spectral analysis in both time and frequency domains are ideally suited for determining the statistical similarity of stratigraphic sequences within the fans.

Because the primary task of this study is to design the random-walk model, validation from a quantitative standpoint, as described above, is not within the scope of the study. Nevertheless, we have given a qualitative validation of the model, as described in the previous sections, and it is hoped that this will provide a basis for more vigorous testing as a part of future studies.

CONCLUSIONS AND FUTURE WORK

The results of this study suggest that a digital model based on a random walk can be used to represent alluvial-fan deposition. The general form of the deposits is that of an alluvial fan, the pattern of simulated flows resembles that of real flows, and fan facies show a concentration of debris flows near the apex and particle-size decrease of water-flow deposits downfan. The model holds promise for further development, and future work should include (1) experiments on the model, (2) possible changes in the algorithms of several parts of the model, (3) sensitivity analysis, and (4) quantitative validation of the model.

Experiments should be conducted by varying the parameters of the model and observing the effect of these variations on the form and lithology of the simulated fan. Only by making such experiments can one use the model as a tool to aid in understanding the relation between geologic processes and the nature of the resulting deposits.

The model possibly could be improved by changing the algorithm in several places. For example, it might be worthwhile to change the method by which the gradient for debris-flow movement is calculated and calculate the gradient from the bottom of the flow (land surface) at the central node instead of from the top of the flow as is done in the present program. If this were done, debris flows would not generally be able to climb slopes but could only move in the direction of the negative gradient, as is true of water flows. Thus, a much smoother surface which is typical of debris flows in nature (Johnson, 1970, p. 513-514) would result. Consideration should also be given to strengthening the correlation between the gradient in a given direction and the probability of movement in that direction. Equation (40) does provide a rational basis for calculating the probability of movement in a given direction but possibly is not sufficiently sensitive to significant variations in land-surface slope.

Some changes could also be made in the mechanics of the program itself. For example, running time of the program could be reduced if only data and maps for certain events, rather than for all events, were printed out.

Sensitivity analysis would provide a testing of the significance of different parameters in the model. Elimination of nonsignificant parameters would simplify the model. Different distributions for the stochastic events or different functional forms might be employed. For example, Wolman and Miller (1960, p. 55-56) suggest that a log-normal distribution might be appropriate for hydrologic events such as flood peaks.

As suggested in the previous section, the model should also be validated quantitatively. This may be accomplished by subjecting field data to statistical tests and comparing the results with statistical analyses of simulated sections from ALFAN. The programs developed by Krumbein (1967, p. 7-9, 17-18) for testing the dependence or independence of stratigraphic sequences should be useful in this respect. Another possible approach is that of the significance of correlations of alluvial-fan strata. Because in ALFAN the complete history of erosion and deposition at any given point is known, it is possible to make a bed correlation that is accurate. It would then be instructive to compare this correlation with one made by conventional means when the only data available are those contained in the log. Ultimately, it is hoped that permeability values may be assigned to the simulated beds generated by ALFAN and the model used as a predictive tool in areas where ground water is undeveloped.

The writer's contribution in this study is the design of a model of alluvial-fan deposition based on a random walk. It is hoped that this model will serve as a basis for more sophisticated models and will provide a stimulus for further research into other areas that experiments on the model may suggest.

