TECHNICAL REPORT

ES-20

PHYSICAL CHARACTERISTICS OF ALLUVIAL FANS

by

Robert L. Anstey, Ph. D.
Earth Sciences Division

December 1965

U. S. Army Materiel Command
U. S. ARMY NATICK LABORATORIES
Natick, Massachusetts

AD

TECHNICAL REPORT
ES-20

PHYSICAL CHARACTERISTICS OF ALLUVIAL FANS

by

Robert L. Anstey, Ph. D.
Earth Sciences Division

Project Reference:
1L013001A91A

December 1965

U.S. Army Materiel Command
U.S. ARMY NATICK LABORATORIES
Natick, Massachusetts

FOREWORD

In May 1959 the Army Research Office requested that specific criteria for terrain elements be devised as a basis for revision of AR 705-15 "Research and Development of Materiel, Operation of Materiel Under Extreme Conditions of Environment," and Military Standards. Knowledge of the percentage frequency of occurrence of specific landform characteristics in representative samples in the major geographic regions of the world would provide a realistic basis for this revision. Such data are essential for the selection of testing areas for new equipment, and as a test of the representativeness of these testing areas. Also, knowledge of the frequency of occurrence of impassable natural obstacles and of unimpeded routes is of special interest to the tactical commander in deciding where he may expect his vehicles or those of the enemy to go and where they will be stopped.

Quantification of landform measurements and description, essential to frequency of occurrence determinations, has not been previously conducted over large areas. The Corps of Engineers' Waterways Experiment Station has proposed a system of landform classification for small areas. The Earth Sciences Division proposed that the common landforms in each of the major regions, or those landforms most frequently encountered, should be studied, e.g., dunes, badlands, canyons, and dry washes, using the Corps of Engineers Waterways Experiment Station system. Previous studies have attempted to quantify all aspects of terrain. This study concentrates on a single type of landform presenting (1) a generalized overview, (2) a selection of militarily significant features, and (3) an analysis of these features. The variety of physical values which have been found for this single type of landform precludes its treatment as a "facet" under the British Military Engineering Experimental Establishment Landscape Pattern Classification System.

This report is a survey of the physical characteristics and geographical distribution of alluvial fans. Based on an investigation to determine, define, and portray the frequency of occurrence of these features, most of the findings are in the form of maps, graphs, and tables.

This report is the first of a series on quantified description of alluvial fans. A second report entitled "Aerial Photo Interpretation of Militarily Significant Features of Alluvial Fans" is in preparation. A third report entitled "A Military Analysis of Alluvial Fans" will treat the details of microrelief, defilades, and obstacles to movement of military vehicles.

L. W. TRUEBLOOD, Ph.D.
Chief
Earth Sciences Division

Approved:

DALE H. SIELING, Ph. D
Scientific Director

W. W. VAUGHAN
Brigadier General, USA
Commanding

CONTENTS

APPENDICES

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (con't)

ABSTRACT

In this study a new technique is developed for analyzing available world maps and aerial photographs in terms of frequency of occurrence of terrain obstacles as related to capabilities of various types of military vehicles. Employing this technique, an areal quantification of the geometry of alluvial fans was completed for a total of seven 1-degree quadrangles (1 degree Latitude x 1 degree Longitude) of representative desert terrain in the United States and West Pakistan.

The greatest development of alluvial fans is associated with mountainous desert regions having wide valleys. Alluvial fans are not related to high mountainous areas or to areas where the mountain mass has been deeply dissected by steep, narrow valleys. Within desert regions it was noted that landform data in one physiographic province were very similar to those in the same type of province (such as a folded-faulted type) and climate elsewhere. Except for similar provinces the agreement was not close.

Approximately 70 percent of all alluvial fans studied were 1 to 5 miles in length and had total slope gradients of 1 to 5 degrees. Gradients up to 600 feet per mile have been measured on the upper slopes of small alluvial fans. Nearly all alluvial fans have deep washes with vertical walls which may be located near their apices or their aprons.

PHYSICAL CHARACTERISTICS OF ALLUVIAL FANS

1. Introduction

Alluvial fans are water-deposited features at the mouths of canyons emptying into wider valleys. They are fan-shaped deposits, consisting of rock debris washed out of the highland in which the parent canyon is located. In western United States approximately one third of all surface material is alluvial. Because of their relatively gentle slopes, good drainage and sorted composition material, they are frequently used for roads, sites for urban development, agriculture, etc., especially in desert regions where the playa is too soft and saline and the mountains are too steep and composed of materials that are too hard for these purposes. Military operations in desert regions, particularly in folded and faulted areas (such as the Basin and Ranges physiographic region) would realize definite advantages if sited on alluvial fans. Because of this potential use, it is mandatory that detailed information be made available concerning these features.

a. Purpose

This report presents results of the first part of a U.S. Army Natick Laboratories Scientific Director's In-house Laboratory research project. The research was conducted (1) to analyze the physical characteristics of alluvial fans in the desert areas of southwestern United States, (2) to show their distribution, and (3) to measure, quantify, and show the frequency of occurrence of their physical characteristics. Data from alluvial fans in a desert area in West Pakistan, as well as from individual fans in humid areas in the United States, are included for purposes of comparison. This report is the first of three on alluvial fans which will present (1) a generalized overview of alluvial fans as a distinct landform in desert regions, (2) a selection of militarily significant features of alluvial fans based on the interpretation of aerial photographs, and (3) an analysis of the military significance of microrelief, defilades and obstacles to movement of military vehicles. Some of these influences were found in the present investigation (see Appendix D).

b. Method of Study

Recognizing the impracticability of studying all the landforms of a particular type, sampling was initiated by (1) inspection of small-scale maps, (2) analysis of individual landforms on selected large-scale maps, (3) detailed interpretation of these features shown on aerial photographs, and (4) field checking and measurement of questionable or unidentifiable features. This sampling was augmented by comparative studies in which landform data from one area were evaluated with data from another area. Every identifiable alluvial fan detected on the small-scale maps was measured on a total of 82 topographic (15 minute quadrangle) sheets in the United States, covering 19,516 square miles of desert landscapes (see Appendix B for list), and 32 topographic (15 minute quadrangle) sheets in West Pakistan (see Fig. 15).

In order to establish a basis for comparing these data on a global scale, and to eventually determine the total geographical distribution of a specific alluvial fan type, data were compiled for 5 one-degree quadrangles (1° Latitude x 1° Longitude) within the sub-regions (physiographic provinces) described below. These data fit into the Quartermaster Degree Quadrangle Data Storage System*, where their relationship with 550 other environmental factors can be found without recompilation or reorganization.

While alluvial fan data compiled for degree quadrangle boundaries will not agree with those commonly accepted for physiographic provinces, they are usually within acceptable transition limits (see Figs. 3 and 14). The study is intended to obtain a total of all significant data, and the frequency distribution of these data, rather than to be an exercise in regional boundary decisions.

This research has been conducted in two mutually supporting phases: laboratory investigations and field investigations. In both instances, library research and training in technique preceded the actual work.

Laboratory Investigation

The following methods were used to differentiate landform types shown on maps and aerial photographs.

(1) Map and aerial photo interpretation. Determination of total number and areal occurrence of alluvial fans in each 15' topographic sheet, and in each degree quadrangle. Determination of the general physical characteristics of ideal-typical alluvial fan types by inspection on aerial photos selected from the areas covered by each 15' topographic sheet. Comparison of specific landforms on map scales 1:25,000, 1:50,000, and 1:250,000.

(2) Stereocomparagraphy. Preparation of local relief, obstacle, slope, and drainage maps.

(3) Planimetry. Determination of total areas of landform types, location and frequency of natural obstacles, and establishment of vehicle passability areas.

---

* See: Digitized Environmental Data Processing, Research Study Report RER-31 (revised), Earth Sciences Division, Quartermaster Research and Engineering Center, Natick, Mass., May 1963

Field Investigation

The following measurements were made of alluvial fan types in the field:

(1) Total relief (elevation of apex minus elevation of apron).

(2) Length (apex to apron).

(3) Total width of the apron.

(4) Radii of curvature.

(5) Gradient (total, homogeneous segments).

(6) Geometry (entrance and exit profiles, number of obstacles in three random lines, width and depth of fan head trench, width and depth of three random distributaries).

It is recognized that each type of landform requires a different series of measurements. The above are specifically for alluvial fans.

The Avawatz Mountain area (Fig. 3) of southern California was selected for a detailed study of alluvial fans, inasmuch as a greater number of these features occur here than in any other area of similar size in the United States. The Avawatz Mountains are located in the Basin and Range physiographic region, an example of block faulting topography. Frequently, this type of faulting has greater local relief, and more examples of this relief than other landform types. Additional examples of this type of topography are located in the Alpine-Himalaya Mountain chain of Eurasia, and in the system of mountain and rift valleys on the eastern edge of the Arabian Shield.

For comparison, alluvial fans were measured in 2 one-degree quadrangle areas in the Baluchistan Group of mountains in West Pakistan (Fig. 14), which is a part of the Alpine-Himalaya chain. Because of the close agreement between this physiographic region and the Basin and Ranges region, in climate, elevations and spacing of mountain masses, and in the geomorphic processes which are or have been at work in the two regions, the physical characteristics of alluvial fans are closely analogous.

c. Limitation of the Present Study

The required topographic maps at scale 1:62,500 or larger were not available for many areas in the Basin and Ranges physiographic region. The available maps afforded complete coverage of only 5 degree quadrangles in this physiographic region. Variations in delineation of details between map compilers prevent close comparability between landform data obtained from neighboring topographic sheets. Wide contour intervals (80 to 100 feet) in many instances made the interpretation of landforms difficult, particularly in the case of small alluvial fans or talus cones. With such widely spaced contour intervals it is impossible to delimit the alluvial fan apron, a significant feature of very low relief. In some instances neighboring sheets had been mapped 80 years apart, and rectification was impossible. For close comparability, landform data should be obtained from maps or aerial photographs of the same date.

Comparison of findings was possible with only one foreign desert area, Baluchistan, West Pakistan, and this comparison was incomplete due to the brief period of time allotted for field work and to the type of map coverage available. Most of the available maps covering the desert areas of West Pakistan were compiled prior to World War II, and some were dated before World War I. While major landforms have not changed markedly, minor landforms such as drainage features on alluvial fans have been altered. In the field it was not possible to make the accurate point-to-point analysis of landform change with time since the last survey, due to the limited size of the field party (one man) and the lack of long-distance survey equipment. Published maps do not cover the entire Baluchistan Group Physiographic Region* at the scale of 1:62,500. Also, the frequent use of hachures on these maps rather than contour lines, as well as the wide interval and casual delineation of these lines, precluded a study of landforms based on this source alone.

d. Definitions

Terrain terms used in this report are defined in Appendix A. Authorities for these definitions or terrain terms are given where the definitions are in agreement with the findings of this study. These may not be the earliest definitions. No attempt has been made to interpret or justify the wide variance in terrain definitions among the various authorities.

Quadrangles of various scales were used in this study. The most common were 15' Longitude x 15' Latitude (scale 1:62,500), which are referred to in this report as topographic sheets. Where more detailed coverage is used, i.e., $7\frac{1}{2}$' quadrangles, they are referenced to the map scale (1:24,000, etc.). In order to relate the findings of this study to the generalized or summarized materials available for other parts of the world, some facts are given for degree quadrangles (1° Latitude x 1° Longitude), each of which includes 16 topographic sheets (15 minute x 15 minute) at the scale 1:62,500 (see Figures 4a, b, c, d, e, and 15a, b).

---

* See: A. K. Lobeck, Physiographic Diagram of Asia, Geographical Press, Columbia University, N. Y., 1945.

e. History of Alluvial Fan Studies

In 1841, the French geologist Surell described the formation of alluvial fans as a process beginning with Alpine torrents, which cut a half funnel-shaped bassin de réception in the upper courses, while in the lower courses the material was deposited in a cône de déjection. In 1882, G. K. Gilbert described the formation of the alluvial fan process "when the water leaves the margin of the rocky mass, it is always united into a comparatively small number of streams, and it is by these that the entire volume of detritus is deposited about the mouth of each gorge in a symmetric heap of alluvium, a conical mass of low slope descending equally in all directions from the point of issue." All authorities agree that the deposition of alluvial material is the direct result of stream flooding, and the accumulation of debris. In 1928, Blackwelder noted that mud flow in certain fans constituted their greatest bulk. In 1954, Blissenbach suggested that there is a correlation between the aridity of climate and a type of deposition on the fans. He noted that mud flows tend to occur under more arid conditions, while stream flood deposition appeared to be more common under wetter climatic conditions.

In 1897, McGee used the term "pediment" for the planed rock surface developed by sheet flood erosion. Davis, in 1938, stated that stream floods are characteristic of alluvial fan washes; although stream channels may be dry most of the time, there are occasional floods of water down them after heavy local rains. Davis preferred to call them "stream floods" rather than sheet floods because of their spasmodic and impetuous flow. Pediments may be stripped of the detrital cover through a deformational increase in slope by faulting or tilting. Davis added that the process of stripping is brought about by the formation of sheet floods and the stream floods. In 1923, Pack recognized three periods of flooding in arid mountains: the first a torrential stream flood, the second a mud flow caused by the breaking up of debris in the mountain canyon, and the third a period of dwindling stream flooding. In 1928, Blackwelder stated that the mud flow of the semi-arid mountain canyon is intermediate between the better known landslide and the ordinary stream flood. He stated that the mud flow behaves more like the lava flow, gliding over the surface without the internal churning that characterizes stream flooding. In 1935, Chawner added that mud flows quickly terminate with sharp, abrupt edges and are deposited in definite sheets; in some localities they have recurred regularly and are superimposed one above another in such a manner as to form distinct terraces. Bull (1963) differentiated between the physical characteristics of mudflows and water-laid deposits on alluvial fans.

Beaty (1963) pointed out that the greatest accumulation of debris on fans, the chief depositional process, occurs during the occasional intensive downpouring of water in the catchment basin at the time of thunderstorms, usually during the summer months in southwestern United States. Between these occasional storms most of these small canyons are dry. There is some detrital accumulation on the canyon floor from landslides, rock slides, solifluction, and aeolian accumulation. Also, small rains high in the mountains may wash small amounts of gravel and sand into the canyon tributaries, even though there may not be any rain over the canyon itself. The gradual accumulation of all of this material prepares a detrital load for the valley flood to carry onto the fan. In the few instances where streams flow continually in the canyon above a fan, it will be found that the water is usually clear and only insignificant amounts of sand are being moved by its force between storms.

Considerable literature, mostly in text books, is available concerning the development of alluvial fans and the dynamics of moving water as an agent of erosion. Very little has been published, however, in the way of physical measurements of these features, and other than by Strahler, there is a marked lack of published frequency of occurrence data on landforms. Authorities such as Dana, Grabau, Scott, Earley, and Vaughan have included measurements of alluvial fans in studies on other subjects. Some of these data are cited elsewhere in this report.

2. Physical Characteristics

a. Map Interpretation of Alluvial Fans

An alluvial fan must (1) be a fan-shaped deposit, and (2) be composed of alluvial materials. It is recognized that in some instances the alluvial surface deposits cover a pediment, talus, or even rock slump debris. The alluvial fan is indicated on a topographic sheet by contour lines which curve or bend downstream (Fig. 1). Contour lines along stream channels or in valleys bend upstream (Fig. 2).

In the mountain canyon, the contour lines bend upstream, but at the apex of the fan near the mouth of the same canyon, they will bend downstream, which leaves a wide contour interval, indicating a leveling of the gradient in the mountain drainage at that point. The spacing of contour lines increases gradually down-slope on the fan but, usually, on the apron or fan outskirt, these lines are more widely spaced or may not be shown by any symbol if the contour interval is too great.

In some instances, the edge of the apron may be indicated by a fringe of desert shrubs shown as a green tinted line on the topographic sheet (Ash Meadows (Nevada-California) and Furnace Creek (California)). These plants are nourished by sub-surface drainage in the fan which approaches the surface near the edge of the apron. In humid areas where the alluvial fan material is relatively sterile rather than fertile as the flood plain on which it was deposited, the entire fan from apex to apron is marked by an absence of vegetation (see Philipp (Mississippi) topographic sheet).

Where the downslope contour arcs are highly irregular due to dissection, it may be necessary to draw a mid-point arc segment on each downstream or upstream bend to obtain an appreciation of the true shape of the feature. If these arc segments do not join, it is not likely that the landform is an alluvial fan. The alluvial fan frequently has a stream or intermittent channel indicated at or near mid point on the arcs. A backwasting slope, which may be shown on a topographic map by a series of downslope arcs, will not have a stream channel (Fig. 2).

Slopes on three sides of Guadalupe Peak, Texas, were studied in the field to determine indicators of difference between backwasting slopes and alluvial slopes that would appear on topographic maps. It was found that although both features have similar map symbolization (i.e., contour lines bending downstream) the backwasting slopes had gradients in excess of 600 feet per mile in nearly all instances. Where land features could be established definitely as alluvial fans, the smallest had upper slope gradients of from 300 to 600 feet per mile, and the largest had upper slope gradients of from 50 to 250 feet per mile. The gradient of the adjacent valley was 7 feet per mile. (Also, see Figs. 6a, 6b, and 6c.)

The interpretation of alluvial fans from maps depends largely on the accuracy of delineation of contour lines on the map. In the United States these are usually carefully plotted on topographic sheets. Fans less than 1760 feet (one-third of a mile) in length usually do not appear on topographic sheets at a scale of 1:62,500 but they are readily seen on aerial photographs. Where the topographic sheet has a contour interval of less than 40 feet, nearly all alluvial fans will be shown, and where the interval is less than 10 feet, nearly all of the physical characteristics of the fans will be shown.

b. Morphological Cycle

Small alluvial fans, or cones, form at the mouths of fissures in a fault scarp or transverse canyons in the valley side, either by the gradual accumulation of water-lain material or by the deposition of this material over a talus cone (Fig. 16a). Fans develop from the disintegration, erosion and redeposition of material in a desert mountain catchment basin. As the fans increase in size, the catchment basin also increases in size until the original scarp wall disintegrates and the fan apex moves uphill from the former fault scarp or valley side to the watershed crest (Fig. 16d). At this stage the fan covers the entire slope of the range on which it is located; an example is seen on the north slope of the Funeral Mountains, Big Dune (Nevada-California) topographic sheet (also, see Fig. 21).

(1) Gradation

Alluvial fans are a product of the gradation of mountain masses by stream cutting and slope wash. All streams tend to form a graded course. Where depositional processes are more active than the erosional processes at the base of the flanks of desert mountains, alluvial fans are produced by streams carrying debris from the highlands through tributary canyons to trunk canyons. A decrease in gradient and a reduction of velocity and transporting power at canyon mouths assist deposition at these sites. Velocity loss is due to both lessened gradient and decrease in volume by seepage into loose, permeable materials. As the velocity of mountain torrents begins to slacken, deposition occurs. The heavier fragments are dropped first, and as the flood subsides, finer and finer particles are deposited during the downslope movement. The finest material is deposited in the fan apron. Concentrations of debris in trunk canyons are deposited in the form of alluvial fans at the foot of the mountain mass.

(2) Deposition

Debris flow deposition is highly irregular and is normally interspaced with long periods of quiescence, during which unconsolidated material accumulates on canyon walls and floors through normal weathering processes. From time to time heavy rainfall shifts an enormous volume of debris from the catchment basins of the mountains to the subjacent fans. The steepness of slopes generally characteristic of desert mountain ranges gives to the torrential streams which develop after each rain storm such an unusual velocity that very large boulders, 25 feet or more in diameter, can be transported together with tremendous mudflows of cobble, gravel, and lottal. When they emerge from the mountain valley onto the desert floor the current is suddenly checked and the burden of sediment is deposited at the mouth of the valley or redeposited in the subsequent storms. During intervals between major rubble flows, while mass movements and other slope processes, such as soil creep, rock drift, rainwash, etc., transfer debris from canyon walls to trunk canyon floors within the catchment basin, morphologic changes on the fan surfaces are minor.

(3) Stabilization

Soil and talus on canyon walls tend to become stabilized during periods of quiescence. Davis (1930) states that "during the delay in the recession of the basal slope by reason of its being talus-covered, the more active recession of the bare rock surfaces in the higher slope will decrease the average declivity of the valley sides; and then, with increasing development of a soil cover and with better establishment of plant growth upon it, the declivity of the valley side will be progressively lessened until all the slope above the retreating talus comes to be cloaked with finer and finer detritus and covered with an increasingly dense plant growth."

In 1913 A. C. Lawson proposed the name "fanglomerate" for the coarser deposits of an alluvial fan. In 1917 W. H. Norton proposed the name "bajada breccia" for the same materials. The name fanglomerate seems to be the more acceptable term. The age of fanglomerate deposits, which in Death Valley fans are of the Nova formation, and which have been classified as Miocene by some students, and as Plio-Pleistocene by others, shows the length of time that the fan-building processes have been going on in these areas. Some of these deposits occur only 2 feet above canyon floors, and some are as much as 75-100 feet above the floor. The position of these deposits indicates that the canyons were first cut to a depth almost as great as at present, and were then filled with alluvial sands and gravels which lay undisturbed for a sufficient amount of time to permit cementation and compaction of the beds, and were then eroded to present depths. The relative softness of the fanglomerate permitted a more rapid erosion in the areas where the material was deposited than in the nearby areas of more resistant rock, so that the fanglomerate was gradually sapped away during the stream flooding in the canyon which carried the rough, sharper materials from the weathered surfaces above the fanglomerate through the canyon to be deposited in the fan below. During this process most of the fanglomerate deposits were carried away. The present deposition of fanglomerate on the sides of the canyon shows that the present alluvial fans are the result of rejuvenation of the mountain mass to a youthful stage following the period when the present exposures were buried under a mantle of material which has been largely redeposited. The present cutting in the fan itself shows that much of the mantle of weathered material has been washed away from the upper slopes of the catchment basin, and that erosion, particularly at the head of the fan, is more active than the depositional process.