APPENDIX

LISTING OF PROGRAM ALFAN

LFN = INPUT

```
      PROGRAM ALFAN (INPUT,OUTPUT)
C A RANDOM-WALK SIMULATION MODEL OF ALLUVIAL-FAN DEPOSITION
C PROGRAMMER - H. E. PRICE
C DATE OF LAST REVISION - AUG., 1971
C
C CARD ORDER
C ***SOURCE DECK
C ***DATA CONTROL CARD 1
C     COL 1 THE NUMBER 1
C     COLS 2-80 TITLE FOR PROGRAM (OR LEAVE BLANK)
C ***DATA CONTROL CARDS 2-5
C     COL 1 THE NUMBER 0
C     COLS 2-80 TITLES FOR PROGRAM (OR LEAVE BLANK), THE PROGRAM MUST
C               HAVE DATA CONTROL CARDS 1-5 WHETHER OR NOT ANYTHING IS
C               PRINTED ON THEM
C ***DATA CONTROL CARD 6
C     COLS 1-10 INITIAL THICKNESS OF ERODIBLE SOIL IN BASIN, IN FEET
C     COLS 11-20 HEIGHT OF INITIAL DISPLACEMENT AT FAN APEX, IN FEET
C     COLS 21-30 COORDINATE OF INITIAL ROW. THIS NUMBER IS ALWAYS 1
C     COLS 31-40 COORDINATE OF INITIAL COLUMN. THIS NUMBER IS DETERMINED
C                BY THE POSITION OF THE CANYON MOUTH AND MAY RANGE FROM 2
C                TO 42
C     COLS 41-50 VERTICAL COORDINATE OF INITIAL DEPOSIT. THIS NUMBER IS
C                ALWAYS 2
C     COLS 51-60 INERTIA TERM FOR STREAMFLOW. THIS TERM IS GENERALLY GREATER
C                THAN 1.0
C ***DATA CONTROL CARD 7
C     COLS 1-10 NUMBER OF FLOW EVENTS. NOT MORE THAN 32 EVENTS MAY BE SPECIFIED.
C               IF 32 EVENTS ARE SPECIFIED, THEN THE MAXIMUM NUMBER OF FLOW
C               EVENTS WILL OCCUR. THIS NUMBER WILL BE 32 OR GREATER
C     COLS 11-20 MAXIMUM TIME, IN 3-PLACE DECIMAL SECONDS, ALLOTED TO RUN FLOW
C                EVENTS ON COMPUTER. WHEN THIS TIME IS EQUALLED OR EXCEEDED
C                GEOLOGIC SECTIONS WILL BE PRINTED AND PROGRAM WILL STOP
C ***DATA CONTROL CARDS 8-11
C     COLS 1-80 FORMAT DATA FOR TOP SECTION OF ALLUVIAL FAN MAP.
C               FORMATTING MUST AGREE WITH STREAM VALLEY LOCATION GIVEN
C               UNDER INPUT PARAMETERS
C ***DATA CONTROL CARDS 12-33
C     COLS 1-43 PUNCH 6 S FOR THE MOUNTAIN BOUNDARY, 7 S FOR THE BOUNDARIES OF
C               ADJACENT ALLUVIAL FANS, 8 S FOR THE PLAYA OR STREAM BOUNDARY,
C               AND A 9 FOR THE POINT WHERE THE FAN-BUILDING STREAM CROSSES
C               THE MOUNTAIN FRONT. LEAVE BLANK OTHERWISE. EACH CARD
C               REPRESENTS A ROW IN THE FAN MAP GRID
C ***DATA CONTROL CARD 34
C     COLS 1-10 GRID SPACING, IN FEET
C     COLS 11-20 ERODIBLE AREA OF BASIN, IN SQUARE FEET
C     COLS 21-30 MAXIMUM LENGTH OF FAN-BUILDING PERIOD, IN YEARS
C     COLS 31-40 DISTANCE CANYON MOUTH EAST OF ORIGIN, IN FEET
C     COLS 41-50 AVERAGE UPLIFT RATE, IN UPLIFTS PER YEAR
C     COLS 51-60 LENGTH OF LOCUS OF POINTS OF MAXIMUM DISPLACEMENT ALONG
C                FAULT, IN FEET
C     COLS 61-70 MEAN THICKNESS OF DEBRIS FLOW DEPOSITS, IN FEET
C     COLS 71-80 MEAN THICKNESS OF WATER FLOW DEPOSITS, IN FEET
C ***DATA CONTROL CARD 35
C     COLS  1-10 AVERAGE RATE OF ACCUMULATION OF WEATHERED MATERIAL, IN FEET
C                PER YEAR
C     COLS 11-20 CRITICAL THICKNESS OF WEATHERED MATERIAL, IN FEET, WITH REGARD
C                TO DEBRIS FLOW
C     COLS 21-30 AVERAGE RATE OF DECLINE OF CHANNEL AT CANYON MOUTH, IN
C                FEET PER YEAR
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C     COLS 31-40 MEAN RATE OF FLOW OCCURRENCE, IN FLOWS PER YEAR
C     COLS 41-50 COEFFICIENT OF FIXATION
C     COLS 51-60 MAXIMUM THICKNESS OF WEATHERED LAYER IN BASIN, IN FEET
C     COLS 61-70 CRITICAL THICKNESS OF WEATHERED MATERIAL, IN FEET, WITH REGARD
C                TO WATER FLOW
C     COLS 71-80 CONSTANT RELATING PEAK FLOW RATE TO NUMBER OF STEPS IN RANDOM
C                WALK
C ***DATA CONTROL CARD 36
C     COLS 1-10 MEAN PEAK FLOW RATE, IN CUBIC FEET PER SECOND
C     COLS 11-20 STANDARD DEVIATION OF DEBRIS FLOW BED THICKNESS
C     COLS 21-30 STANDARD DEVIATION OF WATER FLOW BED THICKNESS
C     COLS 31-40 BED THICKNESS OPTION. IF LOGNORMALLY DISTRIBUTED BEDS OF
C                CONSTANT THICKNESS ARE DESIRED, PUNCH 0. IF BEDS OF DECREASING
C                THICKNESS ARE DESIRED, PUNCH 1
C     COLS 41-50 MEAN DEPTH OF EROSION, IN FEET
C     COLS 51-60 UPPER LIMIT OF MAXIMUM THICKNESS OF DEBRIS FLOW FOR BYPASS
C                CONDITION, IN FEET
C     COLS 61-70 UPPER LIMIT OF MAXIMUM THICKNESS OF WATER FLOW FOR BYPASS
C                CONDITION, IN FEET
C ***DATA CONTROL CARD 37
C     COLS 1-10 NUMBER OF ROWS FOR WHICH PRINTED SECTIONS ARE DESIRED
C     COLS 11-12 NUMBER OF FIRST ROW FOR WHICH A PRINTED SECTION IS DESIRED
C     COLS 13-14 NUMBER OF SECOND ROW FOR WHICH A PRINTED SECTION IS DESIRED
C     COLS 15-16 ETC.
C ***DATA CONTROL CARD 38
C     COLS 1-10 NUMBER OF COLUMNS FOR WHICH PRINTED SECTIONS ARE DESIRED
C     COLS 11-12 NUMBER OF FIRST COLUMN FOR WHICH A PRINTED SECTION IS
C                DESIRED
C     COLS 13-14 NUMBER OF SECOND COLUMN FOR WHICH PRINTED SECTION IS
C                DESIRED
C     COLS 15-16 ETC. A SECOND DATA CONTROL CARD MAY BE USED IF NEEDED
C ***OBJECT-TIME FORMAT CARDS 39-41
C ***SYMBOL CARD 42
C
      DIMENSION TITLE(40)
      COMMON BLOCK(22,43,33),YSUBS,HPRIMEF,A,T,XPRIME,LAMBDAU,LSUBF,C,YS
     1UBC,KAY,LAMBDAF,CSUBF,TSUBF,FORM1(8),FORM2(8),FORM3(8),DASHES1,S,
     2KON,MAP(22,43),ROW(22),COL(43),N,N1,N2,HSUBT,TPRIMEU,L,TIME,
     3W,D,TOPU,MOVE(22,43),INERTIA,MSUBS,HSUB(22,43),GRID,VSUBS,EVENT,
     4NORMAL,FMT(45),TPRIMED,RSUBU,BTHICK,WTHICK,YSUBC1,CONST,GAMMA,
     5FLODIR,FLOCOND,SLOPEN,SLOPEE,SLOPES,SLOPEW,SIGMAD,SIGMAW,TT,
     6PSUBFN,PSUBFE,PSUBFS,PSUBFW,FORM(11),RIGHT(6),DUM1,ROWI(400),DUM2,
     7COLJ(400),FORM4(8),FORM5(8),FORM6(16),FSPEC1,ASPEC1,FSPEC6,VSUBE,
     8ETHICK,IGRADE,FSPEC5,ASPEC5,ISUBN,ISUBE,ISUBS,ISUBW,IL,IW,
     9GMAP(22,43),STEPS,TMAP(22,43),TMTN3,TFAN3,TPLAYA3,TBLANK3,TPRIMEF
      COMMON ELEV(22,43),JJ,FMT2(26),PRIORUP,LEFT1,LEFT2,FSPEC2,ASPEC
     12,BLANK2,IFLOAB,BEDSEC(22),DLIMIT,WLIMIT,WALL,NFLOTYP,INUPFLO,
     2INTRAP,LSTEP,CARRY(1600),NEWCYCL
      COMMON /AST/ ASTER3,SILT3,SILSAN3,SAND3,SANGRA3,DEBRIS3,MTN3,FAN3,
     1PLAYA3,BLANK3
      COMMON /FMOUN/ MTNB,ABSORB,M,NN,NORTH,EAST,SOUTH,WEST,ERODE,DEPOSI
     1T,BYPASS,FANB,HIGH
      COMMON /SILT/ SILTSYM,SISAYM,SANDSYM,SAGRSYM,DEBSYM,ASTER,MTSYM,F
     1ANSYM,ABSYM,BLANK
      INTEGER Y,W,D,ROW,COL,SILTSYM,SISASYM,SANDSYM,SAGRSYM,DEBSYM,ASTER
     1,FANSYM,ABSYM,GMAP,BLANK
      INTEGER ASTER3,SILT3,SILSAN3,SAND3,SANGRA3,DEBRIS3,FAN3,PLAYA3,BLA
     1NK3
      REAL MSUBS,MTNB,NORTH,KAY,LEFT,INERTIA,ISUBN,ISUBE,ISUBS,ISUBW
      REAL LAMBDAF,LAMBDAU,LEFT5,LEFT1,LEFT2
```

```
      DATA (SILTSYM = 1H1),(SISASYM = 1H2),(SANDSYM = 1H3),(SAGRSYM = 1H
     14),(DEBSYM = 1H5),(ASTER = 1H*),(MTSYM = 1HL),(FANSYM = 1HX),(ABS
     1YM = 1H/),(NORTH =5HNORTH),(EAST = 4HEAST),(SOUTH = 5HSOUTH),(WEST
     2 = 4HWEST),(ERODE = 5HERODE),(DEPOSIT = 7HDEPOSIT),(BYPASS = 6HBYP
     3ASS),(BLANK = 1H )
      DATA (ASTER3 = 3R***),(SILT3 = 3R---),(SILSAN3 = 3R-.-),(SAND3 = 3
     1R...),(SANGRA3 = 3R.O.),(DEBRIS3 = 3R-O-),(MTN3 = 3R L ),(FAN3 = 3
     2R X ),(PLAYA3 = 3R / ),(BLANK3 = 3R   )
      DATA M,NN /77777777777777000000B,00000000000000777777B/
      DATA MTNB,FANB,ABSORB,HIGH /6000.,7000.,8000.,9000./
C
C READ AND PRINT TITLE (TITLE)
      READ 100, TITLE
      PRINT 100, TITLE
C READ AND SET INITIAL CONDITIONS
      READ 101, YSUBS,HPRIMEF,L,W,D,INERTIA
      EVENT = 0
      HSUBT = HPRIMEF
      TDPU = 0.0
      TSUBF = 0.0
      ISUBN = 1.0
      ISUBE = 1.0
      ISUBS = INERTIA
      ISUBW = 1.0
      NEWCYCL = 1
C PRINT INITIAL CONDITIONS
      PRINT 108
      PRINT 109
      PRINT 126, HPRIMEF
      PRINT 142, L,W,D
      PRINT 110, YSUBS
C READ FIRST SET OF INPUT PARAMETERS
      READ 160, N,TIME
C READ TOP PORTION OF MAP SHOWING BOUNDARY CONDITIONS (MAP)
      READ 100, FORM1
      READ 100, FORM2
      READ 100, FORM3
C READ TOP PORTION OF GEOLOGIC MAP (GEOMAP) AND TOPOGRAPHIC MAP (TOPMAP)
      READ 100, FORM4
      READ 100, FORM5
      READ 100, FORM6
C READ BOUNDARY CONDITIONS
      DO 1 I = 1,22
      READ 102, (MAP(I,J),J = 1,43)
    1 CONTINUE
C STORE BASAL BOUNDARY CONDITIONS IN MODEL BLOCK (BLOCK)
      DO 3 I = 1,22
      DO 3 J = 1,43
      BLOCK(I,J,1) = 0.0
      BLOCK(I,J,1) = BLOCK(I,J,1) .OR. MTN3
    3 CONTINUE
C STORE SIDE BOUNDARY CONDITIONS AND OTHER DATA IN MODEL BLOCK AND ELEVATION
C    (HSUB) AND GEOLOGY (GMAP) ARRAYS
      NP1 = N + 1
      DO 13 K = 2,NP1
      DO 13 I = 1,22
      DO 13 J = 1,43
      BLOCK(I,J,K) = 0.0
      IF (MAP(I,J) .EQ. 0) GO TO 18
      Y = MAP(I,J) - 5
```

```
      GO TO (14,15,16,17) Y
   14 BLOCK(I,J,K) = BLOCK(I,J,K) .OR. MTN3
      HSUB(I,J) = ELEV(I,J) = MTNB
      GMAP(I,J) = MTN3
      GO TO 13
   15 BLOCK(I,J,K) = BLOCK(I,J,K) .OR. FAN3
      HSUB(I,J) = ELEV(I,J) = FANB
      GMAP(I,J) = FAN3
      GO TO 13
   16 BLOCK(I,J,K) = BLOCK(I,J,K) .OR. PLAYA3
      HSUB(I,J) = ELEV(I,J) = ABSORB
      GMAP(I,J) = PLAYA3
      GO TO 13
   17 BLOCK(I,J,K) = BLOCK(I,J,K) .OR. BLANK3
      HSUB(I,J) = ELEV(I,J) = HSUBT
      GMAP(I,J) = BLANK3
      GO TO 13
   18 HSUB(I,J) = ELEV(I,J) = 0.0
      GMAP(I,J) = BLANK3
   13 CONTINUE
C PRINT MAP OF BOUNDARY CONDITIONS
      PRINT 111
      CALL FANMAP
C PRINT OTHER LITHOLOGIC SYMBOLS
      PRINT 146
      PRINT 147, ASTER3
      PRINT 148
      PRINT 149
      PRINT 150
      PRINT 151
      PRINT 152
      PRINT 153
C READ SECOND SET OF INPUT PARAMETERS
      READ 103, GRID,A,T,XPRIME,LAMBDAU,LSUBF,BTHICK,WTHICK
      READ 103, C,YSUBC,KAY,LAMBDAF,CSUBF,MSUBS,YSUBC1,CONST
      READ 141, GAMMA,SIGMAD,SIGMAW,KON,ETHICK,DLIMIT,WLIMIT
C PRINT INPUT PARAMETERS
      PRINT 112
      PRINT 114, GRID
      PRINT 118, XPRIME
      PRINT 116, T
      PRINT 119, LAMBDAU
      PRINT 120, LSUBF
      PRINT 104, GAMMA
      PRINT 140, CONST
      PRINT 124, LAMBDAF
      PRINT 115, A
      PRINT 121, C
      PRINT 122, YSUBC
      PRINT 139, YSUBC1
      PRINT 113, MSUBS
      PRINT 123, KAY
      PRINT 159, INERTIA
      PRINT 137, BTHICK
      PRINT 138, WTHICK
      PRINT 105, DLIMIT
      PRINT 133, WLIMIT
      PRINT 154, SIGMAD
      PRINT 155, SIGMAW
      PRINT 125, CSUBF
```

```
      PRINT 156, ETHICK
C COMPUTE LENGTH OF INITIAL SOIL DEVELOPMENT PERIOD (TPRIMEO)
      Z = MSUBS - YSUBS
      TPRIMEO = (ALOG(Z) - ALOG(MSUBS)) / (-C)
C READ OUTPUT INFORMATION FOR MAPS AND SECTIONS
      READ 106, N1,(ROW(I), I = 1,N1)
      READ 107, N2,(COL(I), I = 1,N2)
C PRINT OUTPUT INFORMATION
      PRINT 127
      PRINT 129, N
C PRINT OUTPUT INFORMATION FOR MAPS
      NTWO = 2 * N
      PRINT 128, NTWO
C PRINT OUTPUT INFORMATION FOR TRANSVERSE SECTIONS (ROW)
      PRINT 131, N1
      PRINT 132, (ROW(I), I = 1,N1)
C PRINT OUTPUT INFORMATION FOR LONGITUDINAL SECTIONS (COL)
      PRINT 134, N2
      PRINT 135, (COL(I), I = 1,N2)
C PRINT MAXIMUM RUNNING TIME ASSIGNED
      PRINT 157, TIME
C READ FORMAT CARDS
      READ 143, LEFT,(RIGHT(I), I = 1,6),DASHES1
      READ 145, FSPEC1,ASPEC1
      READ 117, LEFT5,RIGHT5,ASPEC5,FSPEC5,FSPEC6
      READ 144, LEFT1,LEFT2,FSPEC2,ASPEC2,BLANK2
C READ LITHOLOGIC SYMBOLS FOR TOPOGRAPHIC MAP BOUNDARY
      READ 136, TMTN3,TFAN3,TPLAYA3,TBLANK3
C SET UP OBJECT TIME FORMATS
      FORM(1) = LEFT
      DO 2 I = 1,6
      FORM(I+5) = RIGHT(I)
    2 CONTINUE
      FMT(1) = LEFT5
      FMT(45) = RIGHT5
      DO 7 I = 1,26
      FMT2(I) = TBLANK3
    7 CONTINUE
      FMT2(1) = LEFT1
      FMT2(2) = LEFT2
      FMT2(26) = RIGHT5
C SAVE INITIAL LOCATION PARAMETERS
      IL = L
      IW = W
C COMPUTE TIME OF FLOW SINCE LAST FLOW (TPRIMEF)
    4 RSUBU = RANF(0.0)
      Z = 1.0 - RSUBU
      TPRIMEF = (-1.0 / LAMBDAF) * ALOG(Z)
C COMPUTE TIME OF FLOW SINCE FIRST UPLIFT AT T(0) (TSUBF)
      TSUBF = TSUBF + TPRIMEF
      IF (TDPU .NE. 0.0) GO TO 6
C SELECT RANDOM NUMBER (RSUBU)
    9 RSUBU = RANF(0.0)
      IF (RSUBU .EQ. 0.0 .OR. RSUBU .EQ. 1.0) GO TO 9
C COMPUTE TIME OF UPLIFT SINCE LAST UPLIFT (TPRIMEU)
      Z = 1.0 - RSUBU
      TPRIMEU = (-1.0 / LAMBDAU) * ALOG(Z)
C COMPUTE TIME OF UPLIFT SINCE FIRST UPLIFT (TDPU)
      PRIORUP = TDPU
      TDPU = TDPU + TPRIMEU
```

```
    6 IF (TSUBF .GT. TDPU) GO TO 5
C CALL SUBROUTINE STORM
      INUPFLO = 0
      CALL STORM
C RESET INITAL LOCATION PARAMETERS
      L = IL
      W = IW
      GO TO 4
C CALL SUBROUTINE UPLIFT
    5 INUPFLO = 1
      CALL UPLIFT
      GO TO 9
C
  100 FORMAT (8A10)
  101 FORMAT (2F10.0,3I10,F10.0)
  102 FORMAT (43I1)
  103 FORMAT (8F10.0)
  104 FORMAT (//20X*MEAN PEAK FLOW RATE IS *F9.0* CUBIC FEET PER SECOND*
     1)
  105 FORMAT (//20X*LOWER LIMIT OF INITIAL DEPOSITIONAL THICKNESS OF DEB
     1RIS FLOW IS *F5.2)
  106 FORMAT (I10,35I2)
  107 FORMAT (I10,35I2/8I2)
  108 FORMAT (////10X*INITIAL CONDITIONS*)
  109 FORMAT (//20X*TIME OF FIRST UPLIFT IS 0.0 YEARS*)
  110 FORMAT (//20X*INITIAL THICKNESS OF WEATHERED LAYER IN BASIN IS *F5
     1.1* FEET*)
  111 FORMAT (////10X*BOUNDARY CONDITIONS*)
  112 FORMAT (////10X*INPUT PARAMETERS*)
  113 FORMAT (//20X*MAXIMUM THICKNESS OF WEATHERED LAYER IN BASIN IS *F4
     1.1* FEET*)
  114 FORMAT (//20X*GRID SPACING IS *F5.0* FEET*)
  115 FORMAT (//20X*ERODIBLE AREA OF BASIN IS *F9.0* SQUARE FEET*)
  116 FORMAT (//20X*MAXIMUM LENGTH OF FAN-BUILDING PERIOD IS *F9.2* YEAR
     1(S)*)
  117 FORMAT (5A6)
  118 FORMAT (//20X*MOUTH OF FAN-BUILDING CANYON IS *F6.0* FEET EAST OF
     1THE WESTERN BORDER OF THE GRID*)
  119 FORMAT (//20X*MEAN UPLIFT RATE IS *F5.3* UPLIFTS PER YEAR*)
  120 FORMAT (//20X*LENGTH OF LOCUS OF POINTS OF MAXIMUM DISPLACEMENT AL
     1ONG FAULT IS *F6.0* FEET*)
  121 FORMAT (//20X*AVERAGE RATE OF DEVELOPMENT OF WEATHERED LAYER IS *F
     15.4* FEET PER YEAR*)
  122 FORMAT (//20X*CRITICAL THICKNESS OF WEATHERED LAYER IN BASIN WITH
     1REGARD TO DEBRIS FLOW IS *F4.1* FEET*)
  123 FORMAT (//20X*AVERAGE RATE OF STREAM BED EROSION WHERE FAULT CROSS
     1ES MAIN STREAM CHANNEL IS *F5.4* FEET PER YEAR*)
  124 FORMAT (//20X*MEAN RATE OF FLOW OCCURRENCE IS *F6.3* FLOWS PER YEA
     1R*)
  125 FORMAT (//20X*COEFFICIENT OF FIXATION IS *F12.3)
  126 FORMAT (//20X*INITIAL ELEVATION OF STREAM CHANNEL AT FAULT IMMEDIA
     1TELY FOLLOWING FIRST UPLIFT IS *F7.2* FEET*)
  127 FORMAT (////10X*OUTPUT INFORMATION FOR MAPS AND SECTIONS*)
  128 FORMAT (//20X*NUMBER OF MAPS TO BE PRINTED IS *I2)
  129 FORMAT (//20X*NUMBER OF FLOW EVENTS SPECIFIED IS *I3)
  130 FORMAT (//30X,10F10.0)
  131 FORMAT (//20X*NUMBER OF TRANSVERSE SECTIONS TO BE PRINTED IS *I2)
  132 FORMAT (//20X*ROWS TO BE PRINTED ARE *18(I5)/4(I5))
  133 FORMAT (//20X*LOWER LIMIT OF INITIAL DEPOSITIONAL THICKNESS OF WAT
     1ER FLOW IS *F5.2)
```

```
 134 FORMAT (//20X*NUMBER OF LONGITUDINAL SECTIONS TO BE PRINTED IS* I2
    1)
 135 FORMAT (//20X*COLUMNS TO BE PRINTED ARE *18(I5)/25(I5))
 136 FORMAT (4A3)
 137 FORMAT (//20X*MEAN THICKNESS OF DEBRIS FLOW DEPOSITS IS *F4.1* FEE
    1T*)
 138 FORMAT (//20X*MEAN THICKNESS OF WATER FLOW DEPOSITS IS *F4.1* FEET
    1*)
 139 FORMAT (//20X*CRITICAL THICKNESS OF WEATHERED LAYER IN BASIN WITH
    1REGARD TO WATER FLOW IS *F4.1* FEET*)
 140 FORMAT (//20X *CONSTANT RELATING PEAK FLOW RATE TO NUMBER OF STEPS
    1 IN RANDOM WALK IS *F10.0)
 141 FORMAT (3F10.0,I10,3F10.0)
 142 FORMAT (//20X*COORDINATES OF INITIAL NODE ARE*I3*,*I3*,*I3)
 143 FORMAT (A7,6A9,A8)
 144 FORMAT (A10,3A6,A5)
 145 FORMAT (2A6)
 146 FORMAT (//10X*OTHER LITHOLOGIC SYMBOLS*)
 147 FORMAT (//20X*BEDROCK UNDERLYING FAN*5X,R3)
 148 FORMAT (//20X*DEBRIS FLOW                    -0-*)
 149 FORMAT (//20X*WATER FLOW*)
 150 FORMAT (//30X*SILT              ---*)
 151 FORMAT (//30X*SILT AND SAND     -.-*)
 152 FORMAT (//30X*SAND              ...*)
 153 FORMAT (//30X*SAND AND GRAVEL   .0.*)
 154 FORMAT (//20X*STANDARD DEVIATION OF DEBRIS FLOW BED THICKNESS IS *
    1F3.1)
 155 FORMAT (//20X*STANDARD DEVIATION OF WATER FLOW BED THICKNESS IS *F
    13.1)
 156 FORMAT (//20X*MEAN DEPTH OF EROSION IS *F5.2* FEET*)
 157 FORMAT (//20X*MAXIMUM TIME FOR MODEL TO BE RUN IS *F4.0* SECONDS*)
 159 FORMAT (//20X*VALUE OF MOMENTUM COEFFICIENT IS *F5.1)
 160 FORMAT (I10,F10.0)
     END
     SUBROUTINE UPLIFT
     COMMON BLOCK(22,43,33),YSUBS,HPRIMEF,A,T,XPRIME,LAMBDAU,LSUBF,C,YS
    1UBC,KAY,LAMBDAF,CSUBF,TSUBF,FORM1(8),FORM2(8),FORM3(8),DASHES1,S,
    2KON,MAP(22,43),ROW(22),COL(43),N,N1,N2,HSUBT,TPRIMEU,L,TIME,
    3J,K,TDPU,MOVE(22,43),INERTIA,MSUBS,HSUB(22,43),GRID,VSUBS,EVENT,
    4NORMAL,FMT(45),TPRIMEO,RSUBU,BTHICK,WTHICK,YSUBC1,CONST,GAMMA,
    5FLODIR,FLOCOND,SLOPEN,SLOPEE,SLOPES,SLOPEW,SIGMAD,SIGMAW,TT,
    6PSUBFN,PSUBFE,PSUBFS,PSUBFW,FORM(11),RIGHT(6),DUM1,ROWI(400),DUM2,
    7COLJ(400),FORM4(8),FORM5(8),FORM6(16),FSPEC1,ASPEC1,FSPEC6,VSUBE,
    8ETHICK,IGRADE,FSPEC5,ASPEC5,ISUBN,ISUBE,ISUBS,ISUBW,IL,IW,
    9GMAP(22,43),STEPS,TMAP(22,43),TMTN3,TFAN3,TPLAYA3,TBLANK3,TPRIMEF
     COMMON ELEV(22,43),JJ,FMT2(26),PRIORUP,LEFT1,LEFT2,FSPEC2,ASPEC
    12,BLANK2,IFLOAB,BEDSEC(22),DLIMIT,WLIMIT,WALL,NFLOTYP,INUPFLO,
    2INTRAP,LSTEP,CARRY(1600)
     INTEGER EVENT
     REAL LAMBDAU,LSUBF,MSUBO,MSUBE,LSUBD
C
C DETERMINE EVENT NUMBER
     EVENT = EVENT + 1
C CALL SUBROUTINE ERODE
     CALL ERODE
C SET LOWER LIMIT FOR MAGNITUDE OF EARTHQUAKE
     MSUBO = 4.0
C CALL RANDOM NUMBER FOR MAGNITUDE OF EARTHQUAKE (MSUBE)
   2 RSUBU = RANF(0.0)
C SET PARAMETER VALUES (BETA,I)
```

```
      BETA = 2.07
      I = 0
C COMPUTE ARGUMENT (Z)
    5 Z = 1.0 - RSUBU
C COMPUTE MAGNITUDE OF EARTHQUAKE
      MSUBE = (-1.0 / BETA) * ALOG(Z) + MSUBO
      IF (I .EQ. 0) GO TO 1
      IF (MSUBE .LT. 6.0) GO TO 3
      GO TO 2
    1 IF (MSUBE .GE. 6.0) GO TO 4
C SET PARAMETER VALUES (BETA,I)
      BETA = 2.02
      I = 1
      GO TO 5
C COMPUTE HEIGHT OF DISPLACEMENT (HSUBF) FOR MAGNITUDES LESS THAN 6.0
    3 HSUBF = (10.0 ** ((MSUBE - 4.35) / 1.32)) / 30.48
C COMPUTE LENGTH OF DISPLACEMENT (LSUBD) FOR MAGNITUDES LESS THAN 6.0
      LSUBD = (10.0 ** ((MSUBE + 3.5) / 1.6)) / 30.48
      GO TO 6
C COMPUTE HEIGHT OF DISPLACEMENT (HSUBF) FOR MAGNITUDES EQUAL TO OR GREATER
C  THAN 6.0
    4 HSUBF = (10.0 ** ((MSUBE - 5.02) / 1.04)) / 30.48
C COMPUTE LENGTH OF DISPLACEMENT (HSUBF) FOR MAGNITUDES EQUAL TO OR GREATER
C  THAN 6.0
      LSUBD = (10.0 ** ((MSUBE - 0.23) / 1.06)) / 30.48
C CALL RANDOM NUMBER FOR POINT OF MAXIMUM DISPLACEMENT (X)
    6 RSUBU = RANF(0.0)
C COMPUTE LOCATION OF POINT OF MAXIMUM DISPLACEMENT
      XLINE = LSUBF * RSUBU
      ENDIS = (43. * GRID - LSUBF) / 2.0
      X = ENDIS + XLINE
      IF (X .GE. XPRIME) GO TO 7
      IF (XPRIME -X .GE. 0.5 * LSUBD) GO TO 8
C COMPUTE DISPLACEMENT AT FAN APEX (HPRIMEF) WHEN POINT OF MAXIMUM DISPLACEMENT
C  IS WEST OF THE STREAM CROSSING
      HPRIMEF = ((X - XPRIME + 0.5 * LSUBD) * HSUBF) / (0.5 * LSUBD)
      GO TO 9
    7 IF (X - XPRIME .GE. 0.5 * LSUBD) GO TO 8
C COMPUTE DISPLACEMENT AT FAN APEX (HPRIMEF) WHEN POINT OF MAXIMUM DISPLACEMENT
C  IS EAST OF THE STREAM CROSSING
      HPRIMEF = ((XPRIME - X + 0.5 * LSUBD) * HSUBF) / (0.5 * LSUBD)
      GO TO 9
    8 HPRIMEF = 0.0
C COMPUTE NEW ELEVATION OF CHANNEL AT FAN APEX (HSUBT)
    9 HSUBT = HSUBT + HPRIMEF
      ELEV(1,22) = HSUB(1,22) = HSUBT
C PRINT TABLE HEADINGS AND OUTPUT DATA
      PRINT 100
      PRINT 101
      PRINT 102
      PRINT 103
      PRINT 104, EVENT,TDFU,BETA,MSUBE,HSUBF,LSUBD
      PRINT 105
      PRINT 106
      PRINT 107, X,HPRIMEF,HSUBT
      RETURN
C
  100 FORMAT (1H1,55X*SUMMARY OF UPLIFT EVENT*)
  101 FORMAT (56X,23(1H-))
  102 FORMAT (//8X*EVENT*9X*TIME, IN YEAR(S)*9X*BETA*7X*MAGNITUDE OF*7X*
```