Deep washes (greater than 10 feet vertical slope) may occur at any point along the fan. They are especially prominent in the zone of degradation near the mountain face (fault scarp) where continued erosion and stream cutting in the mountain canyon has sufficiently lowered the gradient at the fan apex to cause deep cutting into the fan alluvium. These washes are the greatest obstacle to movement of either vehicles or troops. However, they are usually not continuous for the full length of the fan and routes across nearly all parts of the fan can be found in the zone of aggradation. In some instances these fan head trenches or washes may have vertical cliff sides from 10 to 50 feet in height, and total local relief of 70 to 100 feet. Large boulders, boulder trains, steeply beveled ditches and potholes at the head of an arroyo are obstacles to movement on the fan, and other micro-features may have slopes greater than the 25° for short distances. Military vehicles may overturn in moving over rough terrain with such slopes.

(4) Surface Composition

Composition of materials in the mountain mass influences the surface roughness of the fan, as well as the size of materials on fan surfaces. The deposits which constitute an alluvial fan are characterized by their coarseness, the angularity and slight decomposition of their fragments and their low degree of sorting. Layers of exposed fan deposits in a road cut at the southern base of Montgomery Mountain on the Bullfrog (Nevada-California) topographic sheet showed thickness ranging from 1/8 inch of clay to 3 feet of cobble. McGee (1897) described the debris in fans as "varying in thickness from nothing to 40 or 50 feet."

Debris in fans below sections of granitic desert mountain ranges consists of sand, cobbles, and numerous large boulders. Occasionally, boulders of extreme size are found far from canyon mouths. This type of fan surface tends to be rough. Debris in fans below metamorphic and sedimentary sections of desert mountains contains a large proportion of sand, pebbles and cobbles. These fans are characterized by comparatively smooth surfaces with few large boulders. The size distribution of surface materials on fans implies that debris flows contribute by far the greatest amount of the material in the fans, and that deposition by running water is only of minor significance (Beaty 1963).

(5) Drainage

A braided pattern is characteristic of streams flowing across alluvial fans, and as a result of repeated channel shifting, streams at some time flow down almost every possible radius of the fan. Distributary channel changes are usually caused by the plugging of active channels by rubble and large boulders until channel walls were overtopped and the flood-flow turned to one side or the other to continue down the fan along new courses. Abandoned channels are still identifiable below the sites where large boulders were stranded. Large boulders are often found at the upper end of abandoned stretches of channel. In some instances an assortment of small boulders, cobbles, and heavy masses of mud will be found near the point of channel change. Fan mesas, frequently topped with desert pavement, are isolated by these channel changes. Quite frequently a flood-flow of exceptional volume and violence bursts from a canyon mouth to tear a channel across the whole width of the previously accumulated fan mass. Near the fan head such a trench may be 50 or more feet deep and hundreds of feet wide. Below the channeled slopes of the fan, the valley torrents (stream floods) become wide sheet floods or cut characteristic washes (wide, flat-bottomed, steep-walled channels).

In most of the major washes and larger valleys, a surficial deposit of alluvial material occupies most of the wash or valley floor with gradients similar to those of the lower courses and aprons of alluvial fans. In nearly all of these washes and valleys small alluvial fans can be found along their sides at the mouths of tributary canyons. In most instances these fans are quite small and they terminate high on the valley side, or coalesce with the alluvial material on the valley side even though there is no evidence of other alluvial fan-building processes for the basal material. This superimposition of fans upon older alluvial material and the mixed nature of the material itself (talus, loess, boulders, etc.) suggest that these deposits occurred early in Pleistocene times and that recent tectonic action has been responsible for the rejuvenation of the alluvial fan process. In Death Valley, for example, there are Pleistocene benches formed from the alluvial materials on the valley sides. Remnant splinters from the previously uplifted valley sides may interrupt the alluvial drainage pattern at any point from the apex to the apron. Also, the dissection on the older, larger fans in some instances shows no relationship to present drainage patterns.

Unconsolidated alluvial and colluvial accumulations on tributary canyon walls and on trunk canyon floors constitute the primary sources of debris which will be eroded from the mountains and deposited on fans by major rubble flows during or following heavy rainstorms. Canyons which have been scoured of these deposits will not produce morphologically significant debris flows for many years. A build-up of fresh material must take place before canyons will again yield large amounts of rubble. This process is dependent upon the chance concentration of heavy rainfall somewhere in a catchment basin, together with an accumulation of detrital material in this basin.

The growth and coalescence of a series of alluvial fans takes place by repeated lateral shifting of stream courses across the fans. When tectonic movements along the mountain front occur, or when stream cutting on the valley floor results in a steep-sided base on the alluvial outskirt, a secondary alluvial fan or a series of these may be formed at the base of the steep slopes, such as the secondary fans in the Narrows at the base of Confidence Hills, Confidence Hills (California) topographic sheet.

(6) Type Classification

Alluvial fans may be classified primarily into arid and humid types because of the distinct physical characteristics of these landforms in each region. This report is concerned primarily with alluvial fans in arid climatic regions, inasmuch as the greatest number and largest sizes of these features are found where rainfall is extremely infrequent but torrential when it does occur.

For purposes of comparison, some notes on alluvial fans in humid climatic regions have been included. An attempt to correlate mean annual rainfall with alluvial fan characteristics was not successful, however. The Jordan Narrows (Utah) and Sierra Estrella (Arizona) areas receive 16 inches of rain annually, but alluvial features in the former area are grass-covered and show little erosion; in the latter they are covered with heavy bush and are marked by prominent washes. Mean rainfall in both the Yazoo Delta (Mississippi) and the Sequatchie Valley (Tennessee) is 52 inches, but alluvial features in the former area are barren, eroded gravel piles, while in the latter they are heavily forested mounds. However, there is little apparent difference between the physical characteristics of alluvial fans in the Amargosa Desert with 6 inches of annual rainfall, and those in the Guadalupe Mountains with 10 inches of annual rainfall. These data are preliminary findings from sample areas only, and should not be construed as verified generalizations.

c. Alluvial Fans in Arid Climates

The greatest development of alluvial fans occurs in arid and semi-arid regions. The urbanized areas in northern Utah, as well as most of the cultivated areas in that state and neighboring regions are located on alluvial fans. Alluvial fans in the Lake Bonneville area have a distinctive character because the mountainous border immediately adjacent to the former Pleistocene lake is partially covered by benches (heavy beds of sand and gravel) which mark the former shore lines. Alluvial fans formed at the base of these benches are largely composed of the bench material. Because of the cover of grass, scrub oak and mountain mahogany on most of these areas, the present development of the fan is slow and usually occurs only through the washing of fines from the catchment basin.

Fourteen alluvial fans in the Jordan River Valley were examined in the field. These fans are shown on the Jordan Narrows (Utah) topographic sheet only by a wider spacing of the contour lines on the lower slopes of the Traverse Mountains (contour interval of 20 feet). They are not positively identifiable from map symbolism at the scale of 1:250,000.

A reconnaissance was made of the Sierra Estrella in south-central Arizona from the Gila River to the eastern slopes of Picacho Peak. In this area the alluvial fans were clearly identifiable by the density and bright green color of the vegetation. The palo verde, cacti, acacia, mesquite, and other forms grew in thick clumps on the fans, particularly on the lower skirts, but were sparse elsewhere. By way of contrast, it was noted that the vegetation on the alluvial fans in the Death Valley region is more dense only in the stream channels at fanheads and at stream surfacing points elsewhere.

Drainage on an alluvial fan in an arid region follows a dendritic pattern. The major mountain valley stream that carries detritus to the fan naturally bifurcates repeatedly down the fan slope beyond the canyon mouth (Fig. 21). The heavy load of material deposited near this opening frequently causes an accumulation of debris or gravel "plug" in an active channel, diverting subsequent flow to one side or the other. Frequently, also, heavy accumulations of debris on one side of the fan will cause deformation of the fan shape, resulting in greater erosion of midfan detritus on the other side and extending the fan apron on that side. (This action was not observed in humid climate fans.)

Continued erosion resulting in a change in the gradation of the mountain stream will cause the formation of a fanhead trench, which may extend the entire length of the fan (but rarely bisects the fan as in humid regions). Former midfan surfaces may be isolated above this new drainage, and erosion in the form of a wash may cut into the lower surfaces of adjacent fans (see Fig. 13). The deposition from this wash may be spread over a wide area in the valley below or may accumulate at a change in grade in the form of a temporary low-angle fan.

There is no apparent relationship between the size of alluvial fans in arid regions and the area of drainage in the mountain basins above them. For example, the large fans at the mouths of Furnace Creek and Fall Canyon are approximately the same size (each more than 3 miles in radius) but the Fall Canyon drainage basin covers 18 square miles, (Fig. 9b) while that of Furnace Creek covers 222 square miles and connects with Greenwater Valley to the south and Ash Meadows to the east by low divides (Fig. 9a). The very small but similar fans at the mouths of Sheep Canyon and Gold Valley (radii less than 1 mile) are fed by basins 10 and 22 square miles in extent, respectively (Fig. 10a & b). The medium size fans at the mouths of Red Wall Canyon, Rhodes Wash, Mosaic Canyon, and Confidence Wash are each approximately 2 miles in radius, but the areas of their catchment basins are 9.2, 31.5, 4.2, and 17.1 square miles, respectively (Figs. 7 and 11). Although a direct relationship may be expected between the amount of erosion and the amount of deposition within a given system, this balance is frequently upset by diastrophic or tectonic movement, aggradation or degradation of drainage lines, redeposition of detritus, stream capture, density of rock in the mountain mass, rates of weathering, and variability or frequency of heavy rainfall.

There is a definite relationship between the probability of flooding in these drainage basins and their areal extent. The chance of the occasional rainstorm eroding a new channel or causing a mudflow is much greater in the larger basins. Flash floods may occur in these areas after a distant storm. In the small basins an earth or rock slide or even just a freshening of the vegetative cover on mountain valley slopes may result from a single rain, unless it is unusually heavy and is centered directly over the basin (Kesseli and Beaty 1959).

Most of the field studies related to this research effort were conducted in Death Valley, California, and in neighboring areas of Nevada inasmuch as the incidence of alluvial fans of all types appeared from inspection of 1:250,000 scale maps to be greater in these regions than in any other part of the United States. The results of this study are listed in Tables I through VII in Appendix C. Techniques used to obtain these data are discussed later in Section 3, Incidence and Measurement of Alluvial Fans, together with an interpretation of these data for the United States and also those for West Pakistan. Each of the major physical elements of the landform (radii, slope gradient, width, etc.) are treated separately in the tables; combined measurements for individual fans in arid climates are shown in Figure 5.

d. Alluvial Fans in Humid Climates

Alluvial fans are rarely found in humid climates because of the frequency of rainfall. Flood waters carry away any deposition of debris in catchment basins or at points of increased grade. Such flood waters increase in speed with increase in grade, deeply eroding any landform bordering the stream bed. Only where tectonic movements or accelerated erosion of main streams have created a steep cliff for tributary streams to cross, is alluvial deposition likely to occur in the form of a fan in humid climatic regions. Such depositions are short lived because of subsequent erosion which quickly cuts a deep channel across the entire fan and distributary channels are deepened with each rain until only traces of the original alluvial deposition are left on the side of the main valley. The only exception to this general rule is in narrow tributary valleys where small alluvial fans have been developed by the occasional erosion of an upper slope drained by intermittent streams. Where physical conditions favor the development of an alluvial fan in humid climatic regions, these deposits usually are deltas rather than alluvial fans.*

On eastern borderlands of the Yazoo Delta (basin) the loess cliff tops are approximately 100 feet above the floodplain (particularly near the Tallahatchie River). Tributary streams have cut into these cliffs and deposited alluvial material (gravel mixed with red clay) on the flood plain. In most instances, these streams have subsequently cut down to grade through the alluvial fan, cutting it into two parts. In many places the fans are used as pasture, location of farmstead, or as gravel and clay pits. The material removed is used for road surfacing and gives a distinctive red color to country roads; side roads surfaced with floodplain materials are black. The vegetation on these fans is markedly more sparse than that in the surrounding features due to the sterility of the gravel.

---

* In 1903 William Morris Davis wrote "Hoang (sic) Ho, (the world's) largest alluvial fan, issues from its inclosed valley 300 miles inland from the present shoreline at a height of about 400 feet above sea level." This so-called alluvial fan is actually a delta, as are most of these features in humid regions. Although the upper slopes of this feature are alluvial and fan shaped, the lower surfaces were deposited under water.

Along these cliffs, represented by the Philipp (Mississippi) topographic sheet, 17 alluvial fans were positively identified. The largest, on Jackson Creek, was 1.75 miles in length (the "fan" at the outlet to Askalmore Creek is 3.2 miles in length, but it is so deeply dissected in so many distributaries by subsequent drainage that the original shape and dimensions of the fan are indistinct and difficult to identify except for the red color of the gravel beds on the flood plain). The smallest alluvial fan shown on the map was 960 feet from apex to apron. However, some fans measured in the field were only 150 feet in length. The apex of the Jackson Creek fan was only 50 feet above the flood plain. Jackson Creek had cut a channel 10 to 15 feet in depth through this alluvial fan.

The narrow, deeply cut valleys in the Cumberland Plateau in Tennessee show few true alluvial fans. In most instances, stream action has been sufficient to prevent the deposition of tributary stream alluvial loads on valley sides. The valley is characterized by erosion rather than deposition. The Sequatchie Valley is one of the few that is sufficiently wide for alluvial fan development, but here the valley sides are heavily wooded and deep trenching would be required to "prove" the landform type. Elsewhere in the region streams meander in wide valleys, and have eroded most of the alluvial material.

On the Whitwell (Tennessee) topographic sheet (scale 1:24,000) two small fans are located in the vicinity of Red Hill School. These are 3600 and 2600 feet in length, and the apex of each is 120 feet above the flood plain. At the mouth of Alum Cove is a fan 1580 feet long and 80 feet above the Sequatchie River. Other true alluvial fans may be found in this region, but they will be much smaller and more difficult to identify in the field.

Many humid climatic regions contain no alluvial fans. In a degree quadrangle selected at random in central Maine there were no identifiable alluvial fans. However, there were numerous small deltas at the mouths of streams emptying into lakes or slow-moving or meandering streams in this area.

Temporary alluvial fans of low relief may be found in humid regions during or immediately after a flood which deeply scours stream banks, leaving a steep slope for tributary streams to cross. In most instances the tributary stream will merely erode this bank to grade, but where the tributary stream is carrying a heavy load of silt or mud, these materials will be deposited in the form of a fan at its mouth on the bank of the main stream. The next rise in the water level of the main stream, as well as continued scour of the tributary stream, usually removes all traces of this deposit.

e. Classification of Alluvial Fans

Alluvial fans may be classified by physical types. In humid climatic regions deeply dissected or fragmented fans may be found. These are also found occasionally in arid climatic regions together with superimposed, coalesced, and secondary alluvial fans. Secondary fans are formed usually at the base of an older fan when uplift or scour has resulted in a cliff-edge where new deposition takes place. Coalesced fans are formed where drainage lines from the parent mountain mass are closely spaced, or where growing fans tend to deposit on each other's flanks, creating a continuous mantle of alluvial material along the base of the mountain front. Superimposed fans may occur at any place in the midfan when a change of orientation of the drainage lines creates a new fan-shaped deposit over an older deposit, usually with a different angle of slope, from a new apex point. When the deposition of a superimposed fan is caused by an over deepening of a wash on the mid-fan surface, it is sometimes called a secondary alluvial fan.

Alluvial fans may also be classified by size. Small fans have shallow distributaries, are steep and usually less than 3500 feet in radius (Figs. 16a and 16b). Medium-size fans are deeply trenched, and may have old fan surfaces isolated between active distributaries (Fig. 16c). These fans are usually two-thirds of a mile to 3 miles in radius. Large fans, greater than 3 miles in radius, are widely trenched, may contain inselbergs, and may extend back to the watershed boundary (Fig. 16d).

Alluvial fan types depend on climate, nature of local relief, type of drainage (such as (1) a well-integrated drainage system within the mountain basin, or (2) numerous small streams running independently to the valley), hardness of the rock on exposed mountain valley walls, diastrophism and age.

f. Change with Flash Flooding

On July 25, 1950, the effect of a thunderstorm on the landforms in Death Valley was observed by the writer. At a temporary weather station established at Furnace Creek Airport by the U.S. Army Quartermaster Death Valley Expedition, 0.7 inch of rain was recorded. This was only half as much as the heaviest rainstorm ever recorded in the valley. In normal years the rainfall in July in this valley is 0.08 inch. However, orographic influences produce much greater amounts of rain in the surrounding mountains. Almost half of the average annual rainfall occurred in this one storm. Rain fell from 7:35 p.m. to 10:30 p.m. and brought the air temperature down to 71°F at that time, the lowest temperature of record since early in June that summer.

The storm was concentrated in the Furnace Creek catchment basin, a relatively large drainage area of about 220 square miles on the west slopes of the Funeral Mountains and on the northern slopes of the Black Mountains extending nearly 25 miles to the southeast. The nearly dry bed of Furnace Creek at the point of its entry into Death Valley at the head of a 3.25 mile long alluvial fan which is elevated 280 feet above the present valley floor playa, is only 55 feet in width. Behind this narrow opening the valley bifurcates again and again in all directions, and reaches a maximum width of 12 miles.

During the storm all the water collected in tributary gullies and upper valleys quickly filled the gorge to a depth of 25 feet in front of Furnace Creek Inn. The force of the rushing water rolled huge boulders as great as 6 feet in diameter, together with great quantities of smaller rocks, bushes, gravel and mud. This torrent continued to race through the gorge with no apparent weakening for at least 2 hours after the rain had stopped, even though the flood began to rise within a few minutes after the rain started. The stream was still bank-full 12 hours later.

When the rain first hit the ground on the upper slopes of the catchment basin it created a slow moving mud-flow which increased in speed as the rain continued to fall and the mud became thinner. Much of the heavier debris was dropped on the alluvial fan near the mouth of the stream as the water content of the flood decreased by evaporation from the heat of the ground and through seepage and subsurface drainage into the loosely consolidated materials of the fan over which it was flowing. Also, the numerous, shallow distributaries on the fan spread the flood over a wide area as it entered Death Valley proper. Any increase in the size of the fan was hardly noticeable, however, with this amount of deposition.

The flood eroded the road bed of California State Highway No. 190 near Furnace Creek Inn to depths of from 6 to 8 feet, and deposited clay, sand, and rock rubble to depths of from 1 to 4 feet over other parts of the road within a mile of the Inn (Fig. 18). In some places it was possible for road gangs to scrape a temporary road through the flood debris; in other areas an entirely new road bed had to be constructed. A month after the storm some sections of the main roads in Death Valley were still impassable to vehicles without 4-wheel drive.

Great amounts of gravel and heavy rock rubble were washed over the apron, taxiways and runways at Furnace Creek Airport rendering them unusable and necessitating complete reconstruction of the landing surfaces (Fig. 19). Irrigation flumes, gauging stations, and ditch gates serving Furnace Creek Ranch were clogged by the accumulation of sand and mud brought down the irrigation canal by flood water. Several stone cairns over 3 feet high which the writer had constructed on the alluvial fan above the airport were washed out, and the general pre-flood surface arrangement of sand, rock and clay on the fan was completely changed by the shifting meanders of the water which passed over it. Old channels were filled with debris and new channels were cut. Water nearly 1 foot deep overturned a set of heavy metal platform scales on the packed gravel of the apron in front of the hangar. A veneer of clay approximately 1 inch thick was laid over the entire hangar area and in many places on the upper fan surface (Fig. 20).

The limits of flooding were sharply defined by the evidence of new deposition or new erosion of the surface features of the valley. Four miles north of Furnace Creek Inn there were no signs of flooding, and even on some of the surfaces of the fan above Greenland Ranch there were small patches of ground which had not been covered with water, even though rain fell in all parts of the valley. Small stream beds 5 or 6 miles from the storm center were marked by fresh salt crusts evaporated from water which had been carried a great distance from the storm area. The valley playa received surface and subsurface water from the flood and was completely covered with water on the morning after the storm. For several days salt crystallized over the entire valley floor between the alluvial fans on either side. Salt crystals were also seen on many of the clay beds exposed at different places above the valley floor. This crystallization was due primarily to the evaporation of water which had become contaminated with salt while flowing over former shore-lines of salt water lakes, or which had seeped through salt-bearing alluvium. By noon of the following day, the entire fan surface was dry, and the heavy clay deposits in distributary pools were only slightly plastic.