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     1HEIGHT OF DISPLACEMENT,*7X*LENGTH OF DISPLACEMENT,*)
  103 FORMAT (7X*NUMBER*7X*SINCE INITIAL UPLIFT*19X*EARTHQUAKE*16X*IN FE
     1ET*23X*IN FEET*/)
  104 FORMAT (I12,F24.2,F15.2,F15.1,F25.2,F32.0)
  105 FORMAT (//12X,*POINT OF MAXIMUM DISPLACEMENT EAST*13X*DISPLACEMENT
     1 AT FAN*13X*NEW ELEVATION OF CHANNEL AT FAN*)
  106 FORMAT (13X*OF THE WESTERN BOUNDARY, IN FEET*17X*APEX, IN FEET*16X
     1*APEX FOLLOWING UPLIFT, IN FEET*/)
  107 FORMAT (F32.0,2F39.2)
      END
      SUBROUTINE STORM
      COMMON BLOCK(22,43,33),YSUBS,HPRIMEF,A,T,XPRIME,LAMBDAU,LSUBF,C,YS
     1UBC,KAY,LAMBDAF,CSUBF,TSUBF,FORM1(8),FORM2(8),FORM3(8),DASHES1,S,
     2KON,MAP(22,43),ROW(22),COL(43),N,N1,N2,HSUBT,TPPIMEU,L,TIME,
     3W,D,TDPU,MOVE(22,43),INERTIA,MSUBS,HSUB(22,43),GRID,VSUBS,EVENT,
     4NORMAL,FMT(45),TPRIMEO,RSUBU,BTHICK,WTHICK,YSUBC1,CONST,GAMMA,
     5FLODIR,FLOCOND,SLOPEN,SLOPEE,SLOPES,SLOPEW,SIGMAD,SIGMAW,TT,
     6PSUBFN,PSUBFE,PSUBFS,PSUBFW,FORM(11),RIGHT(6),DUM1,ROWI(400),DUM2,
     7COLJ(400),FORM4(8),FORM5(8),FORM6(16),FSPEC1,ASPEC1,FSPEC6,VSUBE,
     8ETHICK,IGRADE,FSPEC5,ASPEC5,ISUBN,ISUBE,ISUBS,ISUBW,IL,IW,
     9GMAP(22,43),STEPS,TMAP(22,43),TMTN3,TFAN3,TPLAYA3,TBLANK3,TPRIMEF
      COMMON ELEV(22,43),JJ,FMT2(26),PRIORUP,LEFT1,LEFT2,FSPEC2,ASPEC
     12,BLANK2,IFLOAB,BEDSEC(22),DLIMIT,WLIMIT,WALL,NFLOTYP,INUPFLO,
     2INTRAP,LSTEP,CARRY(1600),NEWCYCL
      INTEGER W,D
      REAL LAMBDAF,MOVE,NORMAL
C
C CHECK FOR TIME OF FLOW GREATER THAN FAN-BUILDING PERIOD
      IF (TSUBF .GE. T) GO TO 3
C CHECK FOR LIMITATION ON RUNNING TIME
      CALL SECOND(TT)
      IF (TT .GE. TIME) GO TO 4
C ASSIGN VALUES TO ARRAY (MOVE) WHICH PREVENTS REVERSAL OR INTERSECTION
C   OF FLOW
      DO 7 I = 1,946
      MOVE(I) = 0.0
    7 CONTINUE
      MOVE(L,W) = 1.0
C ZERO RETRACE ARRAYS
      DO 8 I = 1,400
      ROWI(I) = 0
      COLJ(I) = 0
    8 CONTINUE
      LSTEP = 1
      INTRAP = 0
C COMPUTE NORMALLY DISTRIBUTED RANDOM NUMBERS (NORMAL)
      RN = 0.0
      DO 11 I = 1,12
      RN = RN + RANF(0.0)
   11 CONTINUE
      NORMAL = RN - 6.0
C CALL SUBROUTINE ERODE
      CALL ERODE
C CALL SUBROUTINE BASOIL
      CALL BASOIL
C DETERMINE TYPE OF FLOW
      IF (YSUBS .LT. YSUBC) GO TO 1
C CALL SUBROUTINE DEBFLOW
      CALL DEBFLOW
      GO TO 2
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C CALL SUBROUTINE WATFLOW
    1 CALL WATFLOW
C CALL PRINT SUBROUTINES
    2 CALL GEOMAP
      CALL TOPMAP
C INCREMENT NUMBER OF FLOW EVENTS
      D = D + 1
      IF (D .EQ. N+2) GO TO 9
      GO TO 6
    9 CALL FANSEC
      IF (NEWCYCL .EQ. 1) GO TO 6
      PRINT 100
      STOP
C RESET NUMBER OF FLOW EVENTS FOR PRINTING OF GEOLOGIC SECTIONS
    4 N = D - 2
      CALL FANSEC
      PRINT 101
      STOP
C RESET NUMBER OF FLOW EVENTS FOR PRINTING OF GEOLOGIC SECTIONS
    3 N = D - 2
      CALL FANSEC
      PRINT 113
      STOP
    6 RETURN
C
  100 FORMAT (////50X*MAXIMUM NUMBER OF FLOW EVENTS REACHED*)
  101 FORMAT (//20X*MAXIMUM TIME LIMIT SPECIFIED FOR RUNNING PROGRAM EXC
     1EEDED*)
  113 FORMAT(//20X*TIME OF NEXT FLOW OCCURS AFTER FAN-BUILDING HAS STOPP
     1ED*)
      END
      SUBROUTINE BASOIL
      COMMON BLOCK(22,43,33),YSUBS,HPRIMEF,A,T,XPRIME,LAMBDAU,LSUBF,C,YS
     1UBC,KAY,LAMBDAF,CSUBF,TSUBF,FORM1(8),FORM2(8),FORM3(8),DASHES1,S,
     2KON,MAP(22,43),ROW(22),COL(43),N,N1,N2,HSUBT,TPRIMEU,I,TIME,
     3J,K,TDPU,MOVE(22,43),INERTIA,MSUBS,HSUB(22,43),GRID,VSUBS,EVENT,
     4NORMAL,FMT(45),TPRIMEO,RSUBU,BTHICK,WTHICK,YSUBC1,CONST,GAMMA,
     5FLODIR,FLOCOND,SLOPEN,SLOPEE,SLOPES,SLOPEW,SIGMAD,SIGMAW,TT,
     6PSUBFN,PSUBFE,PSUBFS,PSUBFW,FORM(11),RIGHT(6),DUM1,ROWI(400),DUM2,
     7COLJ(400),FORM4(8),FORM5(8),FORM6(16),FSPEC1,ASPEC1,FSPEC6,VSUBE,
     8ETHICK,IGRADE,FSPEC5,ASPEC5,ISUBN,ISUBE,ISUBS,ISUBW,IL,IH,
     9GMAP(22,43),STEPS,TMAP(22,43),TMTN3,TFAN3,TPLAYA3,TBLANK3,TPRIMEF
      REAL MSUBS
C
C COMPUTE THICKNESS (YSUBS) OF IMMEDIATELY ERODIBLE MATERIAL IN BASIN
      TPRIMEF = TPRIMEF + TPRIMEO
      YSUBS = MSUBS * (1.0 - EXP(-C * TPRIMEF))
C ZERO INITIAL THICKNESS OF IMMEDIATELY ERODIBLE MATERIAL IN BASIN
      TPRIMEO = 0.0
C COMPUTE VOLUME (VSUBS) OF IMMEDIATELY ERODIBLE MATERIAL IN BASIN
      VSUBS = A * YSUBS
      RETURN
C
      END
      SUBROUTINE ERODE
      COMMON BLOCK(22,43,33),YSUBS,HPRIMEF,A,T,XPRIME,LAMBDAU,LSUBF,C,YS
     1UBC,KAY,LAMBDAF,CSUBF,TSUBF,FORM1(8),FORM2(8),FORM3(8),DASHES1,S,
     2KON,MAP(22,43),ROW(22),COL(43),N,N1,N2,HSUBT,TPRIMEU,I,TIME,
     3J,K,TDPU,MOVE(22,43),INERTIA,MSUBS,HSUB(22,43),GRID,VSUBS,EVENT,
     4NORMAL,FMT(45),TPRIMEO,RSUBU,BTHICK,WTHICK,YSUBC1,CONST,GAMMA,
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      5FLODIR,FLOCOND,SLOPEN,SLOPEE,SLOPES,SLOPEW,SIGMAD,SIGMAW,TT,
      6PSUBFN,PSUBFE,PSUBFS,PSUBFW,FORM(11),RIGHT(6),DUM1,ROWI(400),DUM2,
      7COLJ(400),FORM4(8),FORM5(8),FORM6(16),FSPEC1,ASPEC1,FSPEC6,VSUBE,
      8ETHICK,IGRADE,FSPEC5,ASPEC5,ISUBN,ISUBE,ISUBS,ISUBW,IL,IW,
      9GMAP(22,43),STEPS,TMAP(22,43),TMTN3,TFAN3,TPLAYA3,TBLANK3,TPRIMEF
       COMMON ELEV(22,43),JJ,FMT2(26),PPIORUP,LEFT1,LEFT2,FSPEC2,ASPEC
      12,BLANK2,IFLOAB,BEDSEC(22),DLIMIT,WLIMIT,WALL,NFLOTYP,INUPFLO,
      2INTRAP,LSTEP,CARRY(1600)
       REAL MKAYT,KAY
C
C TEST FOR UPLIFT EVENT OR FLOW EVENT
       IF (INUPFLO .EQ. 0) GO TO 1
C COMPUTE ELEVATION OF ROCK STREAM CHANNEL ABOVE FAULT AT UPLIFT TIME (TPRIMEU)
       MKAYT = -KAY * TPRIMEU
       GO TO 2
C COMPUTE ELEVATION OF ROCK STREAM CHANNEL ABOVE FAULT (HSUBT) AT FLOW TIME
C (TSUBF)
     1 MKAYT = -KAY * (TSUBF - PRIORUP)
C INCREMENT ELEVATION OF ROCK STREAM CHANNEL ABOVE FAULT
     2 HSUBT = HSUBT * EXP (MKAYT)
       RETURN
C
       END
       SUBROUTINE FLOW
       COMMON BLOCK(22,43,33),YSUBS,HPRIMEF,A,T,XPRIME,LAMBDAU,LSUBF,C,YS
      1UBC,KAY,LAMBDAF,CSUBF,TSUBF,FORM1(8),FORM2(8),FORM3(8),DASHES1,S,
      2KON,MAP(22,43),ROW(22),COL(43),N,N1,N2,HSUBT,TPRIMEU,I,TIME,
      3J,K,TOPU,MOVE(22,43),INERTIA,MSUBS,HSUB(22,43),GRID,VSUBS,EVENT,
      4NORMAL,FMT(45),TPRIMEO,RSUBU,BTHICK,WTHICK,YSUBC1,CONST,GAMMA,
      5FLODIR,FLOCOND,SLOPEN,SLOPEE,SLOPES,SLOPEW,SIGMAD,SIGMAW,TT,
      6PSUBFN,PSUBFE,PSUBFS,PSUBFW,FORM(11),RIGHT(6),DUM1,ROWI(400),DUM2,
      7COLJ(400),FORM4(8),FORM5(8),FORM6(16),FSPEC1,ASPEC1,FSPEC6,VSUBE,
      8ETHICK,IGRADE,FSPEC5,ASPEC5,ISUBN,ISUBE,ISUBS,ISUBW,IL,IW,
      9GMAP(22,43),STEPS,TMAP(22,43),TMTN3,TFAN3,TPLAYA3,TBLANK3,TPRIMEF
       COMMON ELEV(22,43),JJ,FMT2(26),PRIORUP,LEFT1,LEFT2,FSPEC2,ASPEC
      12,BLANK2,IFLOAB,BEDSEC(22),DLIMIT,WLIMIT,WALL,NFLOTYP,INUPFLO,
      2INTRAP,LSTEP,CARRY(1600)
       COMMON /FMOUN/ MTNB,ABSORB,M,NN,NORTH,EAST,SOUTH,WEST,ERODE,DEPOSI
      1T,BYPASS,FANB,HIGH
       INTEGER STEPS,ROWI,COLJ
       REAL MOVE,MTNB,NORTH,ISUBN,ISUBE,ISUBS,ISUBW,INERTIA
C
C ZERO COUNTING USED FOR TRAPPED FLOW
       KOUNT = 0
C RECORD COORDINATES OF EACH STEP TAKEN
       ROWI(STEPS) = I
       COLJ(STEPS) = J
       IF (STEPS .EQ. 400) GO TO 38
C DESIGNATE OCCUPIED NODE
       MOVE(I,J) = 1.0
C CHECK FOR BOUNDARY TO NORTH
       IF (I.EQ. 1) GO TO 20
C CHECK FOR REVERSAL OR INTERSECTION OF FLOW TO NORTH
    10 IF (HSUB(I-1,J) .EQ. MTNB . OR. HSUB(I-1,J) .EQ. FANB .OR. MOVE(I-
      11,J) .EC. 1.0) GO TO 20
       FORM(2) = FSPEC1
C COMPUTE TRANSITIONAL PROBABILITY TO NORTH (PSUBN)
       IF (NFLOTYP) 43,43,39
    43 DELTAHN = HSUB(I-1,J) - ELEV(I,J)
       GO TO 40
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   39 DELTAHN = HSUB(I-1,J) - HSUB(I,J)
   40 SLOPEN = DELTAHN / GRID
C TEST FOR POSITIVE GRADIENT TO NORTH
      IF (DELTAHN .GT. 0.0 .AND. HSUB(I-1,J) .NE. ABSORB) GO TO 20
      PSUBN = 0.25 - 0.75 * SLOPEN
C COMPUTE EFFECT OF INERTIA ON FLOW TO NORTH
      FLOWN = PSUBN * ISUBN
      GO TO 21
C SET PROBABILITY OF FLOW TO NORTH EQUAL TO ZERO
   20 PSUBN = 0.0
      FLOWN = 0.0
      FORM(2) = ASPEC1
      SLOPEN = DASHES1
C CHECK FOR BOUNDARY TO EAST
C CHECK FOR REVERSAL OR INTERSECTION OF FLOW TO EAST
   21 IF (HSUB(I,J+1) .EQ. MTNB .OR. HSUB(I,J+1) .EQ. FANB .OR. MOVE(I,J
     1+1) .EQ. 1.0) GO TO 22
      FORM(3) = FSPEC1
C COMPUTE TRANSITIONAL PROBABILITY TO EAST (PSUBE)
      IF (NFLOTYP) 47,47,44
   47 DELTAHE = HSUB(I,J+1) - ELEV(I,J)
      GO TO 56
   44 DELTAHE = HSUB(I,J+1) - HSUB(I,J)
   56 SLOPEE = DELTAHE / GRID
C TEST FOR POSITIVE GRADIENT TO EAST
      IF (DELTAHE .GT. 0.0 .AND. HSUB(I,J+1) .NE. ABSORB) GO TO 22
      PSUBE = 0.25 - 0.75 * SLOPEE
C COMPUTE EFFCT OF INERTIA ON FLOW TO EAST
      FLOWE = PSUBE * ISUBE
      GO TO 23
C SET PROBABILITY OF FLOW TO EAST EQUAL TO ZERO
   22 PSUBE = 0.0
      FLOWE = 0.0
      FORM(3) = ASPEC1
      SLOPEE = DASHES1
C CHECK FOR BOUNDARY TO SOUTH
C CHECK FOR REVERSAL OR INTERSECTION OF FLOW TO SOUTH
   23 IF (HSUB(I+1,J) .EQ. MTNB . OR. HSUB(I+1,J) .EQ. FANB .OR. MOVE(I+
     11,J) .EQ. 1.0) GO TO 24
      FORM(4) = FSPEC1
C COMPUTE TRANSITIONAL PROBABILITY TO SOUTH (PSUBS)
      IF (NFLOTYP) 51,51,48
   51 DELTAHS = HSUB(I+1,J) - ELEV(I,J)
      GO TO 57
   48 DELTAHS = HSUB(I+1,J) - HSUB(I,J)
   57 SLOPES = DELTAHS / GRID
C TEST FOR POSITIVE GRADIENT TO SOUTH
      IF (DELTAHS .GT. 0.0 .AND. HSUB(I+1,J) .NE. ABSORB) GO TO 24
      PSUBS = 0.25 - 0.75 * SLOPES
C COMPUTE EFFECT OF INERTIA ON FLOW TO SOUTH
      FLOWS = PSUBS * ISUBS
      GO TO 29
C SET PROBABILITY OF FLOW TO SOUTH EQUAL TO ZERO
   24 PSUBS = 0.0
      FLOWS = 0.0
      IF (I .EQ. 1) FLOWS = 1.0
      FORM(4) = ASPEC1
      SLOPES = DASHES1
C CHECK FOR BOUNDARY TO WEST
C CHECK FOR REVERSAL OR INTERSECTION OF FLOW TO WEST
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   29 IF (HSUB(I,J-1) .EQ. MTNB .OR. HSUB(I,J-1) .EQ. FANB .OR. MOVE(I,J
     1-1) .EQ. 1.0) GO TO 30
      FORM(5) = FSPEC1
C COMPUTE TRANSITIONAL PROBABILITY TO WEST (PSUBW)
      IF (NFLOTYP) 55,55,52
   55 DELTAHW = HSUB(I,J-1) - ELEV(I,J)
      GO TO 58
   52 DELTAHW = HSUB(I,J-1) - HSUB(I,J)
   58 SLOPEW = DELTAHW / GRID
C TEST FOR POSITIVE GRADIENT TO WEST
      IF (DELTAHW .GT. 0.0 .AND. HSUB(I,J-1) .NE. ABSORB) GO TO 30
      PSUBW = 0.25 - 0.75 * SLOPEW
C COMPUTE EFFECT OF INERTIA ON FLOW TO WEST
      FLOWW = PSUBW * ISUBW
      GO TO 31
C SET PROBABILITY OF FLOW TO WEST EQUAL TO ZERO
   30 PSUBW = 0.0
      FLOWW = 0.0
      FORM(5) = ASPEC1
      SLOPEW = DASHES1
C COMPUTE SUM OF FLOW TERMS (SUMP)
   31 SUMP = FLOWN + FLOWE + FLOWS + FLOWW
C TEST FOR FLOW TRAPPED IN BLIND ALLEY OR HOLE
      IF (SUMP .NE. 0.0) GO TO 3
C RETRACE STEPS
      IF (STEPS .EQ. KOUNT) GO TO 11
      IF (INTRAP .EQ. 1 .AND. STEPS-KOUNT .EQ. LSTEP) GO TO 41
      KOUNT = KOUNT + 1
      I = ROWI(STEPS - KOUNT)
      J = COLJ(STEPS - KOUNT)
      IF (STEPS .GT. KOUNT) GO TO 10
C DETERMINE MINIMUM ELEVATION ON BORDER OF PIT (TEMP)
   41 KK = 0
      DO 34 JJ = 1,STEPS
      II = ROWI(JJ) - 1
      MM = COLJ(JJ)
      IF (HSUB(II,MM) .NE. MTNB .AND. HSUB(II,MM) .NE. FANB .AND. MOVE(I
     1I,MM) .NE. 1.0) GO TO 9
      CARRY(KK+1) = HIGH
      NUM1 = KK + 1
   33 II = ROWI(JJ)
      MM = COLJ(JJ) + 1
      IF (HSUB(II,MM) .NE. MTNB .AND. HSUB(II,MM) .NE. FANB .AND. MOVE(I
     1I,MM) .NE. 1.0) GO TO 13
      NUM = COLJ(JJ) + 1
      CARRY (KK+2) = HIGH
      NUM2 = KK + 2
   35 II = ROWI(JJ) + 1
      MM = COLJ(JJ)
      IF (HSUB(II,MM) .NE. MTNB .AND. HSUB(II,MM) .NE. FANB .AND. MOVE(I
     1I,MM) .NE. 1.0) GO TO 14
      CARRY (KK + 3) = HIGH
      NUM3 = KK + 3
   36 II = ROWI(JJ)
      MM = COLJ(JJ) - 1
      IF (HSUB(II,MM) .NE. MTNB .AND. HSUB(II,MM) .NE. FANB .AND. MOVE(I
     1I,MM) .NE. 1.0) GO TO 15
      CARRY (KK+4) = HIGH
      NUM4 = KK + 4
      GO TO 37
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    9 CARRY (KK+1) = HSUB(II,MM)
      NUM1 = KK + 1
      GO TO 33
   13 CARRY (KK+2) = HSUB(II,MM)
      NUM2 = KK + 2
      GO TO 35
   14 CARRY (KK+3) = HSUB(II,MM)
      NUM3 = KK + 3
      GO TO 36
   15 CARRY (KK+4) = HSUB(II,MM)
      NUM4 = KK + 4
   37 KK = KK + 4
   34 CONTINUE
      LL = STEPS * 4
      TEMP = 10000.
      DO 32 MM = 1,LL
      IF (CARRY(MM) .LT. TEMP) TEMP = CARRY(MM)
   32 CONTINUE
C PICK COORDINATES OF LOWEST ELEVATION FROM ARRAY OF PIT BORDER ELEVATIONS
      DO 5 II = 1,STEPS
      III = ROWI(II) - 1
      MM = COLJ(II)
      IF (HSUB(III,MM) .EQ. TEMP) GO TO 8
      III = ROWI(II)
      MM = COLJ(II) + 1
      IF (HSUB(III,MM) .EQ. TEMP) GO TO 8
      III = ROWI(II) + 1
      MM = COLJ(II)
      IF (HSUB(III,MM) .EQ. TEMP) GO TO 8
      III = ROWI(II)
      MM = COLJ(II) - 1
      IF (HSUB(III,MM) .EQ. TEMP) GO TO 8
    5 CONTINUE
    8 I = III
      J = MM
      IF (I .EQ. 22 .AND. J .EQ. 43) GO TO 7
C SET VARIABLE VALUES TO PREVENT RE-COMPUTATION OF RETRACE (ROWI,COLJ) ARRAYS
      INTRAP = 1
      LSTEP = STEPS
      GO TO 6
C SET INERTIA TERMS TO UNITY
    3 ISUBN = 1.0
      ISUBE = 1.0
      ISUBS = 1.0
      ISUBW = 1.0
C COMPUTE PROBABILITY FRACTIONS
      PSUBFN = FLOWN / SUMP
      PSUBFE = FLOWE / SUMP
      PSUBFS = FLOWS / SUMP
      PSUBFW = FLOWW / SUMP
C COMPUTE PROPABILITY UPPER LIMITS
      PULN = PSUBFN
      PULE = PULN + PSUBFE
      PULS = PULE + PSUBFS
      PULW = 1.00
C SELECT RANDOM NUMBER (RSUBU)
      RSUBU = RANF(0.0)
C DETERMINE DIRECTION OF FLOW MOVEMENT
C DETERMINE WHETHER FLOW IS TO NORTH
      IF (RSUBU .GE. 0. .AND. RSUBU .LT. PULN) GO TO 16
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      GO TO 17
C CHECK FOR ABSORBING BOUNDARY TO NORTH
   16 IF (HSUB (I-1,J) .EQ. ABSORB) 18,25
   25 FLODIR = NORTH
      ISUBN = INERTIA
      S = SLOPEN
      IFLOAB = 0
      I = I - 1
      GO TO 6
C DETERMINE WHETHER FLOW IS TO EAST
   17 IF (RSUBU .GE. PULN .AND. RSUBU .LT. PULE) GO TO 19
      GO TO 1
C CHECK FOR ABSORBING BOUNDARY TO EAST
   19 IF (HSUB (I,J+1) .EQ. ABSORB) 18,26
   26 FLODIR = EAST
      ISUBE = INERTIA
      S = SLOPEE
      IFLOAB = 0
      J = J + 1
      GO TO 6
C DETERMINE WHETHER FLOW IS TO SOUTH
    1 IF (RSUBU .GE. PULE .AND. RSUBU .LT. PULS) GO TO 2
      GO TO 4
C CHECK FOR ABSOBING BOUNDARY TO SOUTH
    2 IF (HSUB (I+1,J) .EQ. ABSORB) 18,27
   27 FLODIR = SOUTH
      ISUBS = INERTIA
      S = SLOPES
      IFLOAB = 0
      I = I + 1
      GO TO 6
C DETERMINE WHETHER FLOW IS TO WEST
C CHECK FOR ABSORBING BOUNDARY TO WEST
    4 IF (HSUB (I,J-1) .EQ. ABSORB) 18,28
   28 FLODIR = WEST
      ISUBW = INERTIA
      S = SLOPEW
      IFLOAB = 0
      J = J - 1
      GO TO 6
C PRINT STOP OR RETURN MESSAGES
   38 PRINT 100
      GO TO 6
    7 PRINT 101
      STOP
   11 PRINT 103
      STOP
   18 PRINT 132
      IFLOAB = 1
    6 RETURN
C
  100 FORMAT (//10X*NUMBER OF STEPS IN WALK EQUALS OR EXCEEDS 400*)
  101 FORMAT (//10X*ERROR IN PIT BORDER ARRAY*)
  103 FORMAT (//10X*FLOW IS TRAPPED AND CANNOT LEAVE VALLEY*)
  132 FORMAT (//10X*FLOW IS ABSORBED*)
      END
      SUBROUTINE DEBFLOW
      COMMON CSUBF(22,43,33),YSUBS,HPRIMEF,A,T,XPRIME,LAMBDAU,LSUBF,C,YS
     1UBC,KAY,LAMBDAF,CSUBF,TSUBF,FORM1(8),FORM2(8),FORM3(8),DASHES1,S,
     2KON,MAP(22,43),ROW(22),COL(43),N,N1,N2,HSUBT,TPRIMEU,I,TIME,
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     3J,K,TOPU,MOVE(22,43),INERTIA,MSUBS,HSUB(22,43),GRID,VSUBS,EVENT,
     4NORMAL,FMT(45),TPRIMEO,RSUBU,BTHICK,WTHICK,YSUBC1,CONST,GAMMA,
     5FLODIR,FLOCOND,SLOPEN,SLOPEE,SLOPES,SLOPEW,SIGMAD,SIGMAW,TT,
     6PSUBFN,PSUBFE,PSUBFS,PSUBFW,FORM(11),RIGHT(6),DUM1,RCHI(400),DUM2,
     7COLJ(400),FORM4(8),FORM5(8),FORM6(16),FSPEC1,ASPEC1,FSPEC6,VSUBE,
     8ETHICK,IGRADE,FSPEC5,ASPEC5,ISUBN,ISUBE,ISUBS,ISUBW,IL,IW,
     9GMAP(22,43),STEPS,TMAP(22,43),TMTN3,TFAN3,TPLAYA3,TBLANK3,TPRIMEF
      COMMON ELEV(22,43),JJ,FMT2(26),PRIORUP,LEFT1,LEFT2,FSPEC2,ASPEC
     12,BLANK2,IFLOAB,BEDSEC(22),DLIMIT,WLIMIT,WALL,NFLOTYP,INUPFLO,
     2INTRAP,LSTEP,CARRY(1600)
      COMMON /AST/ ASTER3,SILT3,SILSAN3,SAND3,SANGRA3,DEBRIS3,MTN3,FAN3,
     1PLAYA3,BLANK3
      COMMON /FMOUN/ MTNB,ABSORB,M,NN,NORTH,EAST,SOUTH,WEST,ERODE,DEPOSI
     1T,BYPASS,FANB,HIGH
      INTEGER TOTSTEP,EVENT,STEPS,GMAP,DEBRIS3,SUMSTEP,ESTEPS
      REAL MTNB,NORTH,NORMAL
C
C DETERMINE EVENT NUMBER
      EVENT = EVENT + 1
C INITIALIZE DATA
      IGRADE = 0
      STEPS = 0
      NOSTEPS = 0
      ESTEPS = 0
      KLIFF = 0
      IF (KON .EQ. 1) GO TO 11
C COMPUTE LOGNORMALLY DISTRIBUTED THICKNESS OF DEBRIS FLOWS (DSUBD)
      RNPMU = SIGMAD * NORMAL + BTHICK
      DSUBD = EXP(RNPMU)
      GO TO 10
C CONVERT MEAN THICKNESS OF CONSTANT BED TO INITIAL THICKNESS OF TAPERED BED
   11 DSUBD = 2.0 * BTHICK
C PRINT TABLE HEADINGS
   10 PRINT 119
      PRINT 106
      PRINT 111
      PRINT 112
      PRINT 114, EVENT,TSUBF,VSUBS,HSUBT
      PRINT 120
      PRINT 121
C CHECK CHANNEL DOWNCUTTING
      IF (HSUB(I+1,J) .LE. HSUBT) GO TO 5
      IGRADE = 1
C CALL SUBROUTINE EROFLOW
      CALL EROFLOW
      IF (IFLOAB .EQ. 1) GO TO 2
C COMPUTE NUMBER OF STEPS NEEDED TO DEPOSIT SEDIMENT FROM CHANNEL (ESTEPS)
      ESTEPS = 2.0 * VSUBE / (DSUBD * GRID ** 2)
      GO TO 12
C ADJUST DEPOSITIONAL THICKNESS TO HEIGHT OF FAULT SCARP IF HEIGHT OF SCARP
C   IS LESS THAN INITIAL DEPOSITIONAL THICKNESS
    5 CLIFF = HSUBT - HSUB(I+1,J)
      IF (CLIFF .GE. DLIMIT .AND. CLIFF .LT. DSUBD) GO TO 6
      GO TO 7
    6 DSUBD = CLIFF
      KLIFF = 1
C COMPUTE TOTAL NUMBER OF STEPS TO BE TAKEN (TOTSTEP) TO DEPOSIT MATERIAL
C   FROM BASIN
   12 IF (KON .EQ. 1) 7,13
    7 TOTSTEP = 2.0 * VSUBS / (DSUBD * GRID ** 2)
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      IF (TOTSTEP .EQ. 0) GO TO 2
      GO TO 17
   13 TOTSTEP = VSUBS / (CSUBD * GRID ** 2)
      IF (TOTSTEP .EQ. 0) GO TO 2
C COMPUTE TOTAL NUMBER OF STEPS REQUIRED TO DEPOSIT MATERIAL FROM BOTH BASIN
C   AND FAN CHANNEL (SUMSTEP)
   17 SUMSTEP = ESTEPS + TOTSTEP
C INDICATE TYPE OF FLOW
      NFLOTYP = 1
C CALL SUBROUTINE FLOW
    4 CALL FLOW
C CHECK FOR ABSORPTION OF FLOW
      IF (IFLOAB .EQ. 1) GO TO 2
C COUNT STEPS FOR ENTIRE FLOW
      STEPS = STEPS + 1
C COMPUTE THICKNESS OF TAPERED BED
      IF (KON .NE. 1) GO TO 14
      DSUBD = DSUBD - DSUBD * FLOAT(NOSTEPS) / FLOAT(SUMSTEP)
C PASS SEDIMENT BEYOND NODE IF RESULTING TOP OF DEPOSIT WILL HIGHER THAN
C   POINT WHERE MAIN STREAM CHANNEL CROSSES FAULT
   14 IF ((HSUB(I,J) + DSUBD) .GT. HSUBT) GO TO 1
      FLOCOND = DEPOSIT
C COUNT STEPS FOR DEPOSITION PART OF FLOW ONLY
      NOSTEPS = NOSTEPS + 1
C COMPUTE NEW ELEVATION OF LAND SURFACE (HSUB)
      HSUB(I,J) = HSUB(I,J) + DSUBD
C PRINT OUTPUT DATA FOR DEPOSITIONAL FLOW
      PRINT FORM, STEPS,SLOPEN,SLOPEE,SLOPES,SLOPEW,PSUBFN,PSUBFE,PSUBF
     1S,PSUBFW,RSUBU,FLODIR,FLOCOND,I,J,HSUB(I,J)
      GO TO 3
    1 FLOCOND = BYPASS
C PRINT OUTPUT DATA FOR BYPASS FLOW
      PRINT FORM, STEPS,SLOPEN,SLOPEE,SLOPES,SLOPEW,PSUBFN,PSUBFE,PSUBF
     1S,PSUBFW,RSUBU,FLODIR,FLOCOND,I,J,HSUB(I,J)
      GO TO 4
C PACK IN THICKNESS OF NEW BED
    3 DSUBF (I,J,K) = DSUBD  .AND. M
C DEPOSIT NEW BED OF DEBRIS FLOW MATERIAL
      DSUBF(I,J,K) = DSUBF(I,J,K) .OR. DEBRIS3
      GMAP(I,J) = DEBRIS3
C RESET BED THICKNESS
      IF (KLIFF .EQ. 1) GO TO 8
      DSUBD = 2.0 *BTHICK
      GO TO 9
    8 DSUBD = CLIFF
C CHECK LENGTH OF FLOW
    9 IF (SUMSTEP .EQ. NOSTEPS) GO TO 2
      GO TO 4
C RETURN TO SUBROUTINE STORM
    2 RETURN
C
  106 FORMAT (53X,28(1H-))
  111 FORMAT (//12X*EVENT NUMBER*12X*TIME,IN YEAR(S),*13X*VOLUME OF SEDI
     1MENT IN*12X*ELEVATION OF STREAM CHANNEL*)
  112 FORMAT (34X*SINCE INITIAL UPLIFT*12X*FLOW,IN CUBIC FEET*14X*AT FAU
     1LT CROSSING, IN FEET*/)
  114 FORMAT (I20,F30.2,F32.2,F35.2)
  119 FORMAT (1H1,52X*SUMMARY OF DEBRIS FLOW EVENT*)
  120 FORMAT (//6X*STEP*7X*SLOPE FROM CENTER NODE*8X*PROBABILITY OF FLOW
     1*5X*RANDOM*4X*DIRECTION*4X*CONDITION*11X*NEW NODE*)
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 121 FORMAT (15X*NORTH    EAST   SOUTH    WEST*5X*NORTH EAST SOUTH WEST*4X
    1*NUMBER*5X*OF FLOW*6X*OF FLOW*5X*COORDINATES ELEVATION*/)
     END
     SUBROUTINE WATFLOW
     COMMON DSUBF(22,43,33),YSUBS,HPRIMEF,A,T,XPRIME,LAMBDAU,LSUBF,C,YS
    1UBC,KAY,LAMBDAF,CSUBF,TSUBF,FORM1(8),FORM2(8),FORM3(8),DASHES1,S,
    2KON,MAP(22,43),ROW(22),COL(43),N,N1,N2,HSUBT,TPRIMEU,I,TIME,
    3J,K,TOPU,MOVE(22,43),INERTIA,MSUBS,HSUB(22,43),GRID,VSUBS,EVENT,
    4NORMAL,FMT(45),TPRIMEC,RSUBU,BTHICK,WTHICK,YSUBC1,CONST,GAMMA,
    5FLODIR,FLOCOND,SLOPEN,SLOPEE,SLOPES,SLOPEW,SIGMAD,SIGMAW,TT,
    6PSUBFN,PSUBFE,PSUBFS,PSUBFW,FORM(11),RIGHT(6),DUM1,ROWI(400),DUM2,
    7COLJ(400),FORM4(8),FORM5(8),FORM6(16),FSPEC1,ASPEC1,FSPEC6,VSUBE,
    8ETHICK,IGRADE,FSPEC5,ASPEC5,ISUBN,ISUBE,ISUBS,ISUBW,IL,IW,
    9GMAP(22,43),STEPS,TMAP(22,43),TMTN3,TFAN3,TPLAYA3,TBLANK3,TPRIMEF
     COMMON ELEV(22,43),JJ,FMT2(26),PRIORUP,LEFT1,LEFT2,FSPEC2,ASPEC
    12,BLANK2,IFLOAB,BEDSEC(22),DLIMIT,WLIMIT,WALL,NFLOTYP,INUPFLO,
    2INTRAP,LSTEP,CARRY(1600)
     COMMON /AST/ ASTER3,SILT3,SILSAN3,SAND3,SANGRA3,DEBRIS3,MTN3,FAN3,
    1PLAYA3,BLANK3
     COMMON /FMOUN/ MTNB,ABSORB,M,NN,NORTH,EAST,SOUTH,WEST,ERODE,DEPOSI
    1T,BYPASS,FANB,HIGH
     INTEGER SUMSTEP,DEPSTEP,EVENT,STEPS,SILT3,
    1SILSAN3,SAND3,SANGRA3,GMAP,ESTEPS
     REAL MTNB,NORTH,NORMAL
C
C DETERMINE EVENT NUMBER
      EVENT = EVENT + 1
C INITIALIZE VALUES
      IGRADE = 0
      STEPS = 0
      NOSTEPS = 0
      KLIFF = 0
      ESTEPS = 0
C DETERMINE NATURE OF BED TO BE DEPOSITED
      IF (KON .EQ. 1) GO TO 26
C COMPUTE LOGNORMALLY DISTRIBUTED THICKNESS OF WATER FLOWS (DSUBW)
      RNPMU = SIGMAW * NORMAL + WTHICK
      DSUBW = EXP(RNPMU)
      GO TO 23
C CONVERT MEAN THICKNESS OF CONSTANT BED TO INITIAL THICKNESS OF TAPERED BED
C  (DSUBW)
   26 DSUBW = 2.0 * WTHICK
C COMPUTE NUMBER OF STEPS NEEDED TO DEPOSIT SEDIMENT FROM BASIN (DEPSTEP)
      DEPSTEP = 2.0 * VSUBS / (DSUBW * GRID  ** 2)
      IF (DEPSTEP .LE. 0) NDEPSP1 = 0
      GO TO 27
C COMPUTE NUMBER OF STEPS NEEDED TO DEPOSIT SEDIMENT FROM BASIN
   23 DEPSTEP = VSUBS / (DSUBW * GRID ** 2)
      IF (DEPSTEP .LE. 0) NDEPSP1 = 0
C ADD ONE STEP TO NUMBER NEEDED TO DEPOSIT SEDIMENT FROM BASIN
   27 NDEPSP1 = DEPSTEP + 1
C SKIP TABLE HEADINGS FOR ERODING WATER FLOW
      IF (YSUBS .LT. YSUBC1) GO TO 1
C PRINT TABLE HEADINGS
      PRINT 100
      PRINT 125
      PRINT 134
      PRINT 135
      PRINT 136, EVENT,TSUBF,VSUBS,HSUBT
      PRINT 131
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      PRINT 132
C CHECK CHANNEL DOWNCUTTING
      IF (HSUB(I+1,J) .LE. HSUBT) GO TO 19
      IGRADE = 1
      GO TO 1
C ADJUST DEPOSITIONAL THICKNESS TO HEIGHT OF FAULT SCARP (CLIFF)
   19 CLIFF = HSUBT - HSUB(I+1,J)
      IF (CLIFF .GE. WLIMIT .AND. CLIFF .LT. DSUBW) GO TO 22
      GO TO 21
   22 DSUBW = CLIFF
      KLIFF = 1
      GO TO 21
C CALL SUBROUTINE EROFLOW
    1 CALL EROFLOW
      IF (IFLOAB .EQ. 1) GO TO 5
C COMPUTE NUMBER OF STEPS NEEDED TO DEPOSIT SEDIMENT FROM CHANNEL (ESTEPS)
      ESTEPS = 2.0 * VSUBE / (DSUBW * GRID ** 2)
C COMPUTE LENGTH OF AREA OF DEPOSITION IN TERMS OF STEPS (SUMSTEP)
   21 SUMSTEP = ESTEPS + NDEPSP1
C CHECK FOR ZERO NUMBER OF STEPS
C IF NUMBER OF STEPS EQUALS ZERO, RETURN TO SUBROUTINE STORM
      IF (SUMSTEP .EQ. 0) GO TO 5
C INDICATE TYPE OF FLOW
      NFLOTYP = 0
C CALL SUBROUTINE FLOW
   17 CALL FLOW
C CHECK FOR ABSORPTION OF FLOW
      IF (IFLOAB .EQ. 1) GO TO 5
C COUNT STEPS FOR ENTIRE FLOW (STEPS)
      STEPS = STEPS + 1
      IF (KON .NE. 1) GO TO 28
C COMPUTE THICKNESS OF TAPERED BED (DSUBW)
      DSUBW = DSUBW - DSUBW * FLOAT(NOSTEPS) / FLOAT(ESTEPS + DEPSTEP)
C PASS SEDIMENT BEYOND NODE IF RESULTING TOP OF DEPOSIT WILL HIGHER THAN
C   POINT WHERE MAIN STREAM CHANNEL CROSSES FAULT
   28 IF ((HSUB(I,J) + DSUBW) .GT. HSUBT) GO TO 20
      FLOCOND = DEPOSIT
C COUNT NUMBER OF STEPS FOR DEPOSITIONAL PART OF FLOW ONLY (NOSTEPS)
      NOSTEPS = NOSTEPS + 1
C COMPUTE NEW ELEVATION OF LAND SURFACE (HSUB)
      ELEV(I,J) = HSUB(I,J)
      HSUB(I,J) = HSUB(I,J) + DSUBW
C PRINT OUTPUT DATA FOR DEPOSITIONAL FLOW
      PRINT FORM,STEPS,SLOPEN,SLOPEE,SLOPES,SLOPEW,PSUBFN,PSUBFE,PSUBFS,
     1PSUBFW,RSUBU,FLODIR,FLOCOND,I,J,HSUB(I,J)
      GO TO 3
   20 FLOCOND = BYPASS
      ELEV(I,J) = HSUB(I,J)
C PRINT OUTPUT DATA FOR BYPASS FLOW
      PRINT FORM,STEPS,SLOPEN,SLOPEE,SLOPES,SLOPEW,PSUBFN,PSUBFE,PSUBFS,
     1PSUBFW,RSUBU,FLODIR,FLOCOND,I,J,HSUB(I,J)
      GO TO 31
C COMPUTE MEDIAN PARTICLE SIZE (SMALLD)
    3 SMALLD = CSUBF * (-S)
C PACK IN THICKNESS OF NEW BED
      DSUBF(I,J,K) = DSUBW  .AND. M
C DETERMINE LITHOLOGIC SYMBOL TO BE USED (DEPLITH)
      IF (SMALLD .LE. 62.) GO TO 4
      IF (SMALLD .GT. 62. .AND. SMALLD .LE. 125.) GO TO 10
      IF (SMALLD .GT. 125. .AND. SMALLD .LE. 500.) GO TO 11
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      IF (SMALLD .GT. 500.) GO TO 12
C DEPOSIT NEW BED OF SILT
    4 DSUBF(I,J,K) = DSUBF(I,J,K) .OR. SILT3
      GMAP(I,J) = SILT3
      GO TO 9
C DEPOSIT NEW BED OF SILT AND SAND
   10 DSUBF(I,J,K) = DSUBF(I,J,K) .OR. SILSAN3
      GMAP(I,J) = SILSAN3
      GO TO 9
C DEPOSIT NEW BED OF SAND
   11 DSUBF(I,J,K) = DSUBF(I,J,K) .OR. SAND3
      GMAP(I,J) = SAND3
      GO TO 9
C DEPOSIT NEW BED OF SAND AND GRAVEL
   12 DSUBF(I,J,K) = DSUBF(I,J,K) .OR. SANGRA3
      GMAP(I,J) = SANGRA3
C RESET BED THICKNESS
   31 IF (KLIFF .EQ. 1) GO TO 29
    9 DSUBW = 2.0 * WTHICK
      GO TO 30
   29 DSUBW = CLIFF
C CHECK FOR COMPLETION OF FLOW
   30 IF (SUMSTEP .EQ. NOSTEPS) GO TO 5
      GO TO 17
C RETURN TO SUBROUTINE STORM
    5 RETURN
C
  100 FORMAT (1H1,53X*SUMMARY OF WATER FLOW EVENT*)
  125 FORMAT (54X,27(1H-))
  131 FORMAT (//6X*STEP*7X*SLOPE FROM CENTER NODE*8X*PROBABILITY OF FLOW
     1*5X*RANDOM*4X*DIRECTION*4X*CONDITION*11X*NEW NODE*)
  132 FORMAT (15X*NORTH   EAST  SOUTH   WEST*5X*NORTH EAST SOUTH WEST*4X
     1*NUMBER*5X*OF FLOW*6X*OF FLOW*5X*COORDINATES ELEVATION*/)
  133 FORMAT (//33X*BEDROCK*)
  134 FORMAT (//12X*EVENT NUMBER*12X*TIME,IN YEAR(S),*13X*VOLUME OF SEDI
     1MENT IN*12X*ELEVATION OF STREAM CHANNEL*)
  135 FORMAT (34X*SINCE INITIAL UPLIFT*12X*FLOW,IN CUBIC FEET*14X*AT FAU
     1LT CROSSING, IN FEET*/)
  136 FORMAT (I20,F30.2,F32.2,F35.2)
      END
      SUBROUTINE EROFLOW
      COMMON DSUBF(22,43,33),YSUBS,HPRIMEF,A,T,XPRIME,LAMBDAU,LSUBF,C,YS
     1UBC,KAY,LAMBDAF,CSUBF,TSUBF,FORM1(8),FORM2(8),FORM3(8),DASHES1,S,
     2KON,MAP(22,43),ROW(22),COL(43),N,N1,N2,HSUBT,TPRIMEU,I,TIME,
     3J,K,TOPU,MOVE(22,43),INERTIA,MSUBS,HSUB(22,43),GRID,VSUBS,EVENT,
     4NORMAL,FMT(45),TPRIMEC,RSUBU,BTHICK,WTHICK,YSUBC1,CONST,GAMMA,
     5FLODIR,FLOCOND,SLOPEN,SLOPEE,SLOPES,SLOPEW,SIGMAD,SIGMAW,TT,
     6PSUBFN,PSUBFE,PSUBFS,PSUBFW,FORM(11),RIGHT(6),DUM1,ROWI(400),DUM2,
     7COLJ(400),FORM4(8),FORM5(8),FORM6(16),FSPEC1,ASPEC1,FSPEC6,VSUBE,
     8ETHICK,IGRADE,FSPEC5,ASPEC5,ISUBN,ISUBE,ISUBS,ISUBW,IL,IW,
     9GMAP(22,43),STEPS,TMAP(22,43),TMTN3,TFAN3,TPLAYA3,TBLANK3,TPRIMEF
      COMMON ELEV(22,43),JJ,FMT2(26),PRIORUP,LEFT1,LEFT2,FSPEC2,ASPEC
     12,BLANK2,IFLOAB,BEDSEC(22),DLIMIT,WLIMIT,WALL,NFLOTYP,INUPFLO,
     2INTRAP,LSTEP,CARRY(1600)
      COMMON /AST/ ASTER3,SILT3,SILSAN3,SAND3,SANGRA3,DEBRIS3,MTN3,FAN3,
     1PLAYA3,BLANK3
      COMMON /FMOUN/ MTNB,ABSORB,M,NN,NORTH,EAST,SOUTH,WEST,ERODE,DEPOSI
     1T,BYPASS,FANB,HIGH
      INTEGER CSTEPS,EROSTEP,STEPS,EVENT,GMAP,BEDSYM,BLANK3
C
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```
C INITIALIZE DATA
      VSUBE = 0.0
      EROSTEP = 0
      KWALL = 0
C COMPUTE INITIAL VALUES FOR THICKNESS OF ERODED MATERIAL (DSUBW)
      DSUBW = 2.0 * ETHICK
C ERODE DEPOSITS AT CANYON MOUTH TO COMPENSATE FOR CHANNEL LOWERING ABOVE
C   FAULT
      IF (IGRADE .NE. 1) GO TO 15
      WALL = HSUB(I+1,J) - HSUBT
      IF (WALL .GT. DSUBW) GO TO 12
      GO TO 15
   12 DSUBW = WALL
      KWALL = 1
C SELECT RANDOM NUMBER (RSUBU)
   15 RSUBU = RANF(0.0)
      IF (RSUBU .EQ. 0.0 .OR. RSUBU .EQ. 1.0) GO TO 15
C COMPUTE A RANDOM VALUE OF THE PEAK FLOW RATE (YPRIME)
      YPRIME = -GAMMA * ALOG(1.0 - RSUBU)
C COMPUTE VOLUME OF SEDIMENT FLOW EVENT IS CAPABLE OF ERODING (VSUBC)
      VSUBC = CONST * YPRIME
      IF (IGRADE .EQ. 1) GO TO 3
C PRINT TABLE HEADINGS
      PRINT 102
      PRINT 103
      PRINT 100
      PRINT 101
C PRINT TABLE DATA
      PRINT 104, EVENT,TSUBF,YPRIME,VSUBS,YSUBS,VSUBC
C PRINT TABLE HEADINGS
      PRINT 105
      PRINT 106
C COMPUTE LENGTH OF CHANNEL IN TERMS OF STEPS (CSTEPS)
    3 CSTEPS = 2.0 * VSUBC / (DSUBW * GRID ** 2)
      NCSTEP1 = CSTEPS + 1
    6 IF (NCSTEP1 .EQ. EROSTEP) GO TO 5
C INDICATE TYPE OF FLOW
      NFLOTYP = -1
C CALL SUBROUTINE FLOW
      CALL FLOW
C CHECK FOR ABSORPTION OF FLOW
      IF (IFLOAB .EQ. 1) GO TO 5
C COUNT STEPS FOR ENTIRE FLOW (STEPS)
      STEPS = STEPS + 1
C COMPUTE THICKNESS OF MATERIAL TO BE ERODED (DSUBW)
      IF (CSTEPS .EQ. 0) GO TO 2
      DSUBW = DSUBW - DSUBW * FLOAT(EROSTEP) / FLOAT(CSTEPS)
      GO TO 7
    2 DSUBW = 0.0
    7 REDOW = DSUBW
C COUNT STEPS FOR EROSION PART OF FLOW ONLY
      EROSTEP = EROSTEP + 1
C CHECK FOR BEDROCK
      IF (K .NE. 2) GO TO 9
      FLOCOND = BYPASS
C PRINT OUTPUT DATA FOR BYPASS FLOW
      PRINT FORM,STEPS,SLOPEN,SLOPEE,SLOPES,SLOPEW,PSUBFN,PSUBFE,PSUBFS,
     1PSUBFW,RSUBU,FLODIR,FLOCOND,I,J,HSUB(I,J)
      GO TO 11
C SEARCH FOR NEXT BED BELOW
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    9 KM1 = K - 1
      DO 4 L = 1,KM1
      IF (K-L .EQ. 1) GO TO 10
      KML = K - L
      IF (DSUBF(I,J,K-L) .NE. 0.0) GO TO 13
      GO TO 4
C UNPACK A THICKNESS OF STRATA (BEDTHIK)
   13 BEDTHIK = DSUBF(I,J,K-L) .AND. M
      IF (REDDW .LE. BEDTHIK) GO TO 14
C ERODE AN ENTIRE BED  (DSUBF)
      DSUBF(I,J,K-L) = 0.0
      REDDW = REDDW - BEDTHIK
C REVEAL UNDERLYING BED
      IF (K-L-1 .EQ. 1) GMAP(I,J) = BLANK3
      GMAP(I,J) = DSUBF(I,J,K-L-1)
    4 CONTINUE
C ASSIGN NEW THICKNESS (BEDIFF) TO TOPMOST REMAINING BED
   14 BEDIFF = BEDTHIK - REDDW
      BEDSYM = DSUBF(I,J,K-L) .AND. NN
      DSUBF(I,J,K-L) = BEDIFF .AND. M
      DSUBF(I,J,K-L) = DSUBF(I,J,K-L) .OR. BEDSYM
      GMAP(I,J) = BEDSYM
C COMPUTE NEW ELEVATION OF LAND SURFACE (HSUB)
   10 IF (HSUB(I,J) - DSUBW .LT. 0.0) GO TO 18
      ELEV(I,J) = HSUB(I,J)
      HSUB(I,J) = HSUB(I,J) - DSUBW
      GO TO 17
   18 DSUBW = HSUB(I,J)
      HSUB(I,J) = 0.000001
      ELEV(I,J) = HSUB(I,J)
   17 FLOCOND = ERODE
C SUM AMOUNT OF MATERIAL ERODED FROM CHANNEL (VSUBE)
      VSUBE = VSUBE + DSUBW * GRID ** 2
C PRINT OUTPUT DATA FOR ERODING FLOW
      PRINT FORM,STEPS,SLOPEN,SLOPEE,SLOPES,SLOPEW,PSUBFN,PSUBFE,PSUBFS,
     1PSUBFW,RSUBU,FLODIR,FLOCOND,I,J,HSUB(I,J)
C RESET EROSIONAL THICKNESS
   11 IF (KWALL .EQ. 1) GO TO 1
      DSUBW = 2.0 * ETHICK
      GO TO 6
    1 DSUBW = WALL
      GO TO 6
    5 RETURN
C
  100 FORMAT (//7X*EVENT*8X*TIME, IN YEAR(S)*8X*PEAK FLOW*7X *ERODIBLE S
     1EDIMENT*9X*THICKNESS OF*11X*CHANNEL SEDIMENT THAT*)
  101 FORMAT(6X*NUMBER*6X*SINCE INITIAL UPLIFT*5X*RATE,IN CFS*6X *IN BAS
     1IN,IN CU.FT.*6X*BASIN SEDIMENT,FT.*6X*CAN BE ERODED, IN CU.FT.*/)
  102 FORMAT (1H1,49X*SUMMARY OF ERODING WATER FLOW EVENT*)
  103 FORMAT (50X,35(1H-))
  104 FORMAT (I11,F23.2,F18.0,F22.0,F20.2,F28.0)
  105 FORMAT (//6X*STEP*7X*SLOPE FROM CENTER NODE*8X*PROBABILITY OF FLOW
     1*5X*RANDOM*4X*DIRECTION*4X*CONDITION*11X*NEW NODE*)
  106 FORMAT (15X*NORTH   EAST  SOUTH   WEST*5X*NORTH EAST SOUTH WEST*4X
     1*NUMBER*5X*OF FLOW*6X*OF FLOW*5X*COORDINATES ELEVATION*/)
  128 FORMAT (//20X*NUMBER OF STEPS FOR WHICH EROSION HAS TAKEN PLACE IS
     1 *I3)
      END
      SUBROUTINE FANMAP
      COMMON BLOCK(22,43,33),YSUBS,HPRIMEF,A,T,XPRIME,LAMBDAU,LSUBF,C,YS
```