Much of the valley floor is normally covered with a crusted mixture of clay, sand and salt, the surface of which has a rough, brownish appearance. This crust was only from 0.25 to 0.5 inch thick, and crumbled as one walked over it. It covered a loose wet sand, salt and alkaline mixture of from 1 to 3 inches thick. In many places this wet layer is underlain by a hard salt bed varying from 2 to 6 inches in thickness, strong enough to support a considerable weight, such as a 6 x 6 truck or similar vehicle. Below this layer are alternating layers of mud, salt, and sand. These alternate layerings of salt, sand and other materials indicate an accumulation of many years of flood debris which is gradually filling the valley. The whiteness of the valley floor was slowly changed as wind and dust removed some of the surface crystallization and efflorescence and soil particles were deposited in drifts over the salt.

3. Incidence and Measurements of Alluvial Fans

a. Areal Occurence

Alluvial fans and bajadas occupy 31.4 percent of the southwest United States deserts (Clements et al, 1957, p. 106). However, in smaller areas these features dominate the landscape. In Death Valley alluvial fans cover approximately 1100 square miles, or 38 percent of the National Monument; but over 73 percent of the main valley floor is covered by alluvial fans. It is possible for alluvial fans to be formed in nearly all regions; however, the contributary circumstances for optimum fan development may not occur in every region. Alluvial fans reach their greatest development in arid regions. In humid regions alluvium may be carried to the sea to be deposited in the form of deltas, but such drainage systems, rainfall conditions, and continuous flow of water, occur rarely in arid regions.

Arid region rainfall usually occurs in the form of thunderstorms and resulting floods carry heavy loads of debris from drainage basins to the valley below. Where conditions are optimum for alluvial fan development, there may be only a few large fans, such as on the Silurian Lake (California) topographic sheet, rather than many small ones. The greatest numbers of fans in a topographic sheet are usually found in a folded-faulted locality with several inselbergs and with only 1,000 to 2,000 feet of relief. Although alluvial fans are valley features rather than mountain features, they depend upon the relief obtained with low mountain elevation for their greatest development, and upon the type of material and erosion within the tributary mountain valleys and catchment basins for their specific material constituency and growth.

At the base of cliffs of low relief, alluvial fans may develop after a thunderstorm but subsequent storms may radically alter their form and/or even their location. Alluvial fans do not develop in large dune fields, or in soft rock. Alluvial fans are usually not found: (a) in high mountains, especially those that are deeply dissected; (b) on the floors of large valleys which are partly covered with dunes or lava fields; (c) in well-developed drainage or in large washes; (d) in very low relief; (e) in areas with large water bodies; or (f) in places with numerous small hills of insufficient height for alluvial fan development. In areas of bajadas a single fan is usually difficult to isolate for study. When coalesced, an alluvial fan may lose its identity as a separate landform.

b. Alluvial Fans in the United States

Total numbers of alluvial fans were determined for 5 degree-quadrangles in the Basin and Ranges region in southwestern United States for convenience of comparison with other world areas. The application of this plan was limited, however, by the sporadic coverage of topographic sheets. In many regions it is not possible to obtain uninterrupted 16-sheet coverage at a scale of 1:62,500 for a single degree-quadrangle. A total of 3876 alluvial fans of all sizes were identified and analyzed. An average of 194 large fans (greater than 3000 feet in length and width) per 1-degree quadrangle and 11.4 per topographic sheet were found. The greatest numbers of identifiable fans were found in the Avawatz Mountains of California (see Fig. 3), a total of 1011 fans in a single degree-quadrangle. The other degree quadrangles had 686, 681, 633, and 790 fans of all types, respectively (Figs. 4a through 4e). The greatest number of fans identified on a single topographic sheet was 116 (Leach Lake, a part of the Avawatz Mountains area). The average number of fans found per topographic sheet in the above areas was 63, 39.5, 42.5, 49.3, and 42.8, or an average of 47.5 per sheet for the entire study area (82 sheets). For purposes of comparison with topographic sheets in other regions of the same physiographic type, it is essential that similar contour intervals, similar datum control, and similar symbolization from similar photogrammetric methods be used in order to obtain the same kind of information from the sheets.

(1) Radius

Figures 4a through 4e show the per-sheet incidence of alluvial fans by size. In this sorting, an arbitrary classification was made, in which the first number given for each topographic sheet is the number of fans with radii greater than 3500 feet, the second number those that are between 1700 and 3500 feet, and the third number those less than 1700 feet in radius. Table I shows the total numbers of fans in the large group. The largest number of these features was in the short radii group. Only 1058 alluvial fans in a total of 3876 identified in this survey had radii greater than 3500 feet, and the number of "large" fans in the United States (greater than 3 miles in length) is relatively low.

Table I shows the incidence of both long and short radii for large fans in a random sample of 588 of the first group of fans in the above series in the United States. Data are not included for small or medium alluvial fans, and the percentage incidences apply only to the large fan group. Although this large size group contained some of the questionable landforms that could not be verified in the field, 277 fans were found to be 3 miles or more in length, only 55 fans were longer than 5.9 miles. The longest landform in this group, over 16 miles, may be more properly classified as an "alluvial plain." However, the average alluvial fan is much smaller. For example, the radii of alluvial fans in the Catalina Mountains, Arizona, average 4 miles, while those in the Black Hills, Arizona, average 500 feet (Blissenbach, 1954, p 177). The radius of a true alluvial fan may be as great as 40 miles under exceptional conditions (Grabau 1913, p 583).

(2) Contour Spacing

The spacing of contours increases from higher to lower elevations. On the Achenbach fan (western slope. Organ Mountains, New Mexico), the spacings are 0.2 mile for the 5,000-foot contour, 0.35 mile for 4,900 feet, 0.75 mile for 4,800 feet, and 2.2 miles for 4,700 feet. On the Soledad fan (also on the western slope of the Organ Mountains) the spacings are 0.38 mile for 5,200 feet, 0.45 mile for 5,100 feet, 0.9 mile for 5,000 feet, 1.6 miles for 4,900 feet, 3.8 miles for 4,800 feet, and 5.2 miles for 4,700 feet. Contour spacings continue to increase per unit of decrease in elevation so that contours become essentially parallel. In these areas the individual fans coalesce laterally to form alluvial piedmonts (Ruhe 1964, p 148).

Contour spacings were measured only on upper fan surfaces, because of the difficulty in determining the outer limit of outwash in the zone of aggradation. In many instances this outer limit is indistinct because of aeolian deposition; in others it is highly irregular, leaving a thin serrated pattern which changes with each storm. Reported radii measurements were made on the right, left, and mid-line of the alluvial fan from the apex downslope to a definite break in slope characteristics. At this point a measurement was taken across the fan from left to right through the mid-line terminus.

Measured radii show definite deformation to the right or left on medium and large-size fans, and these have been indicated where each radius is of a different length. Where only one radius is short, an old raised fan surface will be found on that side. Where radii are of the same length, the fan is usually small. Short widths usually indicate a steep upper-fan slope.

(3) Width

Width data (Table VI) are given for some alluvial fans in this study, but these figures must be interpreted in each case. Many coalesced alluvial fans are narrow. They are bordered by wide washes on either side, and the meandering of these washes results in a variety of widths. The widest area on an isolated fan is at the outer fringe in the zone of aggradation, which usually cannot be identified on a topographic sheet at the scale of 1:62,500. Computation of width by use of total radii length and angles of outer radii is not satisfactory due to the surface deformation of most fans. The measured surface distance, in most instances, cannot be related to the plan width distance because of the varied amounts of deposition.

(4) Microrelief

An analysis of the microgeometry in a typical alluvial fan apron (low relief area) transect, consisting of 3 parallel lines 50 feet in length (selected at random), showed that the greatest local relief in this short distance was 34 inches from plan level (Fig. 12). The greatest relief was 14.8, 5.04, and 6.48 inches, respectively. This apparent difference was caused by lines of large boulders across the transects. If the actual base surface of this portion of the alluvial fan were used, the greatest relief would be 12 inches or less. Microrelief increases rapidly upwards on the alluvial fan surface. The fanhead trench on the same slope had total relief greater than 50 feet, and vertical slopes greater than 10 feet.

The total gradient of the alluvial fan surface rarely exceeds 10° (Dana 1894, p 194-195; Eckis 1928, p 223; Scott 1932, p 269; Eardley 1938, p 1408). Some authorities report no slope angle greater than 5° or 6° (Lawson 1915, p 25; Vaughn 1922, p 341). Blissenbach (1954, p 176) reports 5° gradients on the Aubrey Cliff fans in Arizona, and 9° on fans in the Black Hills of Arizona. He states that "surface angles greater than 5° are characteristic of the upper half or more of small alluvial fans with a radial extent of a few hundred feet like those of the Black Hills of Arizona. Large alluvial fans such as those of the Santa Catalina Mountains, Arizona, with a radial extent of about 4 miles exhibit angles greater than 5° only within the upper one-twentieth or less of their extent."

The overall gradients of alluvial fans in this study were computed (where all measurements are expressed in <u>feet</u>):

$$\text{Gradient in degrees} = \frac{\text{Elevation of Apex - Elevation of Apron x 57.3}}{\text{Radius of Apex to Apron}}$$

or (where measurements are in <u>both feet and miles</u>):

$$\text{Gradient in degrees} = \frac{\text{Relief in feet}}{\text{Length in miles}} \text{ x } .01085227272$$

These gradients were computed for a sample of 588 large alluvial fans (with radii greater than 3500' from apex to apron) in the United States, and findings are given in Table II. Approximately half (296) of this sample had gradients between 1.5° and 3.0°, 416 fans of the 588 in the sample had gradients between 1° and 3.5°. The greatest angular measurement for an entire fan was 9° for those studied in the United States. It is recognized that much steeper slopes are found in small areas within the fan itself (see Figs. 1 and 21).

The factors of slope and relief are determined directly from the alluvial fan profile. Slope in percent is computed:

$$s = \frac{y}{x} 100$$

Where y is the difference in elevations between two adjacent high and low points, and x the horizontal distance between those points. If a slope is divided into homogeneous segments (i.e., each with the same horizontal length) and labeled ab, bc, cd, de, ef, etc., the actual microgeometry of the slope can be determined. For example, where point (a) is 2 feet above plan level, and point (b) is 3 feet above plan level, slope of the portion ab is determined:

$$S = \frac{y_3 - y_2}{x_1 - x_0} 100$$

In order to determine the actual horizontal plan length of a slope, regardless of its gradient, the correction may be computed:

$$s_d = \frac{-p_d}{\text{cosine } S_a}$$

Where sd is the measured slope distance, p_d is the actual horizontal distance, and S_a is the slope angle. Data given in Figures 5 and 8, and in Tables I, II, VII, and VIII are based on these formulae. Similar computations are made for the portions of the profile bc, cd, etc.

Relief is determined:

$$r = y_m - y_n$$

Where y_m and y_n are the elevations of adjacent high and low points in a segment of the profile. For example, relief of the profile segment ab mentioned above may be computed:

$$r = y_3 - y_2$$

Slopes and relief of the alluvial fan profile may be analyzed statistically by determining the values of these factors for equal segments along the line of traverse Σ_x. Analysis of frequencies of slope and relief units can therefore be made:

$$x_1 - x_0 = x_2 - x_1 = x_3 - x_2 \ldots\ldots$$

$$(x_1 - x_0) + (x_2 - x_1) + (x_3 - x_2) \ldots\ldots = \Sigma_x$$

Frequency curves can then be drawn such as on the histogram data shown in Figures 8a and 8b.

c. Alluvial Fans in West Pakistan

In West Pakistan a total of 346 large alluvial fans were identified and measured on 32 topographic sheets in 2-degree quadrangles (an average of 10.8 per topographic sheet, scale 1:62,500). Only 29 small and medium-size fans (less than 3500 feet in maximum radius) were measured in this study. An average of 173 large fans were found in each degree quadrangle. However, numerous other small fans were noted during the field investigation and on aerial photographs which could not be positively identified on 1-inch-to-1-mile scale maps. In this area 317 large fans exhibited physical characteristics similar to those studied in the United States deserts.

Gradients of 90 percent of the measured alluvial fans in West Pakistan were 4.5° or less, and 40 percent were between 1° and 2°. As in the United States, the upper surfaces of the alluvial fans, or fan mesas, were not steep, but the sides of dry washes at the base of these features or near their apices may be vertical cliffs. See Figure 8 and Table IV. Detailed slope segment measurements of the large fan immediately west of Quetta were made by Mr. A. Ahmad Abbasi of the University of the Punjab.

The maximum radii of 90 percent of the measured fans in West Pakistan were 4.5 miles or less, and 45 percent were between 1 mile and 2.5 miles. On the Afghanistan-Pakistan border north of Nushki, 12 slopes were estimated to be 13.3 miles in maximum radius, and may actually be longer, but accurate delineation of slope termini could not be made in Afghanistan. Some alluvial fans in this region may have much greater radii than those measured. A larger sample would tend to smooth the curve which could be inscribed for these data on Figure 8. Such a sample would probably extend the incidence of extreme values. For example, longer fans may be identified in the Chagai region west of Nushki. A great proportion of the landforms on the west flank of the Tabina Plateau extending to the floor of the Dasht-i-Margo are alluvial plains rather than fans. Some of these features may be classified as backwasting slopes.

Only 11 alluvial fans in the 317 large fan sample were more than 4.5 miles in width. Approximately 50 percent of all the fans measured were between 1 mile and 2 miles in width. See Table VI. The alluvial fans in West Pakistan were less frequently coalesced than those in southwestern United States, and therefore width data could be obtained more readily. However, the indistinct delineation of landforms on the maps used imposed a possible error of 0.1 to 0.3 mile in these measurements.

No pattern of incidence of alluvial fans could be found from an analysis of the 32 individual 15-minute topographic sheets included in the 2-degree quadrangles investigated in West Pakistan. The greatest number of fans identified on any of these sheets was 38 (sheet K-10), and the next greatest number was 23, on an adjoining sheet (K-11). One sheet (K-4) contained no identifiable fans, 3 sheets showed 3 fans and 3 showed 5. A meaningful curve of width, gradient or radii data could not be drawn for any of these sheets. It may be possible to derive such information, however, from an aerial photographic analysis of 15-minute quadrangles. With available map sources, realistic frequency of incidence curves can be drawn only for degree quadrangles in West Pakistan.

In order to further test the comparability of the alluvial fans in the Basin and Ranges region with those in the Baluchistan Group region, a random sample of 100 fans in each of these regions was evaluated. It was noted that approximately 70 percent of all alluvial fans in the samples were from 1 to 5 miles in length and had gradients of from 1 to 5 degrees in both regions. Some alluvial fans in United States deserts were shorter than those in West Pakistan, but slightly smaller gradients were noted in West Pakistan at all lengths. In the two 100 landform samples West Pakistan had 19 alluvial fans larger than 6 miles, United States had 3. The United States sample had 10 alluvial fans less than 2 miles in length, the West Pakistan sample had 2. The United States sample had 17 alluvial fans with gradients greater than 5 degrees, West Pakistan had 10; but the West Pakistan sample had 17 alluvial fans with gradients of less than 1 degree, the United States sample had 3. In general, these differences between the two regions are not significant.

4. Conclusions

a. Application to Military Problems

Knowledge of the frequency of occurrence of impassable natural obstacles and of unimpeded routes is of special interest to the tactical commander in deciding where he may expect his vehicles or those of the enemy to go and where they will be stopped. Such knowledge is also valuable to personnel in determining design criteria for new military vehicles, as essential data for the selection of testing areas for new equipment, and as a test of the representativeness of these testing areas.

This investigation has found that alluvial fans, the landform most often used for military highway construction and off-road travel in the desert areas of the world, contain natural obstacles impassable to present military vehicles. Many washes on these fans have vertical slopes greater than 5 feet, which will stop any present military vehicle, and all fans have vertical distributary slopes of 24" or greater which extend from their apex to their aprons which will stop many of the smaller military vehicles. The M-5, 13-ton high-speed tractor will be stopped by an 18" obstacle, as will the T-46 amphibious cargo carrier, the M-36 9-mm gun motor carriage, and the M-29 amphibious cargo carrier. The T-101 105-mm rifle motor carriage, the M-36B2 9-mm gun motor carriage as well as most light and medium track vehicles will be stopped by a vertical obstacle 2 feet high. All wheel vehicles except the BARC, LARC, GOER, and 5-ton trucks with tire size smaller than 1400 x 20 will be stopped by a 2-foot vertical obstacle. All heavier track vehicles, including the M-60 tank will be stopped by a vertical obstacle 4 feet high. Data are from TM 9-2800-1 dated 1953 (with supplements and changes).

Obstacles in each part of a fan may be classified as: non-trafficable, modifiable by dozer-blade, negotiable with winch-assistance, or vehicle negotiable. This determination is made by comparison of the performance characteristics of each vehicle with the landform characteristics given above.

The greatest obstacle to vehicular or foot troop movement on alluvial fans is the deep wash. Washes occur near the apex, as a fanhead trench, or in midfan distributaries; they are usually steepest near the mountain face (in the zone of degradation). Large boulders, boulder trains, steeply beveled ditches, potholes at the head of an arroyo, are obstacles to movement and other microfeatures may have slopes greater than 25° for short distances, but the wash may have vertical cliff sides from 10 to 50 feet in height. These slopes are not continuous and routes across nearly all parts of the fan can be found. The alluvial fan wash is a route of easy access from the valley to the mountain canyon. Crossfan movement is usually easiest in the zone of aggradation. A special report in preparation on "Aerial Photo Interpretation of Militarily Significant Features of Alluvial Fans" shows the difference in wash characteristics between the various types of fans.

Quantification of landform dimensions, and analyses of these data have provided facts for systematic application and represent a departure from traditional narrative description of physical features of the landscape. The change in physical characteristics of landforms can be explained with type examples selected from map studies. Newly discovered features of these landforms, such as the levelling of slopes at the alluvial fan apices can be explained in such a way that the nature and extent of these features are immediately associated with them rather than being the subject of additional field investigations. New techniques of map and aerial photointerpretation permit a rapid analysis of landforms over a wide area and at the same time obtain details finer than those obtainable from previously used techniques, except field plane-tabling. Previous studies have tended to concentrate on a single alluvial fan or a single small area.

b. Comparison of Alluvial Fans

In a study of 82 topographic sheets (15' quadrangles) showing landforms in the Basin and Ranges region in the United States, a total of 3876 alluvial fans of all sizes were identified and analyzed. In this study an average of 11.4 large fans (greater than 3000 feet in length and width) per topographic sheet were found. In 32 topographic sheets of the same scale representing the Baluchistan Group region in West Pakistan, a total of 346 large fans (average 10.8 per sheet) were identified and analyzed (Fig. 15a and b). It is possible that Pakistani maps would show as many medium- and small-size fans per unit area if the same techniques were used in compilation of the maps. Some questionable or unquestionable features in West Pakistan may have been alluvial fans, which would have resulted in even closer agreement than that obtained.

A comparison of large fans in selected degree quadrangle samples in the two above-mentioned areas shows an average of 194 in the United States and 173 in West Pakistan. Such information is directly applicable to world mapping schemes and serves as a ready basis for comparison of landforms in one region with those of another, or as a basis for determining the representatives of a given region.

In a random sample of 100 alluvial fans in each of these regions, it was noted that approximately 70 percent of all alluvial fans were from 1 to 5 miles in length and had gradients of from 1 to 5 degrees in both regions. Some alluvial fans in United States deserts were shorter than those in West Pakistan, but slightly smaller gradients were noted in West Pakistan at all lengths. In the two 100 landform samples West Pakistan had 19 alluvial fans longer than 6 miles, United States had 3. The United

States sample had 10 alluvial fans less than 2 miles in length, the one for West Pakistan had 2. The United States sample had 17 alluvial fans with gradients greater than 5 degrees, West Pakistan had 10; but the West Pakistan sample had 17 alluvial fans with gradients of less than 1 degree, the United States sample had 3.

These facts, together with the graphic and tabular material in this report, are directly applicable to design criteria determinations. Agencies responsible for the preparation of revisions of AR 705-15 pertaining to the critical limits in terrain which must be considered in the engineering and design of military equipment, will find useful information on alluvial fans in the data presented here. Further studies are required, however, in order to prepare a complete statement for terrain.

c. Further Studies Needed

The results reported above require verification by additional research in a program consisting of similar studies of (1) alluvial fans and related landforms in other desert areas of the United States, (2) similar features in other world deserts, (3) other desert landforms in each of the above areas, and (4) significant landforms in each of the major regions of the world, in order to provide a basis for meaningful military application of the data. In order to obtain an application of the areal extent of natural obstacles and critical microgeometry found in the above studies, it will be necessary to conduct a series of aerial photographic interpretations of these landforms by representative types or by sub-region incidence.

Studies in new techniques for a quick and accurate appraisal of landforms over large areas in the field by a small party, or by a single individual, are mandatory. The necessity for a field party to be encumbered with heavy, bulky and team-operated equipment in order to conduct the type of research described above precludes rapid completion of these investigations.

Specific studies of alluvial fans, especially those which relate these features to the structure and form of the parent mountain mass, the gradient of the stream in the mountains, the relief of the mountain front, and the length of this front, should be conducted. The frequency of incidence of types of alluvial fans in given areas should be investigated together with the percent of incidence of critical features (such as cliffs, deep ditches, pot-holes, boulder trains, etc.) in these areas as well as the size of areas involved in each case. The relationship of fan-building processes to climate, and the evaluation of "dead" fans as related to past climates should be investigated, especially where the required drainage lines are no longer used but may be found as an obstacle to movement in an unexpected location.