```
     1UBC,KAY,LAMBDAF,CSUBF,TSUBF,FORM1(8),FORM2(8),FORM3(8),DASHES1,S,
     2KON,MAP(22,43),ROW(22),COL(43),N,N1,N2,HSUBT,TPRIMEU,R,TIME,
     3W,D,TOPU,MOVE(22,43),INERTIA,MSUBS,HSUB(22,43),GRID,VSUBS,EVENT,
     4NORMAL,FMT(45),TPRIMEO,RSUBU,BTHICK,WTHICK,YSUBC1,CONST,GAMMA,
     5FLODIR,FLOCOND,SLOPEN,SLOPEE,SLOPES,SLOPEW,SIGMAD,SIGMAW,TT,
     6PSUBFN,PSUBFE,PSUBFS,PSUBFW,FORM(11),RIGHT(6),DUM1,ROWI(400),DUM2,
     7COLJ(400),FORM4(8),FORM5(8),FORM6(16),FSPEC1,ASPEC1,FSPEC6,VSUBE,
     8ETHICK,IGRADE,FSPEC5,ASPEC5,ISUBN,ISUBE,ISUBS,ISUBW,IL,IW,
     9GMAP(22,43),STEPS,TMAP(22,43),TMTN3,TFAN3,TPLAYA3,TBLANK3,TPRIMEF
      COMMON /SILT/ SILTSYM,SISAYM,SANDSYM,SAGRSYM,DEBSYM,ASTER,MTSYM,F
     1ANSYM,ABSYM,BLANK
      INTEGER ASTER,FANSYM,ABSYM,BLANK
C
C PRINT TOP PORTION OF FAN MAP
      PRINT FORM1
      PRINT FORM2
      PRINT FORM3
C DETERMINE LITHOLOGIC SYMBOL TO BE USED
      DO 1 I = 1,22
      DO 1 J = 1,43
      IF (MAP(I,J) .EQ. 0) GO TO 3
      L = MAP(I,J) - 5
      GO TO (9,10,11,12) L
    3 MAP(I,J) = ASTER
      GO TO 1
    9 MAP(I,J) = MTSYM
      GO TO 1
   10 MAP(I,J) = FANSYM
      GO TO 1
   11 MAP(I,J) = ABSYM
      GO TO 1
   12 MAP(I,J) = BLANK
    1 CONTINUE
      DO 2 I = 1,8
      PRINT 100, (MAP(I,J), J = 1,43)
    2 CONTINUE
      PRINT 101, (MAP(9,J), J = 1,43)
      PRINT 100, (MAP(10,J), J = 1,43)
      PRINT 102, (MAP(11,J), J = 1,43)
      PRINT 100, (MAP(12,J), J = 1,43)
      PRINT 103, (MAP(13,J), J = 1,43)
      DO 13 I = 14,22
      PRINT 100, (MAP(I,J), J = 1,43)
   13 CONTINUE
      PRINT 104
C
  100 FORMAT (46X,43A1)
  101 FORMAT (38X*FAN OR*2X,43A1,2X*FAN OR*)
  102 FORMAT (39X*OTHER*2X,43A1,2X*OTHER*)
  103 FORMAT (37X*BOUNDARY*X,43A1,X*BOUNDARY*)
  104 FORMAT (54X*P L A Y A   O R   S T R E A M*)
      RETURN
      END
      SUBROUTINE GEOMAP
      COMMON DSUBF(22,43,33),YSUBS,HPRIMEF,A,T,XPRIME,LAMBDAU,LSUBF,C,YS
     1UBC,KAY,LAMBDAF,CSUBF,TSUBF,FORM1(8),FORM2(8),FORM3(8),DASHES1,S,
     2KON,MAP(22,43),ROW(22),COL(43),N,N1,N2,HSUBT,TPRIMEU,R,TIME,
     3W,D,TOPU,MOVE(22,43),INERTIA,MSUBS,HSUB(22,43),GRID,VSUBS,EVENT,
     4NORMAL,FMT(45),TPRIMEO,RSUBU,BTHICK,WTHICK,YSUBC1,CONST,GAMMA,
     5FLODIR,FLOCOND,SLOPEN,SLOPEE,SLOPES,SLOPEW,SIGMAD,SIGMAW,TT,
```

```
      6PSUBFN,FSUBFE,PSUBFS,PSUBFW,FORM(11),RIGHT(6),DUM1,POWI(400),DUM2,
      7COLJ(400),FORM4(8),FORM5(8),FORM6(16),FSPEC1,ASPEC1,FSPEC6,VSUBE,
      8ETHICK,IGRADE,FSPEC5,ASPEC5,ISUBN,ISUBE,ISUBS,ISUBW,IL,IW,
      9GMAP(22,43),STEPS,TMAP(22,43),TMTN3,TFAN3,TPLAYA3,TBLANK3,TPRIMEF
       INTEGER GMAP,D
C
C PRINT HEADINGS
       PRINT 100
       PRINT 101
       PRINT 102, TSUBF
C PRINT TOP PORTION OF GEOLOGIC MAP
       PRINT FORM4
       PRINT FORM5
       PRINT FORM6
C PRINT GEOLOGIC MAP
       DO 2 I = 1,22
       PRINT 103, (GMAP(I,J), J = 1,43)
     2 CONTINUE
       RETURN
C
   100 FORMAT (1H1/54X*GEOLOGIC MAP OF ALLUVIAL FAN*)
   101 FORMAT (54X,28(1H-))
   102 FORMAT (47X*TIME = *F9.2* YEAR(S) SINCE FIRST UPLIFT*)
   103 FORMAT (/2X,43R3)
       END
       SUBROUTINE TOPMAP
       COMMON BLOCK(22,43,33),YSUBS,HPRIMEF,A,T,XPPIME,LAMBDAU,LSUBF,C,YS
      1UBC,KAY,LAMBDAF,CSUBF,TSUBF,FORM1(8),FORM2(8),FORM3(8),DASHES1,S,
      2KON,MAP(22,43),ROW(22),COL(43),N,N1,N2,HSUBT,TPRIMEU,L,TIME,
      3W,D,TOPU,MOVE(22,43),INERTIA,MSUBS,HSUB(22,43),GRID,VSUBS,EVENT,
      4NORMAL,FMT(45),TPRIMEO,RSUBU,BTHICK,WTHICK,YSUBC1,CONST,GAMMA,
      5FLODIR,FLOCOND,SLOPEN,SLOPEE,SLOPES,SLOPEW,SIGMAD,SIGMAW,TT,
      6PSUBFN,PSUBFE,PSUBFS,PSUBFW,FORM(11),RIGHT(6),DUM1,ROWI(400),DUM2,
      7COLJ(400),FORM4(8),FORM5(8),FORM6(16),FSPEC1,ASPEC1,FSPEC6,VSUBE,
      8ETHICK,IGRADE,FSPEC5,ASPEC5,ISUBN,ISUBE,ISUBS,ISUBW,IL,IW,
      9GMAP(22,43),STEPS,TMAP(22,43),TMTN3,TFAN3,TPLAYA3,TBLANK3,TPRIMEF
       COMMON /AST/ ASTER3,SILT3,SILSAN3,SAND3,SANGRA3,DEBRIS3,MTN3,FAN3,
      1PLAYA3,BLANK3
       COMMON /FMOUN/ MTNB,ABSORB,M,NN,NORTH,EAST,SOUTH,WEST,ERODE,DEPOSI
      1T,BYPASS,FANB,HIGH
       REAL MTNB
C
C PRINT HEADING
       PRINT 101
       PRINT 102
       PRINT 103, TSUBF
C PRINT TOP PORTION OF TOPOGRAPHIC MAP
       PRINT FORM4
       PRINT FORM5
       PRINT FORM6
C READ ELEVATION DATA (HSUB) INTO TOPOGRAPHIC MAP DATA (TMAP)
       DO 7  I = 1,22
       DO 7 J = 1,43
       TMAP(I,J) = HSUB(I,J)
     7 CONTINUE
       TMAP(IL,IW) = HSUBT
C READ IN DATA FOR PRINTOUT
       DO 6 I = 1,22
       DO 5 J = 1,43
       FMT (J+1) = ASPEC5
```