5. Acknowledgments

Sincere appreciation is extended to Drs. Kazi S. Ahmad, M. K. Elahi, and Mr. A. Ahmad Abbasi, of the Department of Geography, University of the Punjab, Lahore, West Pakistan, for assistance in the field work. Cartography was performed by Mrs. Grace King and Miss Pernel Leuvelink under the supervision of Mr. Aubrey Greenwald, Head, Cartographic Laboratory.

6. References

Anstey, R. L., Agricultural Land Use in Central Kyushu [in Japanese] Geograph Rev Japan, Vol 30, No. 9, Sep 1957, pp 94-95

Beaty, C. B., Origin of Alluvial Fans, White Mountains, California a Nevada, Annals AAG, Vol 53, No. 4, Dec 1963, pp 516-535

Blackwelder, Eliot, Mudflow as a Geologic Agent in Semiarid Mountains, Bull Geol Soc Am,Vol 39, 1928, pp 465-483

Blissenbach, Erich, Geology of Alluvial Fans in Semiarid Regions, Bull Geol Soc Am,Vol 65, No. 2, Feb 1954, pp 175-189

Bryan, Kirk, Erosion and Sedimentation in the Papago Country, Arizona, USGS Bull,730, 1922, pp 19-70

Bryan, Kirk, Formation of Pediments, Transactions, 16th Int Geol Congress, Vol 2, 1936, pp 765-775

Bull, William B., Alluvial Fan Deposits in Western Fresno County, California, J Geol, Vol 71, No. 2, Mar 1963, pp 243-251

Chawner, W. D., Alluvial Fan Flooding, Geog Rev, Vol 25, 1935, pp 255-263

Clements, T., et al, A Study of Desert Surface Conditions, Tech Rpt EP-53, Quartermaster Research & Development Command, Natick, Mass., Apr 1957, pp 69-78, 106, 107

Dana, J. D., Manual of Geology, American Book Company, N. Y., 1894, 4th Ed., 1087, pp

Davis, W. M., Baselevel, Grade and Peneplain, J Geol, Vol 10, 1902, pp 77-111

Davis, W. M., Elementary Physical Geography, Ginn & Co., Boston, Mass., 1903, p 266

Davis, W. M., Rock Floors in Arid and Humid Climates, J Geol, Vol 38, No. 1, Jan-Feb 1930, p 27

Davis, W. M., Piedmont Benchlands and Primarrumpfe, Bull Geol Soc Am, Vol 43, June 1932, pp 399-440

Davis, W. M., Sheetfloods and Streamfloods, Bull Geol Soc Am, Vol 49, 1938, pp 1347-48

Eardley, A. J., Sediments of Great Salt Lake, Utah, Am Assoc Petrol Geol Bull, Vol 22, 1938, pp 1305-1411

Eckis, Rollin, Alluvial Fans of Cucamonga District, Southern California, J Geol, Vol 36, 1928, pp 224-247

Frye, J. C., and A. R. Leonard, Some Problems of Alluvial Terrace Mapping, Am J Sci, Vol 252, Apr 1954, pp 242-251

Gilbert, G. K., Report on Geology of the Henry Mountains, US Geog Serv, Rocky Mt. Region, 1877, 160 pp

Gilbert, G. K., Contributions to the History of Lake Bonneville, US Geological Survey, 2d An Report, 1882, pp 167-200

Grabau, A. W., Principles of Stratigraphy, A. G. Seiler Co., N.Y., 1913, 1185 pp

Hobbs, William H., Earth Features and Their Meaning, Macmillan, N. Y. 1913, pp 213-214

Johnson, Douglas, Rock Fans of Arid Regions, Am J Sci 5th Ser, Vol 23, No. 137, May 1932, p 389

Kesseli, J. E., The Concept of the Graded River, J Geol, Vol 49, 1941, pp 561-588

Kesseli, J. E., and C. B. Beaty, Desert Flood Conditions in the White Mountains of California and Nevada, Tech Rpt EP-108, Quartermaster Research & Engineering Command, Natick, Mass., April 1959, pp 5-101

King, L., Morphology of the Earth, Hafner, N. Y., 1962, p 179

Lahee, Frederic H., Field Geology, McGraw Hill, N.Y., 1941, pp 56, 77, 95

Lawson, A. C., The Petrographic Designation of Alluvial Fan Formations, Univ Calif Pubs., Bull Dept Geol Sci, Vol 7, No. 15, 1931, pp 325-334

Lawson, E. A., The Epigene Profiles of the Desert, University of California, Dept Geol, Bull. 9, 1915, pp 23-48

Mackin, J. H., Concept of the Graded River, Bull Geol Soc Am, Vol 59, May 1948, pp 463-512

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

Miller, J. P., and F. Wendorf, Alluvial Chronology of the Tesuque Valley, New Mexico, J Geol, Vol 66, 1958, pp 182-187

Norton, W. H., A Classification of Breccias, J Geol, Vol 25, 1917 pp 160-194

Pack, F. J., Torrential Potential of Desert Waters, Pan-Am Geologist, Vol 40, 1923, pp 349-356

Ruhe, Robert V., Landscape Morphology and Alluvial Deposits in Southern New Mexico, Annals, AAG, Vol 54, No. 1, March 1964, pp 147-159

Schumm, Stanley A., The Role of Creep and Rainwash on the Retreat of Badland Slopes, Am J Sci, Vol 254, Nov 1956, p 704

Scott, W. B., An Introduction to Geology, Vol 1, Macmillan Co., N.Y., 1932, 604 pp

Sharpe, C. F. S., Landslides and Related Phenomena, Columbia Univ Press, New York, 1938, pp. 18, 31, 34-35.

Sissenwine, N., R. Anstey, and P. Meigs, Studies on Clothing for Hot Environments. Death Valley, 1950, Part II: Environment, Environmental Protection Sec Rpt No. 178, Office Quartermaster General, Dept. Army, Wash., DC., June 1951, pp 2-10

Strahler, A. N., Davis' Concepts of Slope Development Viewed in the Light of Recent Quantitative Investigations, Annals, AAG, Vol 40, No. 3, Sep 1950, pp 209-213

Thornbury, W. D., Principles of Geomorphology, Wiley, N.Y., 1954, pp 174, 280

Tuan, Yi-Fu, Pediments in Southeastern Arizona, Univ Cal Pubs in Geog, Vol 13, 1959, pp 1-4

Vaughan, F. E., Geology of the San Bernardino Mountains, Calif., Univ Geol Sci Bull, Vol B, No. 9, 1922, pp 319-411

Von Engeln, O. D., Geomorphology, Macmillan, N. Y., 1949, pp 403, 409

Woolridge, S. W., and R. S. Morgan, An Outline of Geomorphology, Longmans, London, 1959, pp 155-156

Wright, L. A., and B. W. Troxel, Western Mojave Desert and Death Valley Region, Geologic Guide No. 1, Dept. Natural Resources, State of Calif., San Francisco, Sep 1954, pp 27, 31.

BLANK PAGE

APPENDIX A

Glossary

Alluvial Apron - recently deposited alluvium on the surface of a piedmont (Tuan 1959)

Alluvial Bench - a gravel piedmont at the foot of a mountain range formed by the coalescence of neighboring alluvial fans as they enlarge their boundaries (Hobbs 1931)

Alluvial Cone (Gilberq 1882) see Alluvial Fan

Alluvial Fan - a body of detrital sediments built up by a mountain stream at the base of a mountain front (Blissenbach 1954)

Alluvial Outskirt - an Alluvial Piedmont at the fringe of a hard-rock piedmont (Tuan 1959)

Alluvial Piedmont Slope (Lahee 1941) see Compound Alluvial Fan

Alluvial Plain - a depositional surface with gentle slopes (McGee 1897)

Alluvial Terrace (Von Engeln 1949) see Alluvial Bench

Angle of Repose - the angle of internal friction in loosely deposited materials (King 1962)

Arroyo - the deeper continuations of washes extending to the mouths of mountain canyons (Von Engeln 1949)

Backwasting Slope - creep of debris, mud and rock waste on a flowing slope (Sharpe 1938)

Badland - a land area with fine drainage texture, gullying (Thornbury 1954)

Bajada (Blackwelder 1931) see compound alluvial fan

Bajada Breccia (Norton 1917) see Fanglomerate

Bassin de Réception (Surell 1841) see Drainage Basin

Bolson - a basin rimmed by mountains (Thornbury 1954)

Catchment Basin (Anstey 1951) see Drainage Basin

APPENDIX A (con't)

Colluvium - alluvial debris mixed with talus carried by slope wash (Thornbury 1954)

Compound Alluvial Fan - lateral coalesence of single alluvial fans (Blissenbach 1954).

Cône de Déjection (Surell 1841) see Alluvial Fan

Creep - imperceptible mass transport of material on gentle slopes (Von Engeln 1949)

Desert Pavement - smooth floor of coarse angular and subangular rock fragments, particularly on the upper surfaces of desert fans between washes (Von Engeln 1949)

Diluvium - older alluvium, consolidated beds of sand and gravel deposited in Pleistocene time (Anstey 1957)

Drainage Basin - a mountain valley system consisting of the watershed of a single stream and its tributaries (Mackin 1948)

Dry Delta (Hobbs 1931) see Alluvial Fan

Dry Wash - Dry Stream Bed - an intermittent stream channel, particularly the floor of the course (Thornbury 1954)

Fan-Apex - Fanhead - the area of the alluvial fan close to the point where the parent stream emerges from the mountain (Blissenbach 1954)

Fan-Bay - a fanhead reaching far into the mountain canyon (Davis 1938)

Fanhead Trench - deep channel at the head of a fan (Thornbury 1954)

Fan-Mesa - an Alluvial Fan remnant left standing in the process of degradation of a fan (Eckis 1928)

Fanglomerate - the coarse deposits of an alluvial fan (Lawson 1913)

Graded Stream - slope of stream bed, provides velocity required to transport load supplied from the Drainage Basin (Mackin 1948)

Gravel Plug - deposition of coarse debris in a shallow wash (Eckis 1928)

Inselberg - mountain island isolated by erosion (Davis 1905)

Lottal - aqueous clayey mixtures formed by mass movement down hillslopes (King 1962)

Midfan - area between the fanhead and the outer, lower margins of the fan (Blissenbach 1954)

Mudflow - mass movement of coarse material together with aqueous fines caused by the breaking of debris dams in the mountain canyons (Pack 1923)

Pediment - the planed rock surface near the base of a mountain front (McGee 1897)

Piedmonts - foothills (Davis 1902)

Playa - level plain site of dry lake bed (Thornbury 1954)

Rainwash - sheet erosion, a process of backwasting in desert areas due to torrential rainstorms (Schumm 1956)

Rock Drift (Sharpe 1938) see Creep

Rockfan - deposition of coarse material where the retreat of a mountain front has let streams operate on the solid mass of the range (Johnson 1932)

Rock Plane - a pediment which may or may not be covered with alluvium (Johnson 1932)

Sheetflood - broad sheets of storm-borne waters which move in a system of small enmeshed channels rather than in definite stream courses (McGee 1897)

Streamfloods - the spasmodic and impetuous flow of water down stream channels after local heavy rains (Davis 1938)

Sub Alluvial Bench (Lawson 1915) see pediment

Talus Slope - a body of detrital sediments built up predominantly by gravitational sliding (Blissenbach 1954)

Wadi (Von Engeln 1949) see Dry Wash

Zone of Aggradation - the outer zone in the drainage area of a desert mountain range where deposition of alluvium is greatest (Johnson 1932)

APPENDIX A (con't)

Zone of Corrosion - the intermediate zone in the drainage area of a desert mountain range where lateral cutting by streams is greatest (Johnson 1932)

Zone of Degradation - the inner zone in the drainage area of a desert mountain range in which vertical down-cutting of streams reaches its maximum (Johnson 1932)

APPENDIX B

List of U.S. Topographic Sheets (15' x 15' 1:62,500)
(in the sequence studied)

1. Confidence Hills
2. Siluvian Hills
3. Baker
4. Shoshone
5. Wingate Wash
6. Tecopa
7. Soda Lake
8. Grapevine Peak
9. Funeral Peak
10. Ryan
11. Eagle Mountain
12. Ash Meadows
13. Bennetts Well
14. Big Dune
15. Furnace Creek
16. Emigrant Canyon
17. Telescope Peak
18. Stovepipe Wells
19. Chloride Cliff
20. Bullfrog
21. Marble Canyon
22. Goldstone Lake
23. Topopah Spring
24. Lathrop Wells
25. Bare Mountain
26. Tin Mountain
27. Quail Mountains
28. Teefort Mountains
29. Cave Mountain
30. Alvord Mountain
31. Avawatz Pass
32. Red Pass Lake
33. Leach Lake
34. Lane Mountain
35. Kerens
36. Flynn
37. Colton Well
38. Fenner
39. Bagdad
40. Cadiz
41. Danby
42. Essex
43. Lead Mountain
44. Bristol Lake
45. Cadiz Lake
46. Milligan
47. Valley Mountain
48. Dale Lake
49. Cadiz Valley
50. Iron Mountains
51. Dogskin Mountain
52. Sutcliffe
53. Nixon
54. Fireball Ridge
55. Reno
56. Spanish Springs Valley
57. Wadsworth
58. Two Tips
59. Mount Rose
60. Virginia City
61. Churchill Butte
62. Silver Springs
63. Carson City
64. Dayton
65. Como
66. Wabuska
67. Dunphy
68. Beowawe
69. Carlin
70. Dixie Flats
71. Crescent Valley
72. Frenchie Creek
73. Pine Valley
74. Robinson Mountain
75. Cortez
76. Horse Creek Valley
77. Mineral Hill
78. Railroad Pass
79. Walti Hot Springs
80. Roberts Creek Mountain
81. Garden Valley
82. Diamond Springs

BLANK PAGE

APPENDIX C

TABLES OF MEASUREMENTS OF SOUTHWESTERN UNITED STATES AND WEST PAKISTAN

TABLE I

Percent Incidence of Length, Large Alluvial Fans* in the United States and Pakistan

Length in Miles	Pakistan (Total 346)		United States (Total 588)	
	Percent	Number	Percent	Number
0.5	8.38	28	0.85	5
0.5-0.9	3.18	11	3.23	19
1.0-1.4	17.05	58	9.18	54
1.5-1.9	11.27	39	14.12	83
2.0-2.4	17.05	59	13.10	77
2.5-2.9	8.38	29	12.93	76
3.0-3.4	9.83	34	09.18	54
3.5-3.9	4.62	16	09.18	54
4.0-4.4	4.05	14	06.80	40
4.5-4.9	5.49	19	05.44	32
5.0-5.4	1.15	4	05.12	30
5.5-5.9	0.57	2	02.04	12
6.0-6.4	1.44	5	03.57	21
6.5-6.9	0.86	3	0.51	3
7.0-7.4	0.86	3	1.53	9
7.5-7.9	0.57	2	0.68	4
8.0-8.4	0.57	2	0.85	5
8.5-8.9	0.28	1	0.51	3
9.0-9.4	0.28	1	0.34	2
9.5-9.9	0.28	1	0.17	1
10.0-10.4	0.28	1	0.51	3
10.5-10.9	-	0	0.34	2
11.0-11.4	-	0	-	0
11.5-11.9	-	0	0.17	1
12.0-12.4	0.28	1	-	0
12.5-12.9	-	0	-	0
13.0-13.4	3.75	13	-	0
13.5-13.9	-	0	-	0
14.0-14.4	-	0	-	0
14.5-14.9	-	0	-	0
15.0-15.4	-	0	-	0
15.5-15.9	-	0	-	0
16.0-16.4	-	0	0.17	1
16.5-16.9	-	0	-	0

---

* Large alluvial fans for the purposes of this study do not include those with radii of less than 3500 feet from apex to apron.

TABLE II

Percent Incidence of Gradient, Large Alluvial Fans* In the United States and Pakistan

Gradient in Degrees	Pakistan (Total 317)		United States (Total 588)	
	Percent	Number	Percent	Number
0.5	00.63	2	0.17	1
0.5-0.9	07.57	24	1.87	11
1.0-1.4	20.50	65	10.20	60
1.5-1.9	19.24	61	15.81	93
2.0-2.4	08.83	28	19.38	114
2.5-2.9	10.73	34	15.13	89
3.0-3.4	08.20	26	10.20	60
3.5-3.9	06.62	21	9.01	53
4.0-4.4	06.62	21	6.12	36
4.5-4.9	01.89	6	4.08	24
5.0-5.4	02.75	8	3.57	21
5.5-5.9	00.63	2	2.38	14
6.0-6.4	01.58	5	0.85	5
6.5-6.9	01.89	6	0.68	4
7.0-7.4	00.94	3	0.34	2
7.5-7.9	00.63	2	0.17	1
8.0-8.4	00.31	1	0.34	2
8.5-8.9	-	0	0.17	1
9.0-9.4	00.63	2	0.17	1
9.5-9.9	-	0	-	0
10.0-10.4	-	0	-	0
10.5-10.9	-	0	-	0
11.0-11.4	-	0	-	0
11.5-11.9	-	0	-	0
12.0-12.4	-	0	-	0
12.5-12.9	-	0	-	0
13.0-13.4	-	0	-	0
13.5-13.9	-	0	-	0
14.0-14.4	-	0	-	0
14.5-14.9	-	0	-	0
15.0-15.4	-	0	-	0
15.5-15.9	-	0	-	0
16.0-16.4	-	0	-	0
16.5-16.9	-	0	-	0

---

* Large alluvial fans for the purposes of this study do not include those with radii of less than 3500 feet from apex to apron.

TABLE III

Number of Alluvial Fans per Topographic Sheet by Length Class in the United States

Sheet No.	at Length > 3500'	at 1700'-3500'	at < 1700'	Total No.
1	30	8	20	58
2	1	8	9	18
3	17	16	15	48
4	5	23	14	42
5	11	10	10	31
6	19	12	11	42
7	12	25	15	52
8	12	3	3	18
9	6	17	14	37
10	10	13	11	34
11	21	31	14	66
12	8	13	9	30
13	18	15	19	52
14	8	15	11	34
15	15	24	8	47
16	4	21	14	39
17	6	18	12	36
18	11	18	7	36
19	14	22	10	46
20	11	20	20	51
21	7	10	10	27
22	5	24	31	60
23	1	9	10	20
24	2	22	15	39
25	18	15	15	48
26	12	28	5	45
27	18	64	20	102
28	12	58	22	92
29	12	40	25	77
30	14	26	8	48
31	12	44	26	82
32	21	36	16	73
33	15	66	35	116
34	20	30	20	70
35	15	22	10	47
36	16	12	6	34
37	13	13	3	29
38	13	23	6	42
39	12	23	21	56

TABLE III (cont'd)

Sheet No.	at Length > 3500'	at 1700'-3500'	at < 1700'	Total No.
40	11	23	21	55
41	16	16	26	58
42	10	10	5	25
43	15	36	30	81
44	8	23	10	41
45	9	11	9	29
46	10	10	14	34
47	16	9	21	46
48	13	21	10	44
49	8	5	14	27
50	10	14	9	33
51	16	26	20	62
52	13	29	25	67
53	18	25	21	64
54	23	26	25	74
55	19	20	31	70
56	13	31	11	55
57	12	17	10	39
58	26	20	6	52
59	14	11	12	37
60	10	12	11	33
61	18	26	14	58
62	11	21	6	38
63	6	14	5	25
64	7	13	14	34
65	15	22	12	49
66	12	15	6	33
67	10	30	27	67
68	11	31	5	47
69	2	27	10	39
70	6	12	8	26
71	21	9	4	34
72	29	30	20	79
73	9	18	3	30
74	8	4	6	18
75	20	22	9	51
76	15	12	10	37
77	17	4	3	24
78	17	23	5	45
79				
80	12	18	7	37
81	14	27	16	57
82	16	17	20	53
Totals:	1043	1687	1101	3831

TABLE IV

Alluvial Fan Gradients per Topographic Sheet
(50 USA, 32 Pakistan)

Topographic Sheet Numbers

Gradient (degrees)	1	2	3	4	5	6	7	22	27	28	29	30	31	32	33	34	
Less than 0.5			1														1
0.5 - 0.99				1			1					2					4
1.0 - 1.49	2					1	4	1		2	5	4	1	5	2	1	28
1.5 - 1.99			2		3	2	1	1	1		2	4	1	3	2	7	29
2.0 - 2.49	1		4	1	2			1	3	1	2	3	2	5	4	8	37
2.5 - 2.99	4		4	1	1	5	1	1	7	3	1		2	3	2	1	36
3.0 - 3.49	9		3		2	2	1	1	1	2	1	1	4	2	2	2	33
3.5 - 3.99	3			1	1	4	2		4	1	1		1		3		21
4.0 - 4.49	4		2		1				1								8
4.5 - 4.99	2	1		1	1				1	1			1	2		1	11
Above 5.0	5		1			5	2			2				1			16
	30	1	17	5	11	19	12	5	18	12	12	14	12	21	15	20	224

Note: See Appendix B for list of topographic sheet titles and Figure 4 for locations.

TABLE IV (Cont'd.)