```
      IF (HSUB(I,J) .EQ. MTNB) GO TO 1
      IF (HSUB(I,J) .EQ. FANB) GO TO 2
      IF (HSUB(I,J) .EQ. ABSORB) GO TO 3
      IF (HSUB(I,J) .EQ. 0.0) GO TO 4
      IF (HSUB(I,J) .GE. 9.95) GO TO 8
      FMT(J+1) = FSPEC5
      GO TO 5
    8 FMT(J+1) = FSPEC6
      GO TO 5
    1 TMAP(I,J) = TMTN3
      GO TO 5
    2 TMAP(I,J) = TFAN3
      GO TO 5
    3 TMAP(I,J) = TPLAYA3
      GO TO 5
    4 TMAP(I,J) = TBLANK3
    5 CONTINUE
C PRINT TOPOGRAPHIC MAP
      PRINT FMT, (TMAP(I,J), J = 1,43)
    6 CONTINUE
      RETURN
C
  100 FORMAT (48X*TIME = *F9.2* YEAR(S) SINCE FIRST UPLIFT*)
  101 FORMAT (////1H1,50X*ELEVATIONS ON SURFACE OF ALLUVIAL FAN*)
  102 FORMAT (51X,37(1H-))
      END
      SUBROUTINE FANSEC
      COMMON BLOCK(22,43,33),YSUBS,HPRIMEF,A,T,XPRIME,LAMBDAU,LSUBF,C,YS
     1UBC,KAY,LAMBDAF,CSUBF,TSUBF,FORM1(8),FORM2(8),FORM3(8),CASHES1,S,
     2KON,MAP(22,43),ROW(22),COL(43),N,N1,N2,HSUBT,TPRIMEU,R,TIME,
     3W,D,TOPU,MOVE(22,43),INERTIA,MSUBS,HSUB(22,43),GRID,VSUBS,EVENT,
     4NORMAL,FMT(45),TPRIMEO,RSUBU,BTHICK,WTHICK,YSUBC1,CONST,GAMMA,
     5FLODIR,FLOCOND,SLOPEN,SLOPEE,SLOPES,SLOPEW,SIGMAD,SIGMAW,TT,
     6PSUBFN,PSUBFE,PSUBFS,PSUBFW,FORM(11),RIGHT(6),DUM1,ROWI(400),DUM2,
     7COLJ(400),FORM4(8),FORM5(8),FORM6(16),FSPEC1,ASPEC1,FSPEC6,VSUBE,
     8ETHICK,IGRADE,FSPEC5,ASPEC5,ISUBN,ISUBE,ISUBS,ISUBW,IL,IW,
     9GMAP(22,43),STEPS,TMAP(22,43),TMTN3,TFAN3,TPLAYA3,TBLANK3,TPRIMEF
      COMMON ELEV(22,43),JJ,FMT2(26),PRIORUP,LEFT1,LEFT2,FSPEC2,ASPEC
     12,BLANK2,IFLOAB,BEDSEC(22),DLIMIT,WLIMIT,WALL,NFLOTYP,INUPFLO,
     2INTRAP,LSTEP,CARRY(1600),NEWCYCL
      COMMON /AST/ ASTER3,SILT3,SILSAN3,SAND3,SANGRA3,DEBRIS3,MTN3,FAN3,
     1PLAYA3,BLANK3
      COMMON /FMOUN/ MTNB,ABSORB,M,NN,NORTH,EAST,SOUTH,WEST,ERODE,DEPOSI
     1T,BYPASS,FANB,HIGH
      INTEGER BED,ROW,COL,D,FAN3,PLAYA3,BLANK3
C
C SETTLE AND COMBINE BEDS IN MODEL BLOCK
      NM1 = N - 1
      DO 1 KK = 1,NM1
      DO 1 K = 2,N
      DO 1 I = 1,22
      DO 1 J = 1,43
      INCHAR1 = BLOCK(I,J,K) .AND. NN
      INCHAR2 = BLOCK(I,J,K+1) .AND. NN
      IF (INCHAR1 .NE. INCHAR2 .AND. BLOCK(I,J,K) .NE. 0.0 .OR. INCHAR1
     1.EQ. MTN3 .OR. INCHAR1 .EQ. FAN3 .OR. INCHAR1 .EQ. PLAYA3) GO TO 1
      BLOCK(I,J,K) = ((BLOCK(I,J,K) + BLOCK(I,J,K+1)) .AND. M) .OR. INCH
     1AR2
      BLOCK(I,J,K+1) = 0.0
    1 CONTINUE
```