Alluvial Fan Gradients per Topographic Sheet
(50 USA, 32 Pakistan)

Topgraphic Sheet Numbers

Gradient (degrees)	8	9	10	11	12	13	14	15	16	17	18	19	20	23	24	25	Total
Less than 0.5																	
0.5 - 0.99					1							2			1	1	5
1.0 - 1.49					1		1	1					4			1	8
1.5 - 1.99		1		4	2		1	1				1	3			4	17
2.0 - 2.49				2	1		2	2			1	4	2			1	15
2.5 - 2.99				9	2	1		1				3		1		1	18
3.0 - 3.49	1	1	2	2		2		3	1		1	3	1				17
3.5 - 3.99	2		4	1		5	2	3	1	3	2	1				1	25
4.0 - 4.49	2	3		3		2		2		1	5		1			5	24
4.5 - 4.99	1	1	1		1	2	1	1	1		2					2	13
Above 5.0	6		3			6	1	1	1	2					1	2	23
Total:	12	6	10	21	8	18	8	15	4	6	11	14	11	1	2	18	165

Note: See Appendix B for list of topographic sheet titles and Figure 4 for locations.

TABLE IV (Cont'd.)

Alluvial Fan Gradients per Topographic Sheet
(50 USA, 32 Pakistan)

Topographic Sheet Numbers

Gradient (degrees)	50	49	48	47	46	45	44	43	42	41	40	39	38	37	36	35	Total
Less than 0.5																	
0.5 - 0.99				2													2
1.0 - 1.49	2			4		3	2			2	1	3	4	1		2	24
1.5 - 1.99	4	1	3	2	4	4	2	4	1	5	1	6	3	2		5	47
2.0 - 2.49	3	7	6	4	5	1	2	2	2	6	3	3	4	3	7	4	62
2.5 - 2.99			4	1	1		2	4	6	3	4		1	3	4	2	35
3.0 - 3.49	1					1		1	2					1	3	1	10
3.5 - 3.99			1						1		1			2	1	1	7
4.0 - 4.49				1					3								4
4.5 - 4.99																	
Above 5.0				2					2		1		1	1	1		8
Total:	10	8	14	16	10	9	8	11	17	16	11	12	13	13	16	15	199

Note: See Appendix B for list of topographic sheet titles and Figure 4 for locations.

TABLE IV (cont'd)

Alluvial Fan Gradients per Topographic Sheet
(50 USA, 32 Pakistan)

Gradient (degrees)	Topographic Sheet Numbers																
	*K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	K11	K12	K13	K14	K15	K16	Total
Less than 0.5									2								2
0.5 - 0.99						4	5	3	1		2	2	2	1	1		21
1.0 - 1.49			2		3	5	5	5	3	2	3	2	7	5		1	43
1.5 - 1.99	5		1			1		3	5	5	2	2	3	4		3	34
2.0 - 2.49									3	3	1	3	1		1		12
2.5 - 2.99		1					1		2	6	1		2	1	2	1	17
3.0 - 3.49		1						2		5	2	2			1	1	14
3.5 - 3.99								3		1		2	1	1			8
4.0 - 4.49	1	8							1		1	1					12
4.5 - 4.99	1									1	1						3
Above 5.0								1		1			1				3
Total:	7	10	3		3	10	11	17	17	24	13	14	17	12	5	6	169

---

* See Figure 15 for Pakistan topographic sheet number locations.

TABLE IV (Cont'd.)

Alluvial Fan Gradients per Topographic Sheet
(50 USA, 32 Pakistan)

Topographic Sheet Numbers

Gradient (degrees)	*N1	N2	N3	N4	J5	J6	J7	J8	J9	J10	J11	J12	J13	J14	J15	J16	
Less than 0.5																	
0.5 - 0.99	1	2															3
1.0 - 1.49	2	3		2	3			1	3		3	2	2	1			22
1.5 - 1.99	1	2	2	3	6	5		1			1	3	2	1			27
2.0 - 2.49	1	1	1	1			4			1	1		1		3	2	16
2.5 - 2.99		2	2	3		4	1			3				1		1	17
3.0 - 3.49		1				3			3						4	1	12
3.5 - 3.99		1	3			4				3		1				1	13
4.0 - 4.49			2			2				1		1				3	9
4.5 - 4.99			1			1								1			3
Above 5.0		1	2	2		3		1		1	2	5	1	2	4	2	26
Total:	5	13	13	11	9	22	5	3	6	9	7	12	6	6	11	10	148

---

* See Figure 15 for Pakistan topographic sheet number locations.

TABLE V

Alluvial Fan Radii per Topographic Sheet
(50 USA, 32 Pakistan)

Topographic Sheet Numbers

Radii (miles)	1	2	3	4	5	6	7	22	27	28	29	30	31	32	33	34	Total
Less than 0.5			1			1	2										4
0.5 - 0.99	3				1	1	2				1						8
1.0 - 1.49	7			1		3	2	1	1	2	2	1	1	2		1	24
1.5 - 1.99	10		4		1	7	1	2	7	6	2	2		3	2	7	54
2.0 - 2.49	1		1	2	2	2	2		5	1	3	3	3	2	5	2	34
2.5 - 2.99	5		1		2	2	2	1	1	1	1	3	1	5	4	3	32
3.0 - 3.49	2		3			1			1			1	2	5	2	3	20
3.5 - 3.99	1		2		1				3	1	1	1	2	4	1	3	20
4.0 - 4.49			1	1	3	1						3	1		1	1	12
4.5 - 4.99	1	1	2		1	1							1				7
Above 5.0			2	1			1	1		1	2		1				9
Total:	30	1	17	5	11	19	12	5	18	12	12	14	12	21	15	20	224

Note: See Appendix B for list of topographic sheet titles and Figure 4 for locations.

TABLE V (Cont'd.)

Alluvial Fan Radii per Topographic Sheet
(50 USA, 32 Pakistan)

Topographic Sheet Numbers

Radii (miles)	*K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	K11	K12	K13	K14	K15	K16	Total
Less than 0.5										14	10		5				29
0.5 - 0.99								2	3	3		2					10
1.0 - 1.49	1		1					4	1	12	6	5	3	1	1	2	37
1.5 - 1.99	1	2	1				2	3	1	3	1	2	4	1	1	3	25
2.0 - 2.49		6						3	4	5	1	1	3	1	2	1	27
2.5 - 2.99		2	1		3	3	1		3	1		1	1	4			20
3.0 - 3.49						3	2	1	3		2	2	1	4			18
3.5 - 3.99						4	1	2	1		1		1				10
4.0 - 4.49							1	1	1		1		1		1		6
4.5 - 4.99	5						3	1				1	1	1			12
Above 5.0							1				1		2				4
Total:	7	10	3		3	10	11	17	17	38	23	14	22	12	5	6	198

---

* See Figure 15 for Pakistan topographic sheet number locations.

TABLE V (Cont'd.)

Alluvial Fan Radii per Topographic Sheet
(50 USA, 32 Pakistan)

Topographic Sheet Numbers

Radii (miles)	*N1	N2	N3	N4	J5	J6	J7	J8	J9	J10	J11	J12	J13	J14	J15	J16	Total
Less than 0.5																	
0.5 - 0.99			1														1
1.0 - 1.49	1	3	8	1		3					1	3			2		22
1.5 - 1.99	2	2				3	2	1			1	2			1		14
2.0 - 2.49	1	2	1	2		5	3	1		3	1	2	3	2	3	3	32
2.5 - 2.99		2	3	1		1				1				1			9
3.0 - 3.49				4					6	1				3	2		16
3.5 - 3.99	1					3									1	1	6
4.0 - 4.49				2				1					1			4	8
4.5 - 4.99		1				3							2			1	7
Above 5.0		3		1	9	4				4	4	5			2	1	33
	5	13	13	11	9	22	5	3	6	9	7	12	6	6	11	10	148

---

* See Figure 15 for Pakistan topographic sheet number locations.

TABLE V (Cont'd.)

Alluvial Fan Radii per Topographic Sheet
(50 USA, 32 Pakistan)

	Topographic Sheet Numbers																
Radii (miles)	50	49	48	47	46	45	44	43	42	41	40	39	38	37	36	35	Total
Less than 0.5																	
0.5 - 0.99																	
1.0 - 1.49			1	1					2	1				2		1	8
1.5 - 1.99	1		2	1		1			1		2		3	2		3	16
2.0 - 2.49			3	1					3		2		1	2	1	2	15
2.5 - 2.99	1		4	5		1	1	1	3			1	1		2	1	21
3.0 - 3.49		2	1	1			1		1	2	3	1		4	2	2	20
3.5 - 3.99	1		1	1		1	1		4	2		1	2	2	1	2	19
4.0 - 4.49			2	1		1		3		3		3	1	1	2	1	18
4.5 - 4.99	1			2	3		1	2	1	2		2			1		15
Above 5.0	6	6		3	7	5	4	5	2	6	4	4	5		7	3	67
Total:	10	8	14	16	10	9	8	11	17	16	11	12	13	13	16	15	199

Note: See Appendix B for list of topographic sheet titles and Figure 4 for locations.

TABLE V (Cont'd)

Alluvial Fan Radii per Topographic Sheet
(50 USA, 32 Pakistan)

Topographic Sheet Numbers

Radii (miles)	8	9	10	11	12	13	14	15	16	17	18	19	20	23	24	25	
Less than 0.5						1											1
0.5 - 0.99		1				5	1	2		2							11
1.0 - 1.49	6	2		2	1	1		2	1		1	4	1			1	22
1.5 - 1.99	1			2				1	1	2	1	2	1			2	13
2.0 - 2.49	3	1	4	5			1	2	1	1	2	1	1			6	28
2.5 - 2.99	1	1	2	3		1	2	3	1		1	2		1		5	23
3.0 - 3.49	1	1		3		1		1			2	1	2		1	1	14
3.5 - 3.99			1	2	3	3	2				1		2			1	15
4.0 - 4.49			3	1		1		1			2		1			1	10
4.5 - 4.99				2	1	2		1		1	1	1				1	10
Above 5.0				1	3	3	2	2				3	3		1		18
	12	6	10	21	8	18	8	15	4	6	11	14	11	1	2	18	165

Note: See Appendix B for list of topographic sheet titles and Figure 4 for locations.

TABLE VI

Alluvial Fan Widths per Topographic Sheet
(16 USA, 32 Pakistan)

Topographic Sheet Numbers

Width (Miles)	50	49	48	47	46	45	44	43	42	41	40	39	38	37	36	35	Total
Less than 0.5																	
0.5 - 0.99			2	1		1	1	3	4	1	3	1	5	1		2	25
1.0 - 1.49	1		8	7	3	3	4	2	4	3	3	5	7	10	7	8	75
1.5 - 1.99	1	4	1	2	2		1	2	4	8	2	2		1	2	3	35
2.0 - 2.49	4	3		2	3	3	2	1	3	1	1	3		1	5		32
2.5 - 2.99	2		2	2	1	2		2	1	1	1	1			1	2	18
3.0 - 3.49	1		1	2	1			1	1	1							8
3.5 - 3.99	1	1								1					1		4
4.0 - 4.49													1				1
4.5 - 4.99																	
Above 5.0											1						1
Total:	10	8	14	16	10	9	8	11	17	16	11	12	13	13	16	15	199

Note: See Appendix B for list of topographic sheet titles and Figure 4 for locations.

TABLE VI (Cont'd.)

Alluvial Fan Widths per Topographic Sheet
(16 USA, 32 Pakistan)

Topographic Sheet Numbers

Width (miles)	*K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	K11	K12	K13	K14	K15	K16	Total
Less than 0.5										14	10		5				29
0.5 - 0.99		7						3	2	8	1	1	7			1	30
1.0 - 1.49	3	3	1		2	1	4	7	3	7	6	5	2	3	2	2	51
1.5 - 1.99						4	2	1	7	4	3	5	3	2		3	34
2.0 - 2.49			2		1	1	3	4	3	3	1	1	1	4	2		26
2.5 - 2.99	4					4			1	1	1	1	2	3	1		18
3.0 - 3.49							1		1	1		1	2				6
3.5 - 3.99								1									1
4.0 - 4.49								1			1						2
4.5 - 4.99							1										1
Above 5.0																	
	7	10	3		3	10	11	17	17	38	23	14	22	12	5	6	198

---

* See Figure 15 for Pakistan topographic sheet number locations.

TABLE VI (Cont'd.)

Alluvial Fan Widths per Topographic Sheet
(16 USA, 32 Pakistan)

Topographic Sheet Numbers

Width (miles)	*N1	N2	N3	N4	J5	J6	J7	J8	J9	J10	J11	J12	J13	J14	J15	J16	Total
Less than 0.5																	
0.5 - 0.99		3	6			7						2			1		19
1.0 - 1.49	4	4	3	3		8	4	2	3	2	3	5	2		2		45
1.5 - 1.99		1	2	4		1	1	1	3	3		2	3	3	4	1	29
2.0 - 2.49	1	1	1	3		3					1	2	1		2	3	18
2.5 - 2.99																1	1
3.0 - 3.49		2	1													3	6
3.5 - 3.99		2		1	9						3	1			2		18
4.0 - 4.49						3				1				3		1	8
4.5 - 4.99																	
Above 5.0										3						1	4
	5	13	13	11	9	22	5	3	6	9	7	12	6	6	11	10	148

---

* See Figure 15 for Pakistan topographic sheet number locations.

TABLE VII

Number of Alluvial Fans by Length and Gradient in the United States

	Length (in miles)														
Gradient (degrees)	Less than 1	1	2	3	4	5	6	7	8	9	10	11	12	13	Total
Less than 0.5															
0.5 - 0.99			4	1	3				1						9
1.0 - 1.49		9	11	11	9	4	8	2	2	1	2				59
1.5 - 1.99	1	16	22	25	15	9	2	3	2		2				97
2.0 - 2.49	2	21	26	22	17	13	9	3	2		1	1			117
2.5 - 2.99	1	22	25	22	8	8	4			1					91
3.0 - 3.49	3	16	19	11	10	2	2								63
3.5 - 3.99	6	12	19	8	5	3	1	1							55
4.0 - 4.49	1	16	15	6	1										39
4.5 - 4.99	2	8	6	4	3	1	1								25
Over 5.0	8	21	12	4	1	1		4	1	1				1	54
Total:	24	141	159	114	72	41	27	13	8	3	5	1	0	1	609

TABLE VIII

Number of Alluvial Fans by Length and Gradient in Pakistan

Gradient (degrees)	Length (in miles)														
	Less than 1	1	2	3	4	5	6	7	8	9	10	11	12	13	Total
Less than 0.5															
0.5 - 9.99	2	3	5	6	6	1	2		1						26
1.0 - 1.49		11	20	20	3	2	2	2		1				3	64
1.5 - 1.99		17	10	11	11	1	1		1	1				9	62
2.0 - 2.49	1	11	11	2	3										28
2.5 - 2.99		13	14	3	2			1				1			34
3.0 - 3.49	5	8	5	3	4	1									26
3.5 - 3.99	1	10	7	2									1		21
4.0 - 4.49	2	7	9	1	1						1				21
4.5 - 4.99		5						1							6
Over 5.0		13	3	3	3	1	4	1	1						29
Total:	11	98	84	51	33	6	9	5	3	2	1	1	1	12	317

TABLE IX

Length of Sample Alluvial Fans in United States Deserts (in feet)

(Random sample of 10 alluvial fans on each of 10 topographic 15' sheets)

Sheet No.*	Alluvial Fan No.	Right Radius	Mid Radius	Left Radius	Width
1	1	1901	1901	1901	2534
	2	2323	2323	2323	3168
	3	1478	1478	1267	1901
	4	2745	2745	2534	3801
	5	4224	4646	4224	4013
	6	2745	2745	2745	2534
	7	5280	5280	5491	6336
	8	1689	1901	1689	2323
	9	3379	3379	3590	3590
	10	2956	2956	2956	3801
3	1	4646	5069	4646	4013
	2	3590	3590	3590	2112
	3	5913	5913	5913	3590
	4	2112	2112	2112	2745
	5	3168	3379	3379	2745
	6	4435	4646	4646	2745
	7	4435	4435	4646	4224
	8	5280	5702	5702	5491
	9	3168	3168	3168	2323
	10	3590	3801	3590	3590
6	1	2534	2956	3168	3379
	2	1689	1689	1689	2534
	3	4224	4224	4224	6547
	4	3590	3801	3168	3379
	5	5913	5913	5280	5702
	6	3801	4224	3801	4224
	7	4013	4435	4013	2956
	8	3379	4013	3801	3801
	9	3801	4224	3801	4224
	10	4013	4435	4013	2956
8	1	4224	4013	4224	5913
	2	2534	2534	2534	3379
	3	5280	6124	6547	5491
	4	2112	2112	2323	3168
	5	2956	2745	2745	3379
	6	2112	2112	1901	2534
	7	2534	2534	2112	3168
	8	5491	6547	4857	6969
	9	6547	6758	6758	5069
	10	6336	6336	5280	5913

---

* See Appendix B for topographic sheet titles, and Figure 4 for locations.

TABLE IX (Cont'd.)

Length of Sample Alluvial Fans in United States Deserts
(in feet)

(Random sample of 10 alluvial fans on each of 10 topographic 15' sheets)

Sheet No.	Alluvial Fan No.	Right Radius	Mid Radius	Left Radius	Width
11	1	3590	3801	3590	3379
	2	3379	4013	4013	3801
	3	5280	5069	5280	5069
	4	2745	2956	2745	4013
	5	2745	2956	2745	2956
	6	4646	4646	4224	3801
	7	4435	4646	5069	5702
	8	4857	4857	4857	6758
	9	3801	3590	3801	4013
	10	4435	4435	4435	4646
13	1	1689	1689	1267	2323
	2	2112	2745	2745	4435
	3	1901	2112	1901	2956
	4	1901	2112	1901	2745
	5	1056	1056	1056	1901
	6	1478	2112	1478	2956
	7	1689	2534	1689	3379
	8	5913	5913	5913	5913
	9	6336	6336	6336	5913
	10	2956	2956	2956	2956
15	1	2323	2323	2323	4646
	2	4013	4435	4013	4435
	3	3379	3379	3379	3801
	4	3168	3168	3168	3801
	5	2323	2745	2323	2323
	6	3590	3590	3590	3590
	7	1901	1901	1901	2956
	8	3590	3801	4013	2745
	9	4013	4435	4857	3168
	10	2112	2112	2112	2745
25	1	3590	3590	3379	2745
	2	2112	1901	1901	2323
	3	1901	2112	1901	1901
	4	2323	2323	2323	1901
	5	1689	1689	1478	1478
	6	1478	1478	1267	1689
	7	1901	1901	1901	1901
	8	2534	2956	2534	2534
	9	6124	6124	6124	6336
	10	3590	3590	3590	4224

TABLE IX (Cont'd.)

Length of Sample Alluvial Fans in United States Deserts
(in feet)

(Random sample of 10 alluvial fans on each of 10 topographic 15' sheets)

Sheet No.	Alluvial Fan No.	Right Radius	Mid Radius	Left Radius	Width
26	1	4646	4646	4646	5702
	2	5913	6336	6758	6336
	3	5491	5491	5913	6750
	4	4224	4646	4224	5069
	5	5280	5280	5280	6336
	6	5491	5913	5913	6124
	7	3379	3801	3379	3801
	8	4013	4435	4013	4857
	9	3801	3801	4224	5913
	10	3590	3590	3590	4224
29	1	3379	3379	3379	2112
	2	3168	3168	3168	3590
	3	3590	3801	3590	3168
	4	3590	3590	3590	2534
	5	3379	3590	4013	5280
	6	3801	4013	5069	5280
	7	5280	5280	4857	4857
	8	3168	3168	3168	4646
	9	2323	2323	2323	3168
	10	5280	4857	5280	4646

APPENDIX D

Obstacles to Military Vehicles

Vertical Climb Limits: (natural obstacles)	Vehicles which will be stopped by these obstacles:
18 inch	M-5 Tractor
	T-46 Amphibian
	M-36 Gun carrier
	M-29 Amphibian
	M-116 Personnel carrier
	M-35 Truck
	M-52 Cargo vehicle
	M-127 Cargo vehicle
24 inch	T-101 105mm carrier
	M-36B2 Gun carrier
	M-113 Personnel carrier
	M-114 Personnel carrier
	XM-434 Truck
	XM-548 Cargo Vehicle
48 inch	BARC
	LARC
	GOER
	M-60 Tank
60 inch	all track and wheel vehicles

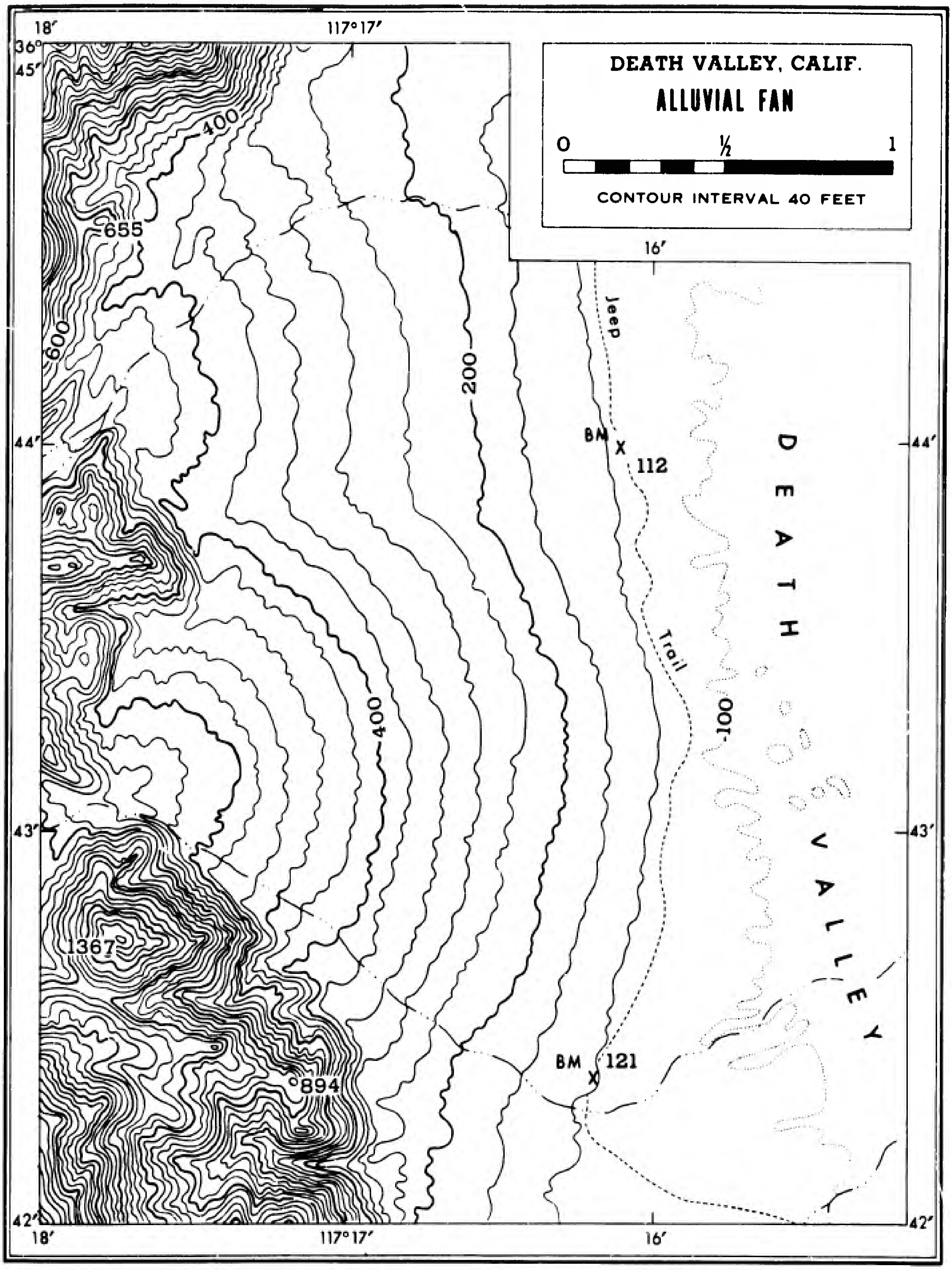

DEATH VALLEY, CALIF.
ALLUVIAL FAN
0
½
1
CONTOUR INTERVAL 40 FEET
18′
117°17′
16′
36°
45′
44′
43′
42′
400
655
600
200
1367
894
Jeep
Trail
BM
112
121
100
DEATH
VALLEY

Figure 1

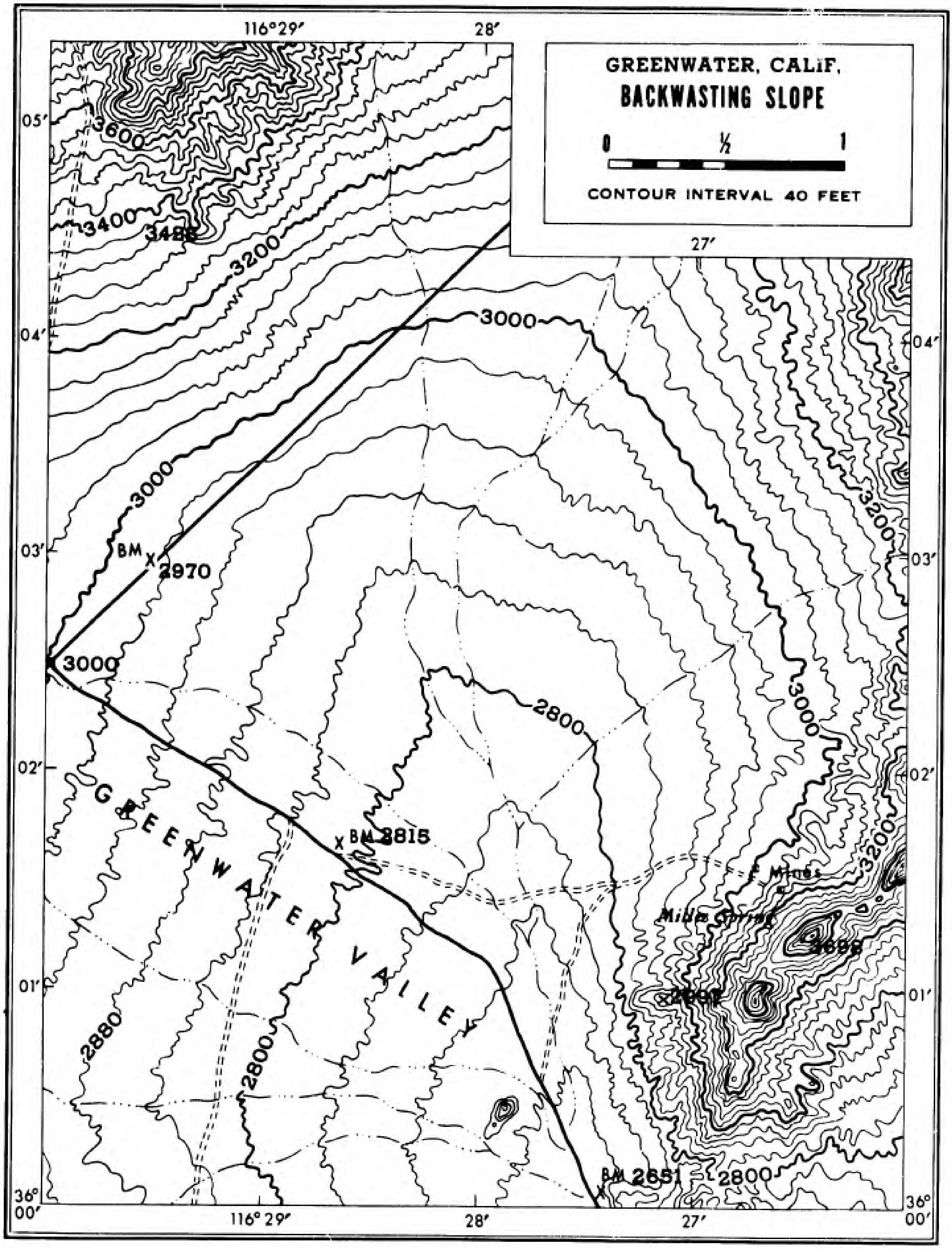

GREENWATER, CALIF.
BACKWASTING SLOPE
0 ½ 1
CONTOUR INTERVAL 40 FEET
116°29′
28′
27′
05′
04′
03′
02′
01′
36° 00′
3600
3400
3200
3000
BM 2970
2800
BM 2815
GREENWATER VALLEY
Mines
2880
BM 2651

Figure 2

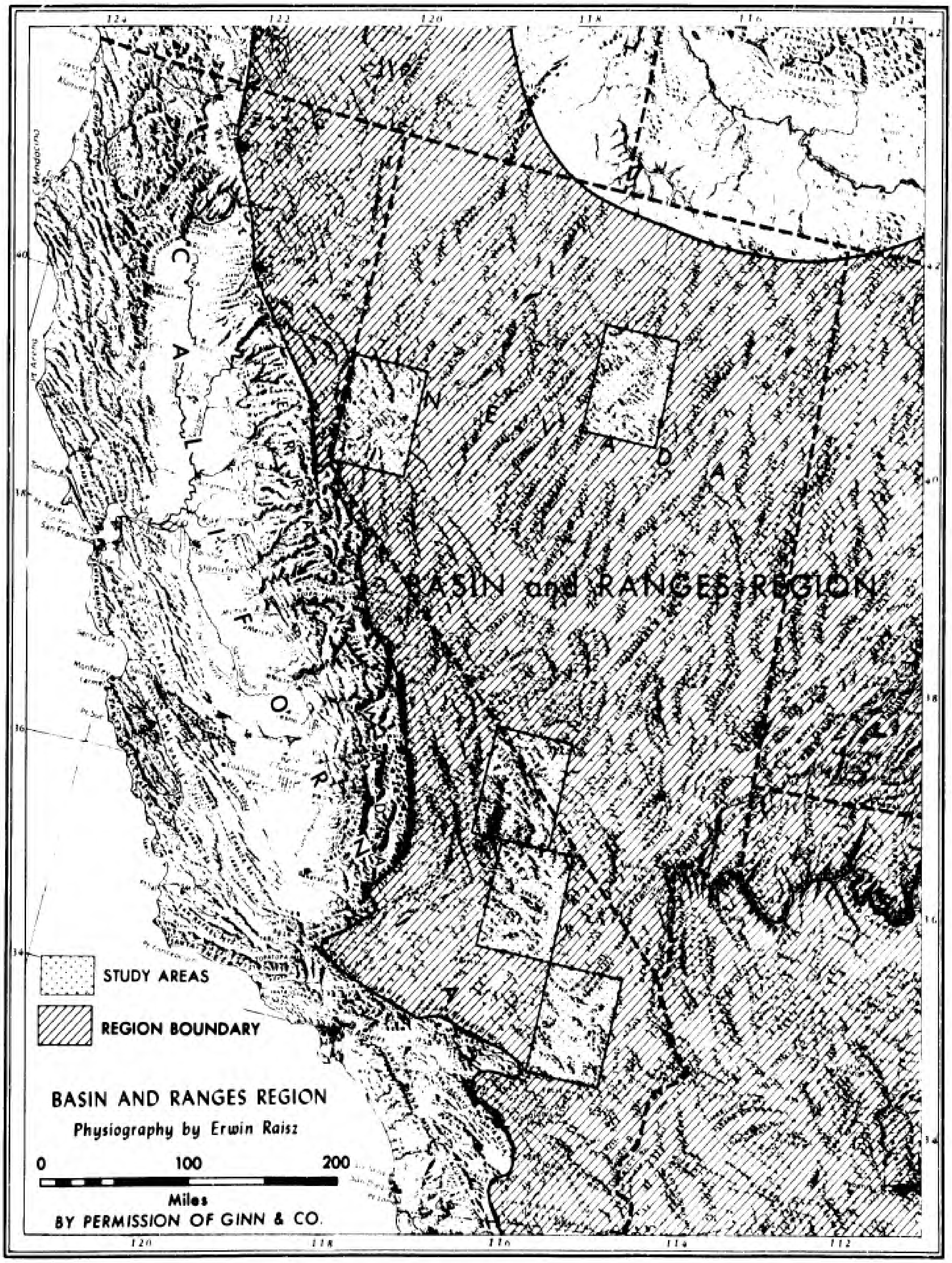

CALIFORNIA
NEVADA
BASIN and RANGES REGION
STUDY AREAS
REGION BOUNDARY
BASIN AND RANGES REGION
Physiography by Erwin Raisz
0
100
200
Miles
BY PERMISSION OF GINN & CO.
124
122
120
118
116
114
112
42
40
38
36
34
San Francisco
Monterey
Pt. Sur

Figure 3

BLANK PAGE

00 — Sheet Number
Large fan total 3500'
Middle fan total 1700'-3500'
00-00-00 — Small fan total 1700'
(00) — Total per sheet

NUMBER OF ALLUVIAL FANS, BASIN AND RANGES REGION

Lists of Topographic Sheets
(Scale 1:62,500)

117°W 36°N — 116°W 36°N

5 11-10-10 (31)	1 30-8-20 (58)	41 5-23-14 (42)	6 19-12-11 (42)
27 18-64-20 (102)	33 15-66-35 (116)	31 12-44-26 (82)	2 1-8-9 (18)
22 5-24-31 (60)	28 12-58-22 (92)	32 21-36-16 (73)	3 17-16-15 (48)
34 20-30-20 (70)	30 14-26-8 (48)	29 12-40-25 (77)	7 12-25-15 (52)

35°N 117°W — 35°N 116°W

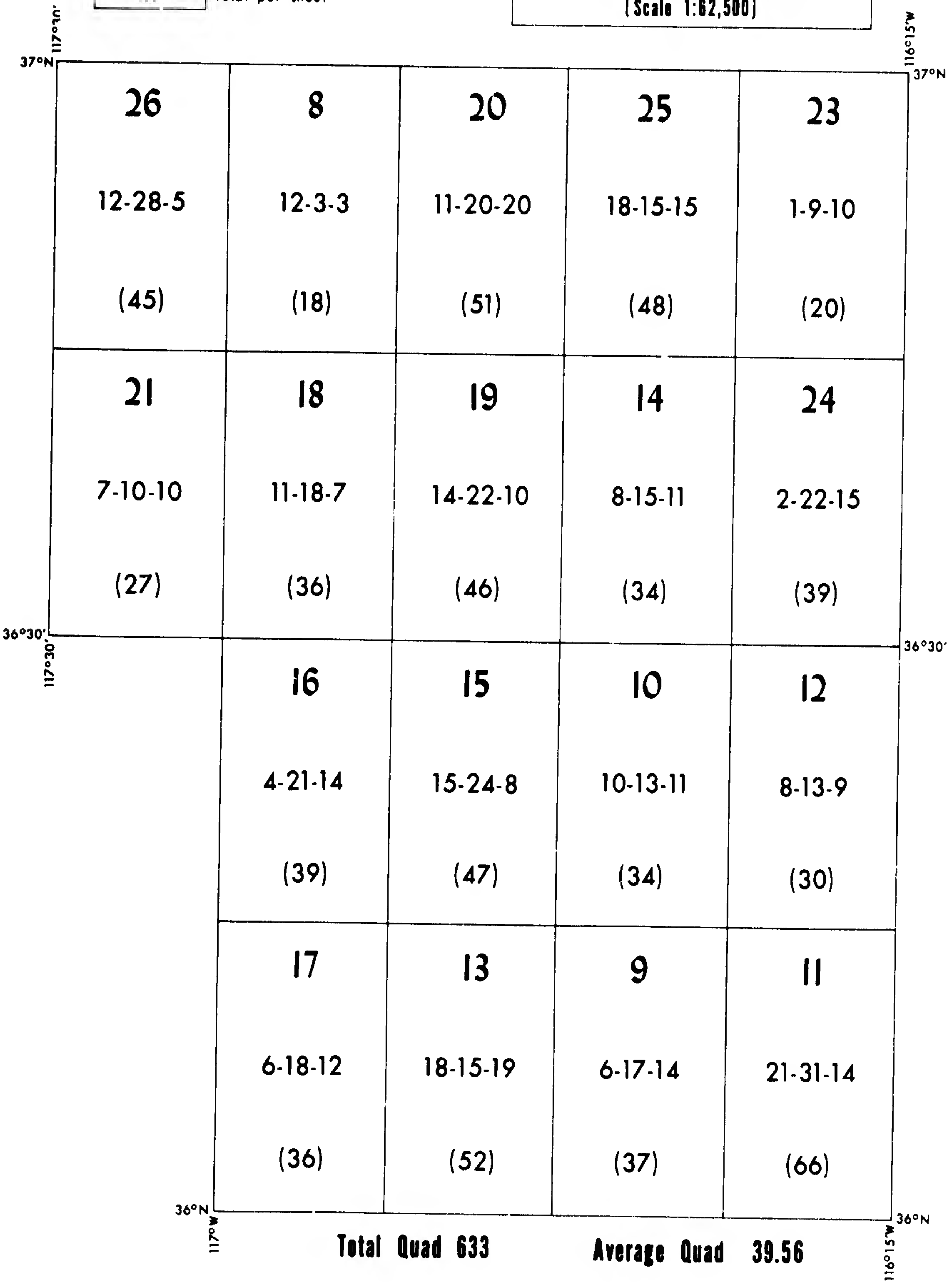
Total Quad 1011 **Average Quad 63**

Figure 4a

NUMBER OF ALLUVIAL FANS, BASIN AND RANGES REGION

Lists of Topographic Sheets
(Scale 1:62,500)

00 — Sheet Number
00-00-00 — Large fan total 3500'; Middle fan total 1700'-3500'; Small fan total 1700'
(00) — Total per sheet



26 12-28-5 (45)	8 12-3-3 (18)	20 11-20-20 (51)	25 18-15-15 (48)	23 1-9-10 (20)
21 7-10-10 (27)	18 11-18-7 (36)	19 14-22-10 (46)	14 8-15-11 (34)	24 2-22-15 (39)
	16 4-21-14 (39)	15 15-24-8 (47)	10 10-13-11 (34)	12 8-13-9 (30)
	17 6-18-12 (36)	13 18-15-19 (52)	9 6-17-14 (37)	11 21-31-14 (66)

Total Quad 633 **Average Quad 39.56**

Figure 4b

00 — Sheet Number
Large fan total 3500'
Middle fan total 1700'-3500'
00-00-00 — Small fan total 1700'
(00) — Total per sheet

NUMBER OF ALLUVIAL FANS, BASIN AND RANGES REGION

Lists of Topographic Sheets
(Scale 1:62,500)

116°W 35°N — 115°W 35°N

35 15-22-10 (47)	36 16-12-6 (34)	37 13-13-3 (29)	38 13-23-6 (42)
39 12-23-21 (56)	40 11-23-21 (55)	41 16-16-26 (58)	42 10-10-5 (25)
43 15-36-30 (81)	44 8-23-10 (41)	45 9-11-9 (29)	46 10-10-14 (34)
47 16-9-21 (46)	48 13-21-10 (44)	49 8-5-14 (27)	50 10-14-9 (33)

34°N 116°W — 34°N 115°W

Total Quad 681 **Average Quad 42.5**

Figure 4c

00 — Sheet Number
Large fan total 3500'
Middle fan total 1700'-3500'
00-00-00 — Small fan total 1700'
(00 — Total per sheet

NUMBER OF ALLUVIAL FANS, BASIN AND RANGES REGION

Lists of Topographic Sheets
(Scale 1:62,500)

120°W 40°N — 119°W 40°N

51 16-26-20 (62)	52 13-29-25 (67)	53 18-25-21 (64)	54 23-26-25 (74)
55 19-20-31 (70)	56 13-31-11 (55)	57 12-17-10 (39)	58 26-20-6 (52)
59 14-11-12 (37)	60 10-12-11 (33)	61 18-26-14 (58)	62 11-21-6 (38)
63 6-14-5 (25)	64 7-13-14 (34)	65 15-22-12 (49)	66 12-15-6 (33)

39°N 120°W — 39°N 119°W

Total Quad 790 **Average Quad 49.3**

Figure 4d

00 — Sheet Number
00-00-00 — Large fan total 3500' / Middle fan total 1700'-3500' / Small fan total 1700'
(00) — Total per sheet

NUMBER OF ALLUVIAL FANS, BASIN AND RANGES REGION

Lists of Topographic Sheets
(Scale 1:62,500)

116°45'W 40°45'N — 115°45'W 40°45'N

67 10-30-27 (67)	89 11-31-5 (47)	69 2-27-10 (39)	70 6-12-8 (26)
71 21-9-4 (34)	72 29-30-20 (79)	73 9-18-3 (30)	74 8-4-6 (18)
75 20-22-9 (51)	76 15-12-10 (37)	77 17-4-3 (24)	78 17-23-5 (45)
79 15-12-18 (45)	80 12-18 7 (37)	81 14-27-16 (57)	82 16-17-20 (53)