```
      NP1   N+1
C CHECK FOR K ARRAYS WITH ALL ZEROS
      DO 13 K = 1, NP1
      BED = NP1 + 1 - K
      DO 13 I = 1,22
      DO 13 J = 1,43
      INCHAR = BLOCK(I,J,BED) .AND. NN
      IF (BLOCK(I,J,BED) .NE. 0.0 .AND. INCHAR .NE. MTN3 .AND. INCHAR .N
     1E. FAN3 .AND. INCHAR .NE. PLAYA3 .AND. INCHAR .NE. BLANK3) GO TO 1
     16
   13 CONTINUE
   16 IF (N .EQ. 32) 17,18
   17 D = BED + 1
      IF (D .EQ. N+2) GO TO 15
      NEWCYCL = 1
      GO TO 14
   18 NP1 = BED
C TEST TO DETERMINE WHICH ROWS ARE TO BE PRINTED
   15 DO 11 II = 1,N1
      I = ROW(II)
C PRINT HEADINGS FOR WEST PART OF ROW TABLE
      PRINT 100
      PRINT 101, ROW(II)
      PRINT 102
C PRINT TABLE ENTRIES
      DO 4 K = 1,NP1
      BED = NP1 + 1 - K
      DO 5 J = 1,22
      BEDTHIK = BLOCK(I,J,BED) .AND. M
      IF (BEDTHIK .EQ. 0.0) GO TO 6
      FMT2(J+2) = FSPEC2
      BEDSEC(J) = BEDTHIK
      GO TO 5
    6 FMT2(J+2) = ASPEC2
      BEDSEC(J) = BLANK2
    5 CONTINUE
      PRINT 103, BED,(BLOCK(I,J,BED),J = 1,22)
      PRINT FMT2,(BEDSEC(J), J = 1,22)
    4 CONTINUE
      PRINT 109
C PRINT HEADINGS FOR EAST PART OF ROW TABLE
      PRINT 100
      PRINT 104, ROW(II)
      PRINT 105
C PRINT TABLE ENTRIES
      DO 2 K = 1,NP1
      BED = NP1 + 1 - K
      DO 7 J = 23,43
      BEDTHIK = BLOCK(I,J,BED) .AND. M
      IF (BEDTHIK .EQ. 0.0) GO TO 8
      FMT2(J-20) = FSPEC2
      BEDSEC(J) = BEDTHIK
      GO TO 7
    8 FMT2(J-20) = ASPEC2
      BEDSEC(J) = BLANK2
    7 CONTINUE
      PRINT 108, BED,(BLOCK(I,J,BED),J = 23,43)
      PRINT FMT2,(BEDSEC(J),J = 23,43)
    2 CONTINUE
      PRINT 109
```