39°45'N 6°45'W — 39°45'N 115°45'W

Total Quad 686 **Average Quad 42.8**

Figure 4e

RADII AND GRADIENT RELATIONSHIPS OF ALLUVIAL FANS IN RANDOM SAMPLES

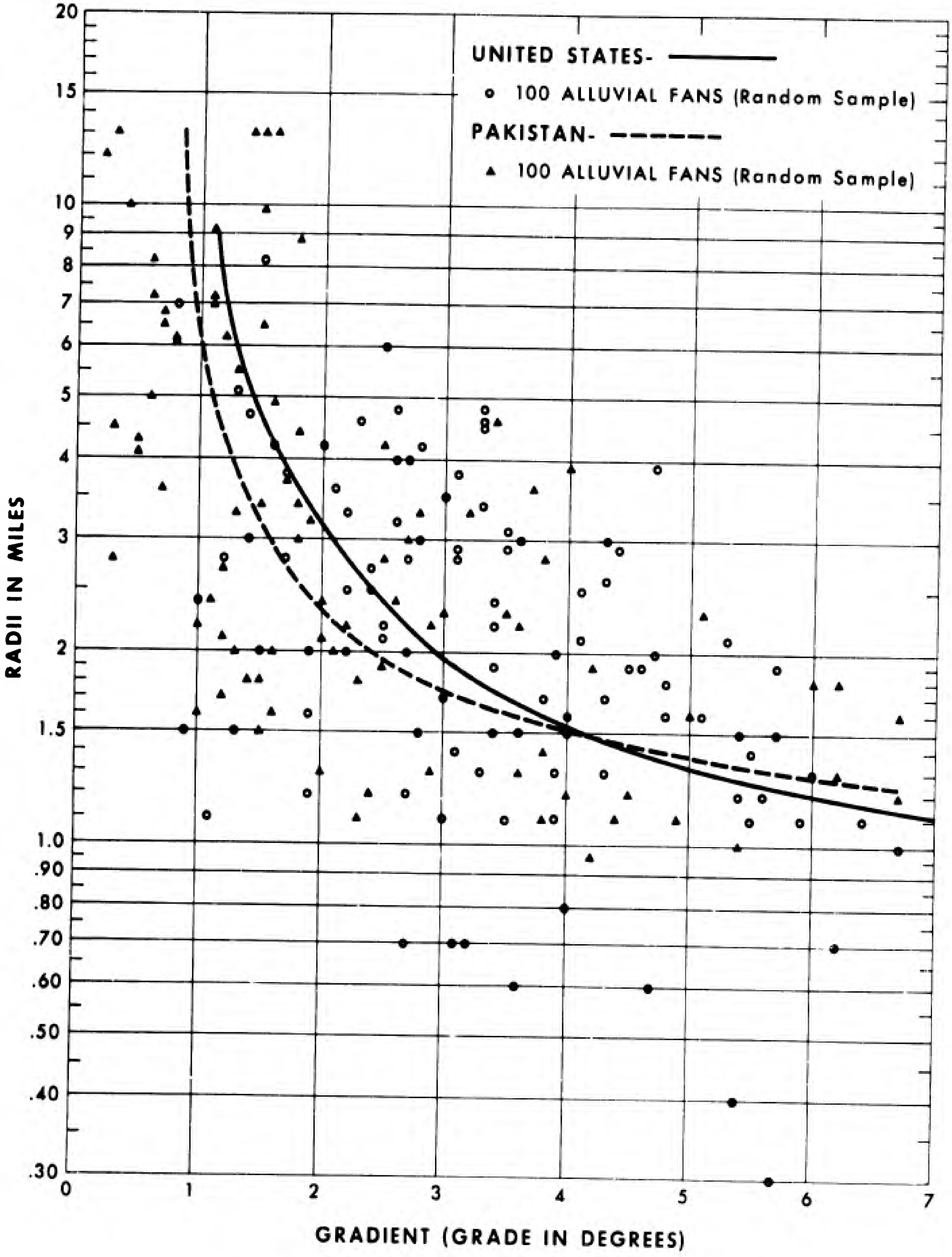


Figure 5

COMPARATIVE SLOPE GRADIENTS

ALLUVIAL FANS AND BACKWASTING SLOPES

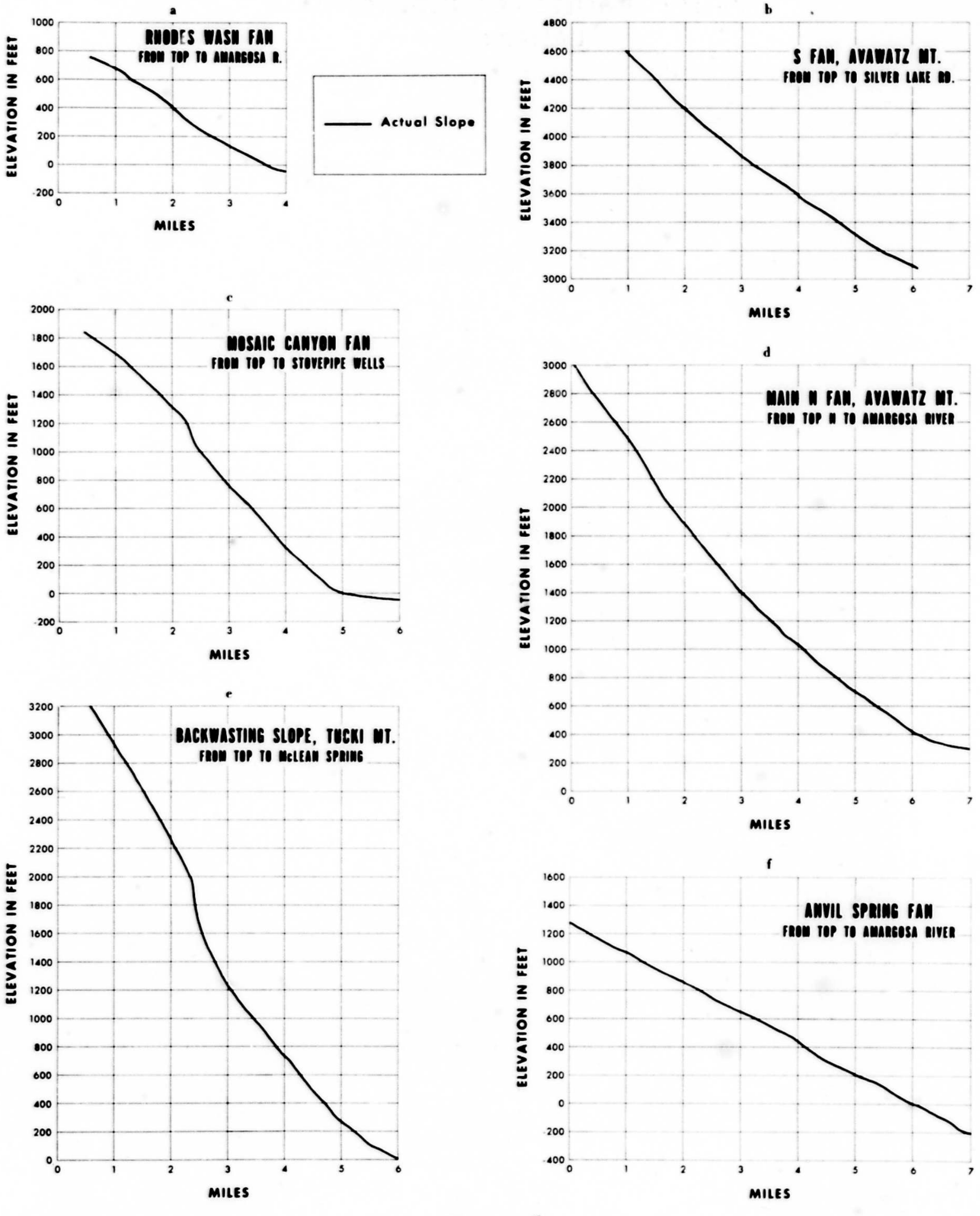


Figure 6

VALLEY PROFILES - CONFIDENCE WASH
CALIFORNIA

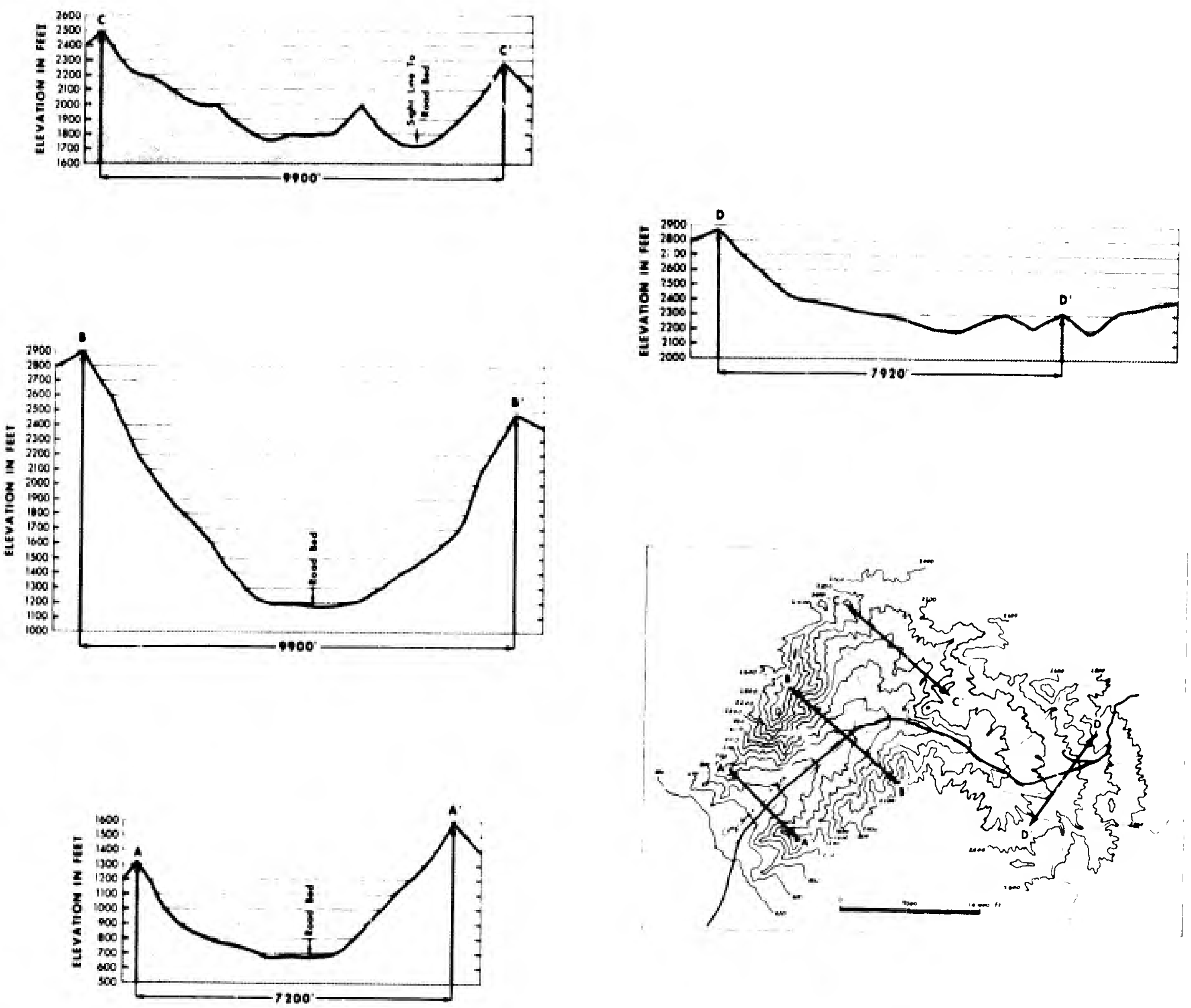


Figure 7

ALLUVIAL FANS
RADII AND GRADIENT FREQUENCY OF INCIDENCE

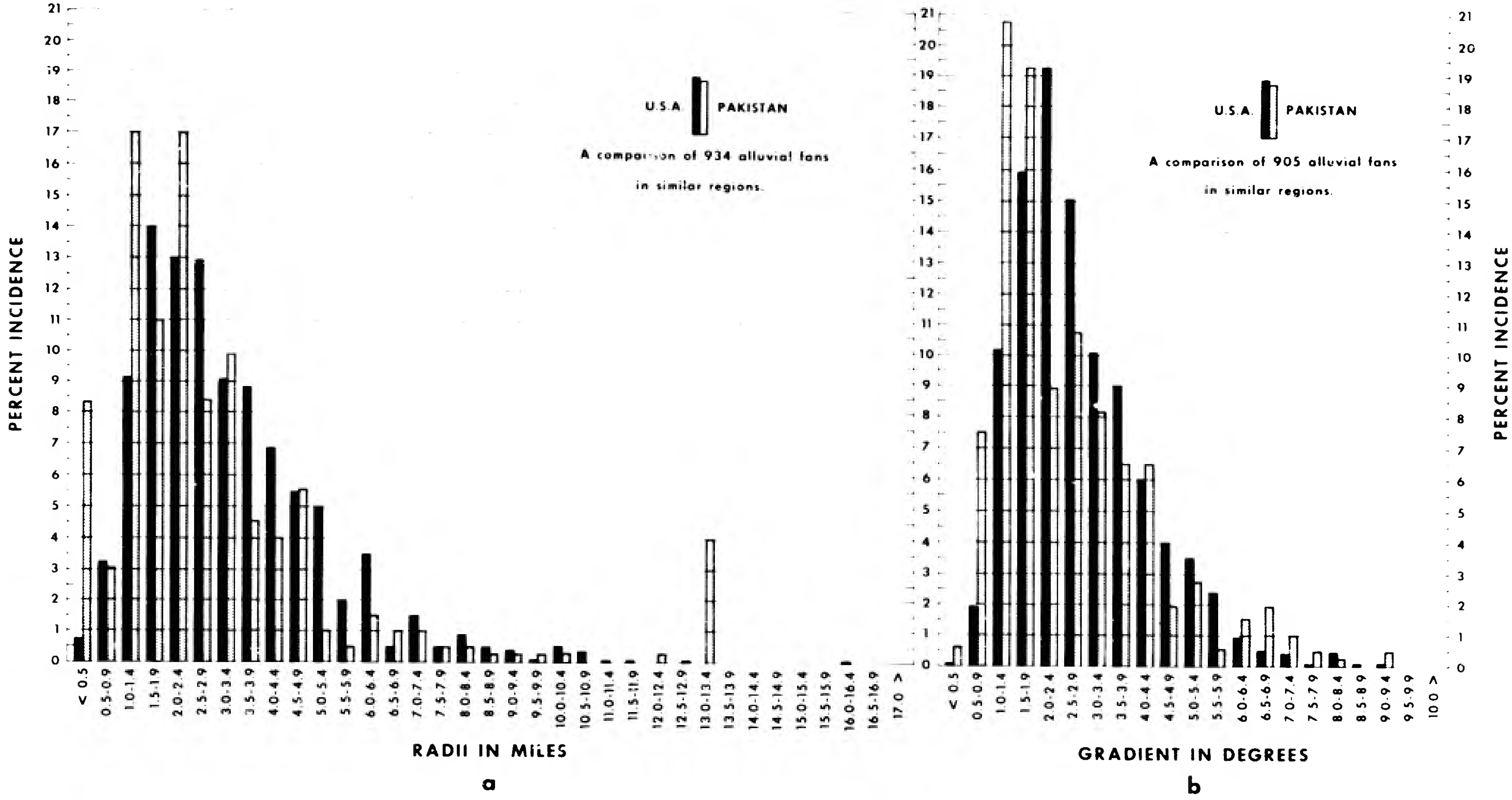


Figure 8

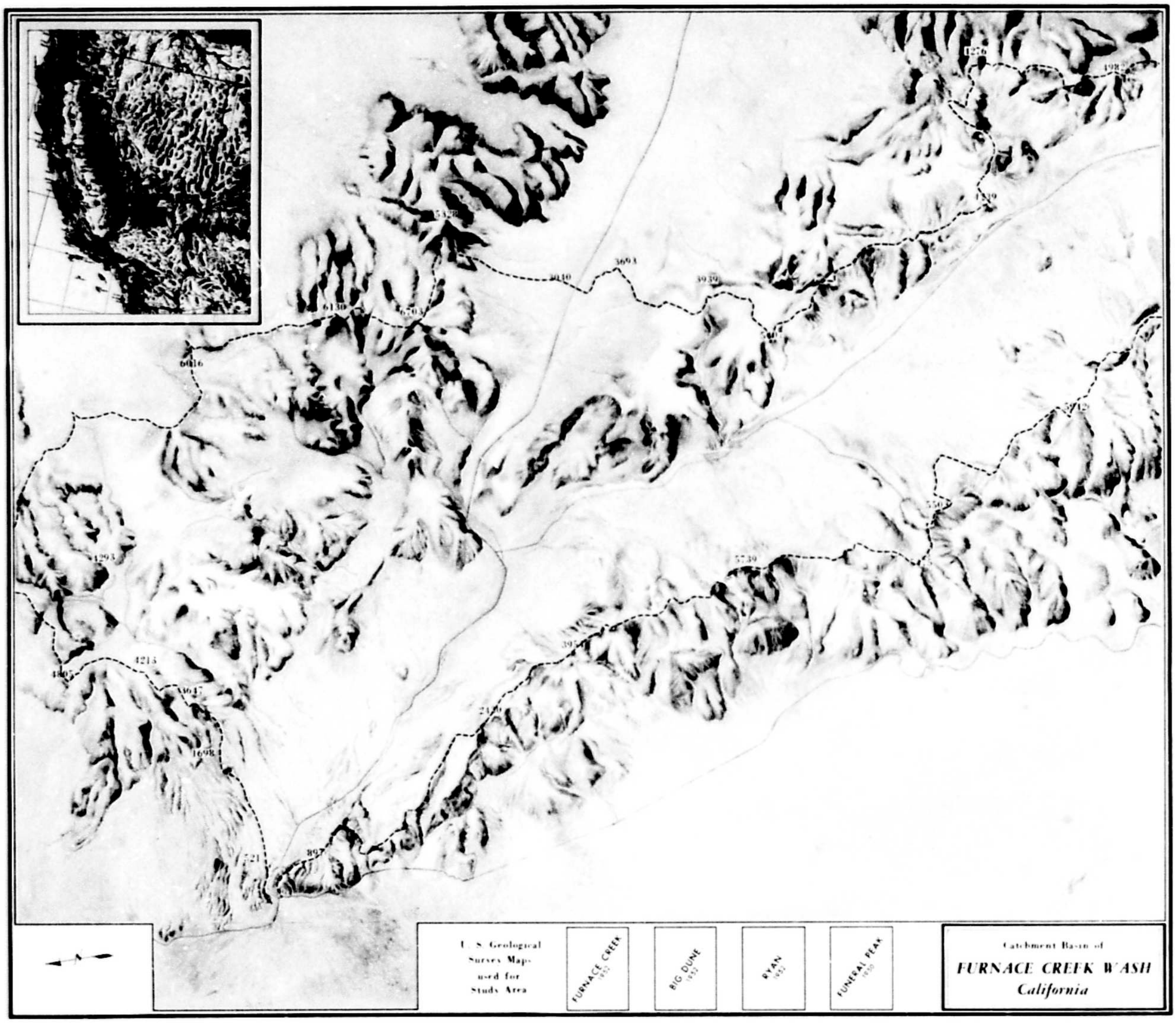

5328
3693
3939
6130
6703
6016
4293
4215
3647
1698
721
897
5739
5712
1276
U. S. Geological
Survey Maps
used for
Study Area
FURNACE CREEK
1952
BIG DUNE
1952
RYAN
1952
FUNERAL PEAK
1950
Catchment Basin of
FURNACE CREEK WASH
California