```
   11 CONTINUE
C TEST TO DETERMINE WHICH COLUMNS ARE TO BE PRINTED
      DO 12 II = 1,N2
      J = COL(II)
C PRINT TABLE HEADINGS
      PRINT 100
      PRINT 106, COL(II)
      PRINT 107
C PRINT TABLE ENTRIES
      DO 3 K = 1, NP1
      BED = NP1 + 1 - K
      DO 9 I = 1,22
      BEDTHIK = BLOCK(I,J,BED) .AND. M
      IF (BEDTHIK .EQ. 0.0) GO TO 10
      FMT2(I+2) = FSPEC2
      BEDSEC(I) = BEDTHIK
      GO TO 9
   10 FMT2(I+2) = ASPEC2
      BEDSEC(I) = BLANK2
    9 CONTINUE
      PRINT 103, BED,(BLOCK(I,J,BED),I = 1,22)
      PRINT FMT2, (BEDSEC(I),I=1,22)
    3 CONTINUE
      PRINT 109
   12 CONTINUE
      NEWCYCL = 0
   14 RETURN
C
  100 FORMAT (1H1,55X*DATA FOR GEOLOGIC SECTIONS*/56X,26(1H-))
  101 FORMAT (//60X*ROW*I3* WEST PART*)
  102 FORMAT (//8X*BED  COLUMN     1    2    3    4    5    6    7    8
     1    9    10    11    12    13    14    15    16    17    18    19    20    21
     2 22*/)
  103 FORMAT (I10,2X*LITHOLOGY  *22(1R3,2X))
  104 FORMAT (//60X*ROW*I3* EAST PART*)
  105 FORMAT (//8X*BED  COLUMN    23    24    25    26    27    28    29    30
     1  31    32    33    34    35    36    37    38    39    40    41    42    43*/
     1)
  106 FORMAT (//64X*COLUMN*I3)
  107 FORMAT (//8X*BED*6X,*ROW     1    2    3    4    5    6    7    8
     1  9    10    11    12    13    14    15    16    17    18    19    20    21
     222*/)
  108 FORMAT (I10,2X*LITHOLOGY  *21(1R3,2X))
  109 FORMAT (//10X*SYMBOLS SHOWN WITH .0 THICKNESS REPRESENT DEPOSITS B
     1ETWEEN 0.0 AND 0.05 FEET IN THICKNESS*)
      END
7/8/9
1         PROGRAM FOR RANDOM-WALK SIMULATION OF ALLUVIAL-FAN DEPOSITION
0
0
0
0
       1.0       4.0        1        22        2        1.5
        32       350
           (//64X*STREAM*/64X*VALLEY*)
           (66X*I I*/66X*I I*)
           (49X*M O U N T A I N  I I   F R O N T*)
(//59X*S  T  R  E  A  M*//59X*V  A  L  L  E  Y*)
(2(//63X*I     I*))
(/ 12X*M    O    U    N    T    A    I    N      I    I
```

```
F      R      O      N      T*)
666666666666566656666669666656656666666666666
7       666                               66 7
7                                            7
7                                            7
7                                            7
77                                           7
777                                         77
77                                          77
7                                           77
7                                           77
7                                           77
7                                           77
7                                           77
7                                           77
7                                           77
7                                           77
7                                           77
7                                           77
7                                           77
7                                           77
788                                       8887
7888888888888888888888888888888888888888887
       100      25000      10000      2150       .01      4300      1.0      0.1
       .01        9.9       .001       .01    100000        10      0.1      100
      1000        0.5        0.5         1       0.1       0.5     0.05
          8 2 3 4 5 6 7 8 9
          918192021222324252 6
(I9,4X,F10.2,F5.2,F6.2,F5.2,F10.5,6X,A7,6X,A7,I9*,*I3,F9.2)       --
 F7.4,    A7,
  (/2X      )     A3   F3.1   F3.0
(12X*FT. THICK*  F5.1,    A5,
 L  X  /
7/8/9
6/7/8/9
```

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