Figure 9a

Catchment Basin - Fall Canyon

Figure 9b

Catchment Basin - Sheep Canyon

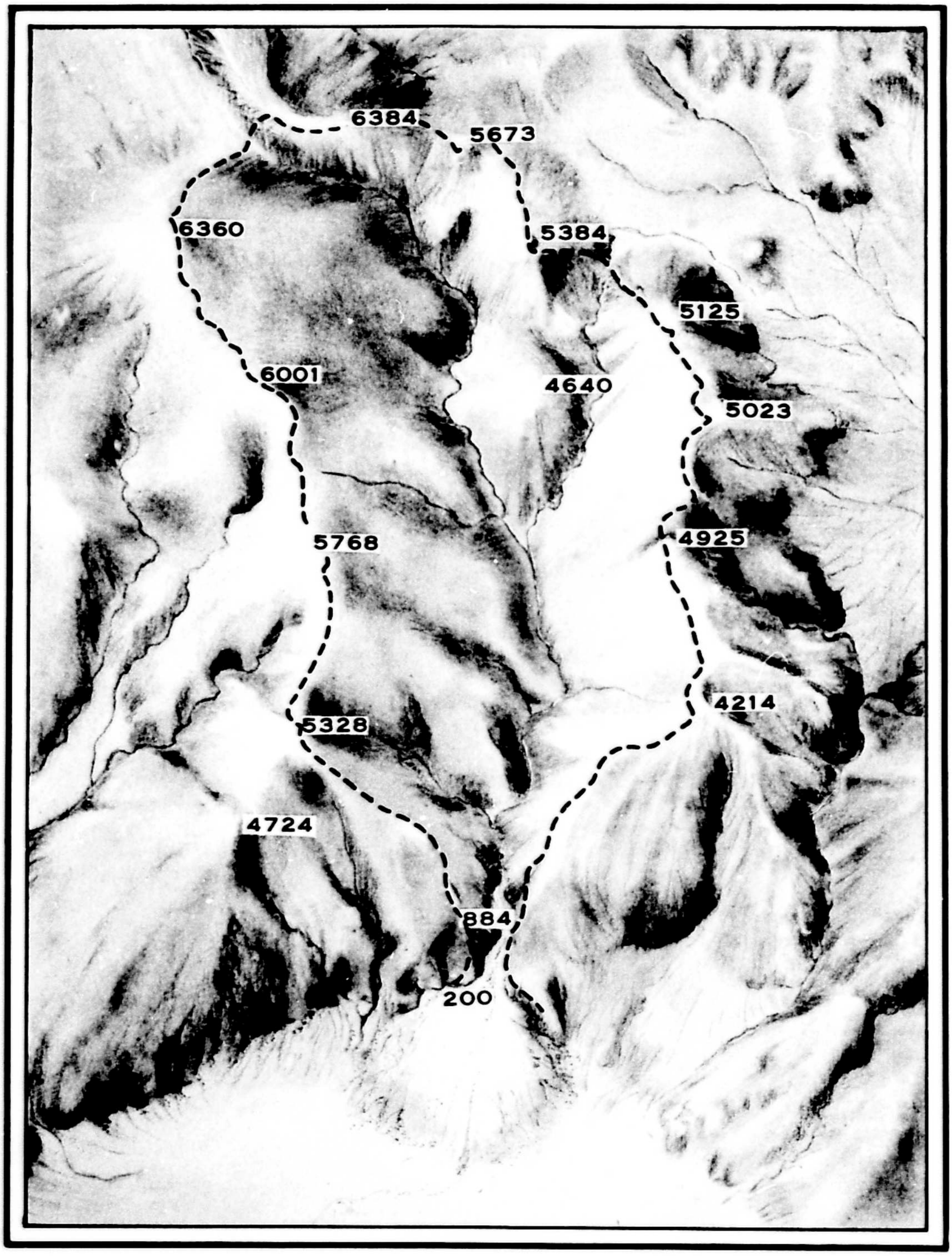


Figure 10a

Catchment Basin - Gold Valley

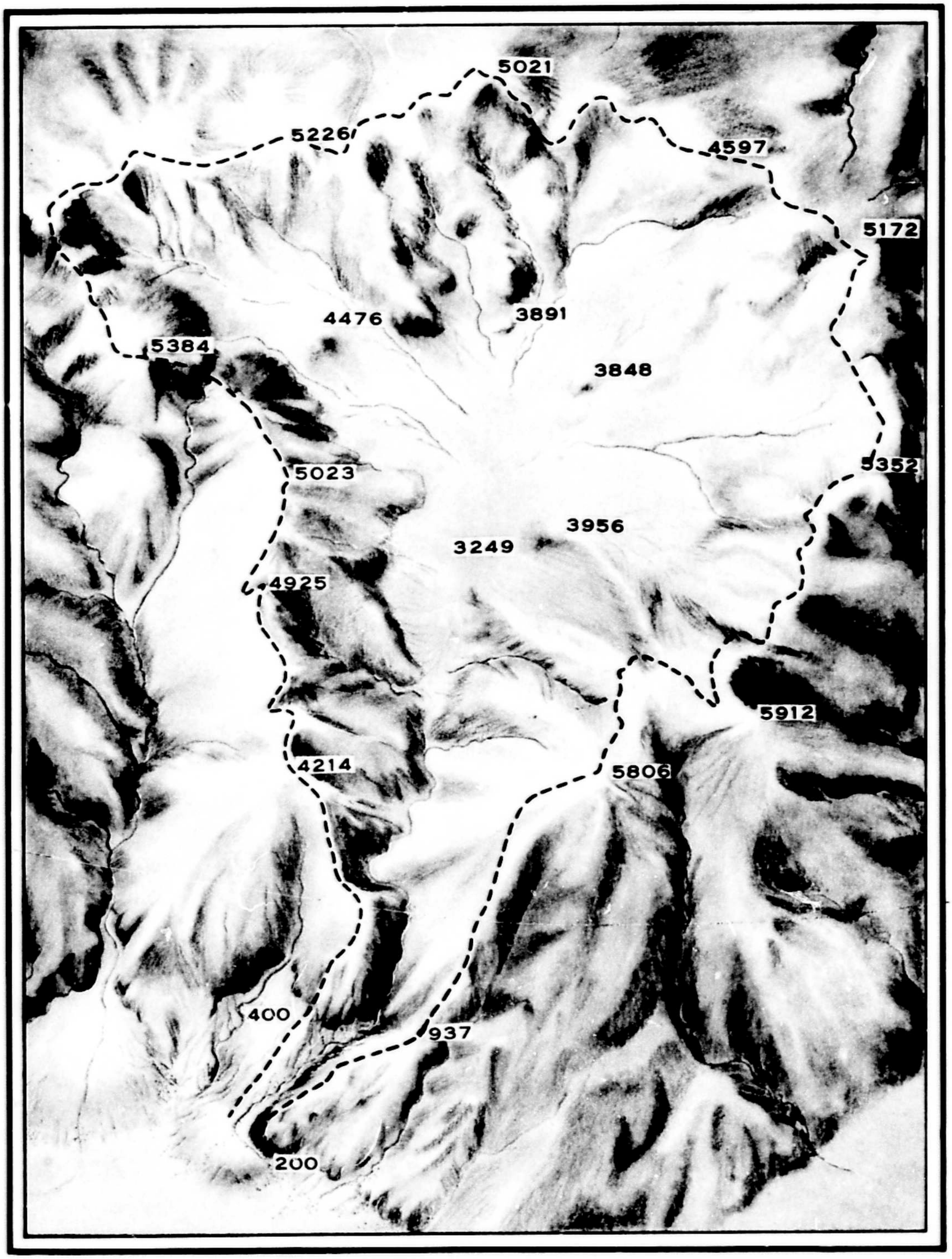


Figure 10b

Catchment Basin - Red Wall Canyon

Figure 11a

Catchment Basin - Confidence Wash

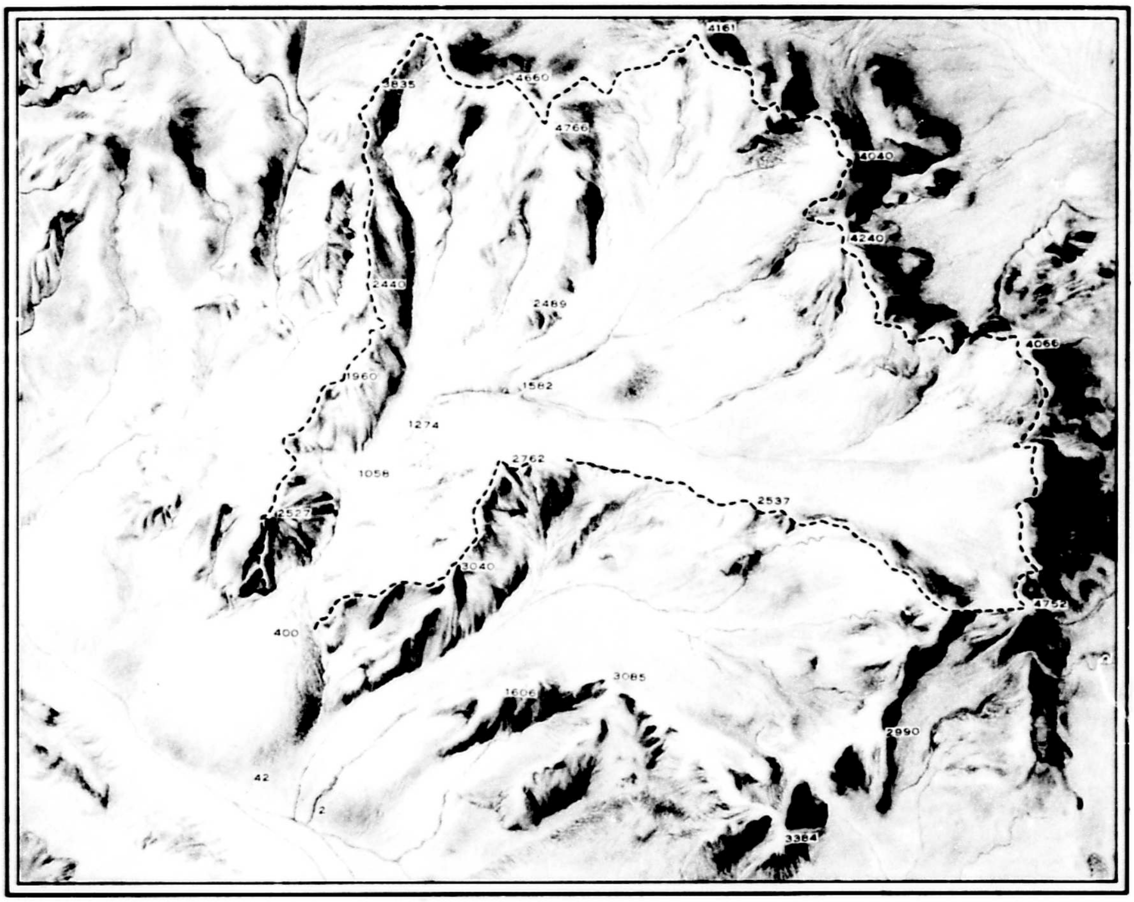


Figure 11b

Catchment Basin - Rhodes Wash

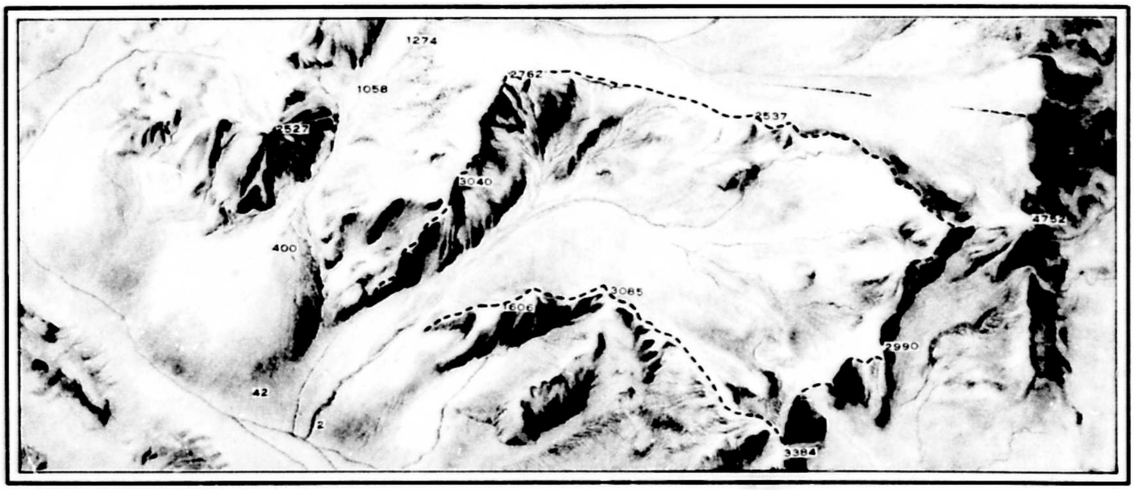


Figure 11c

Catchment Basin - Mosaic Canyon

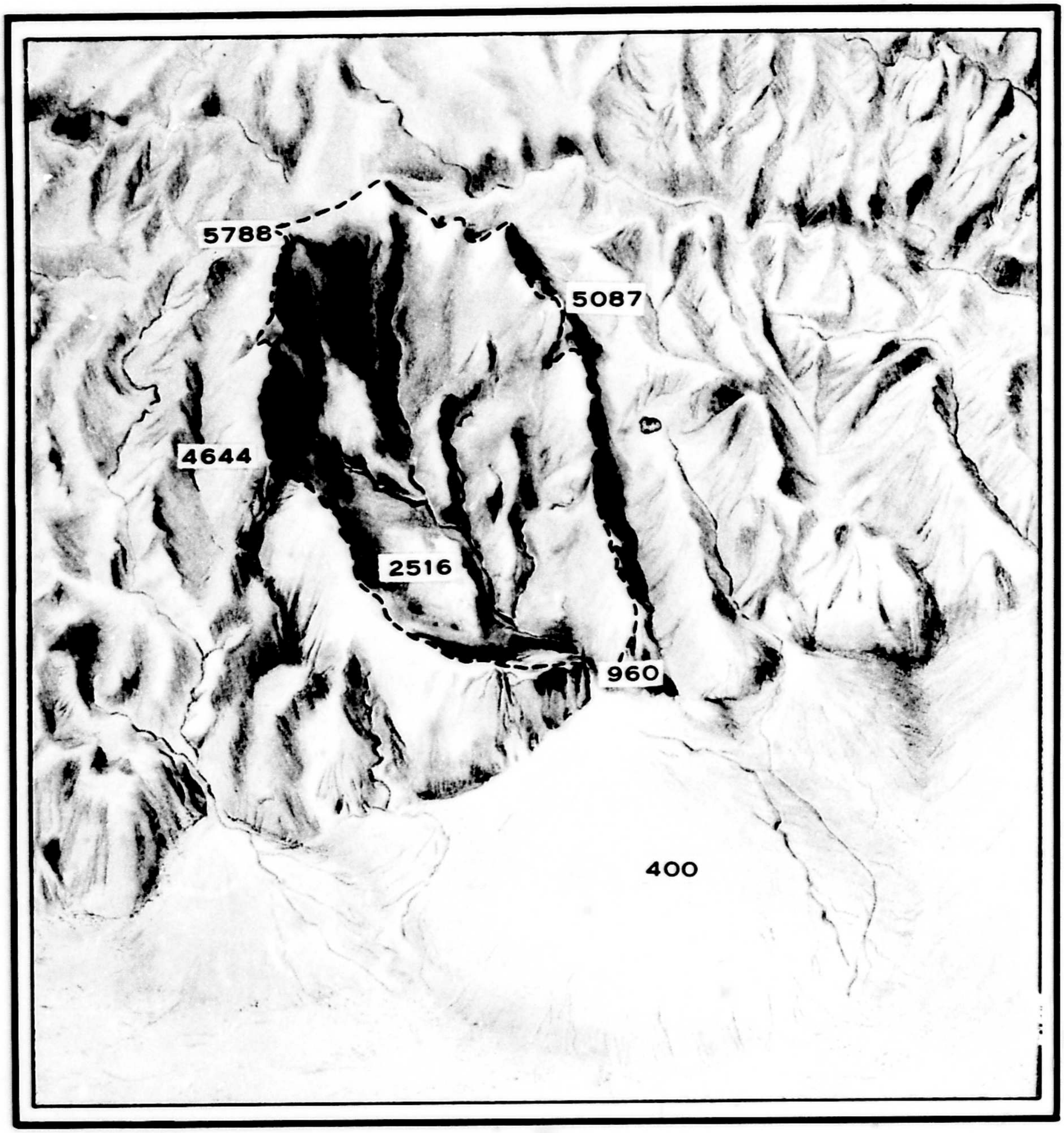
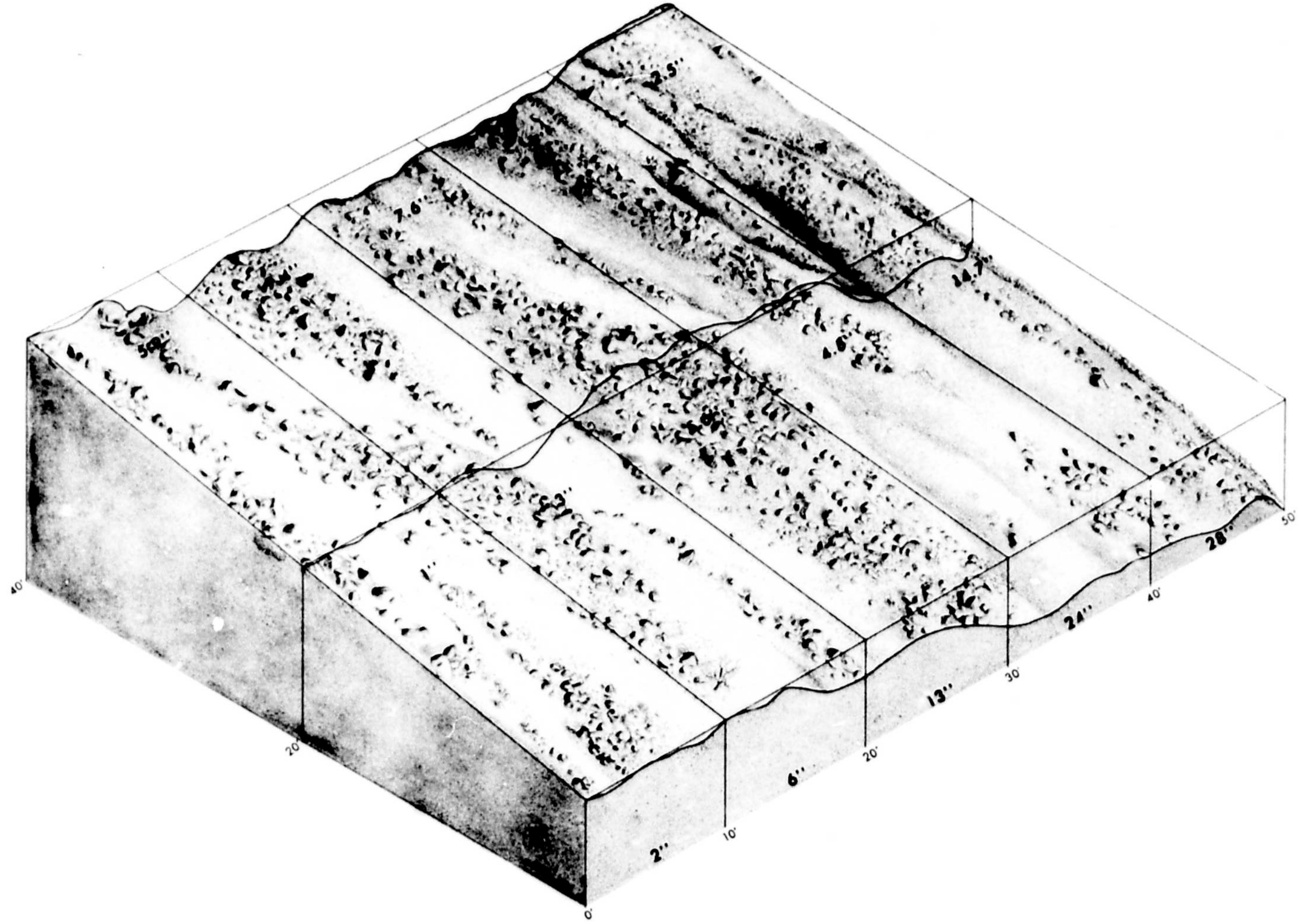


Figure 11d

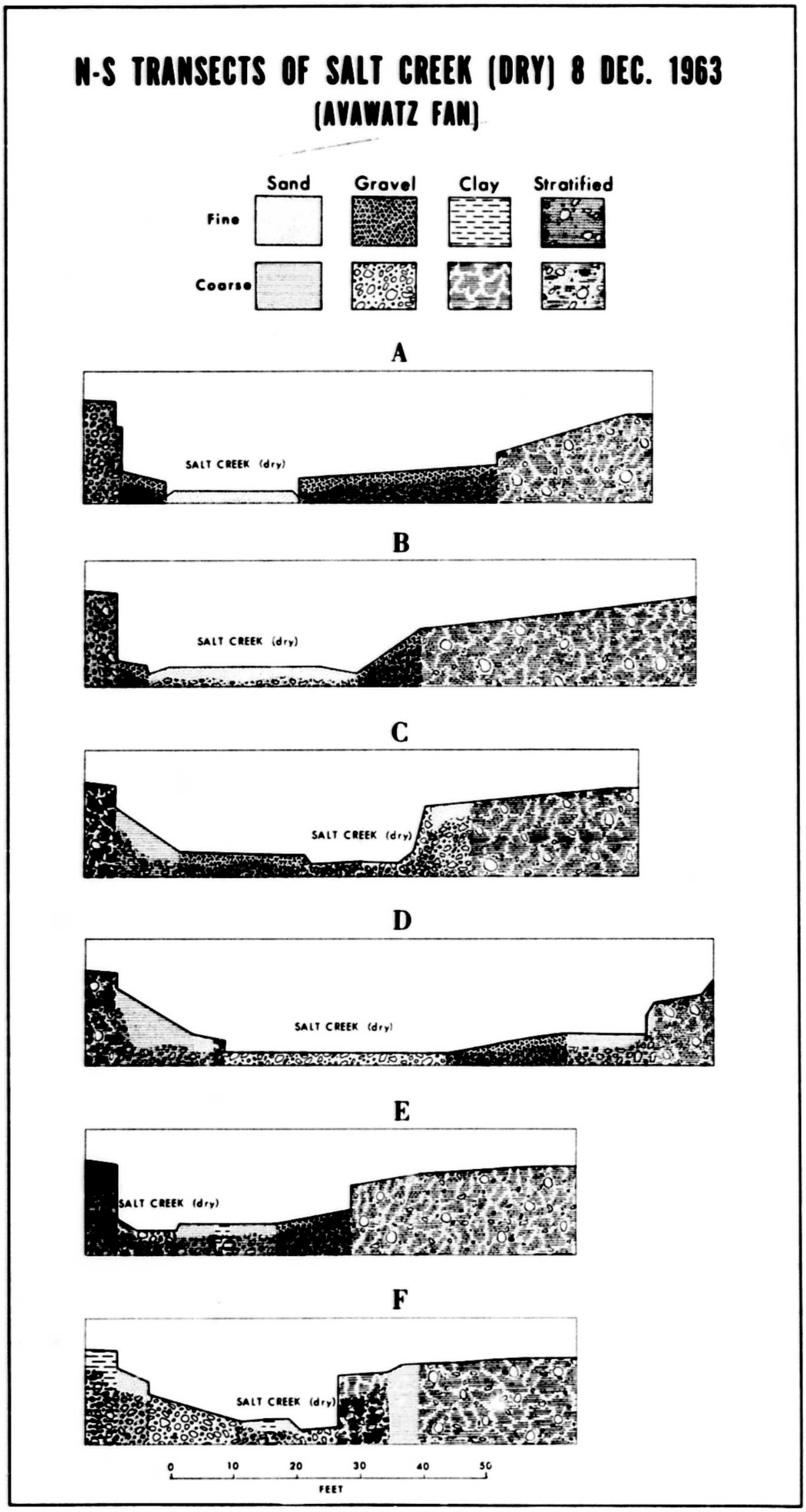
Microgeometry of a Portion of Grotto Canyon Fan



Minor Distributaries on Three Parallel Transects Ten Feet Apart and Fifty Feet in Length

Average relief shown in inches for each 10 foot interval

Figure 12



N-S TRANSECTS OF SALT CREEK (DRY) 8 DEC. 1963 (AVAWATZ FAN)

Figure 13

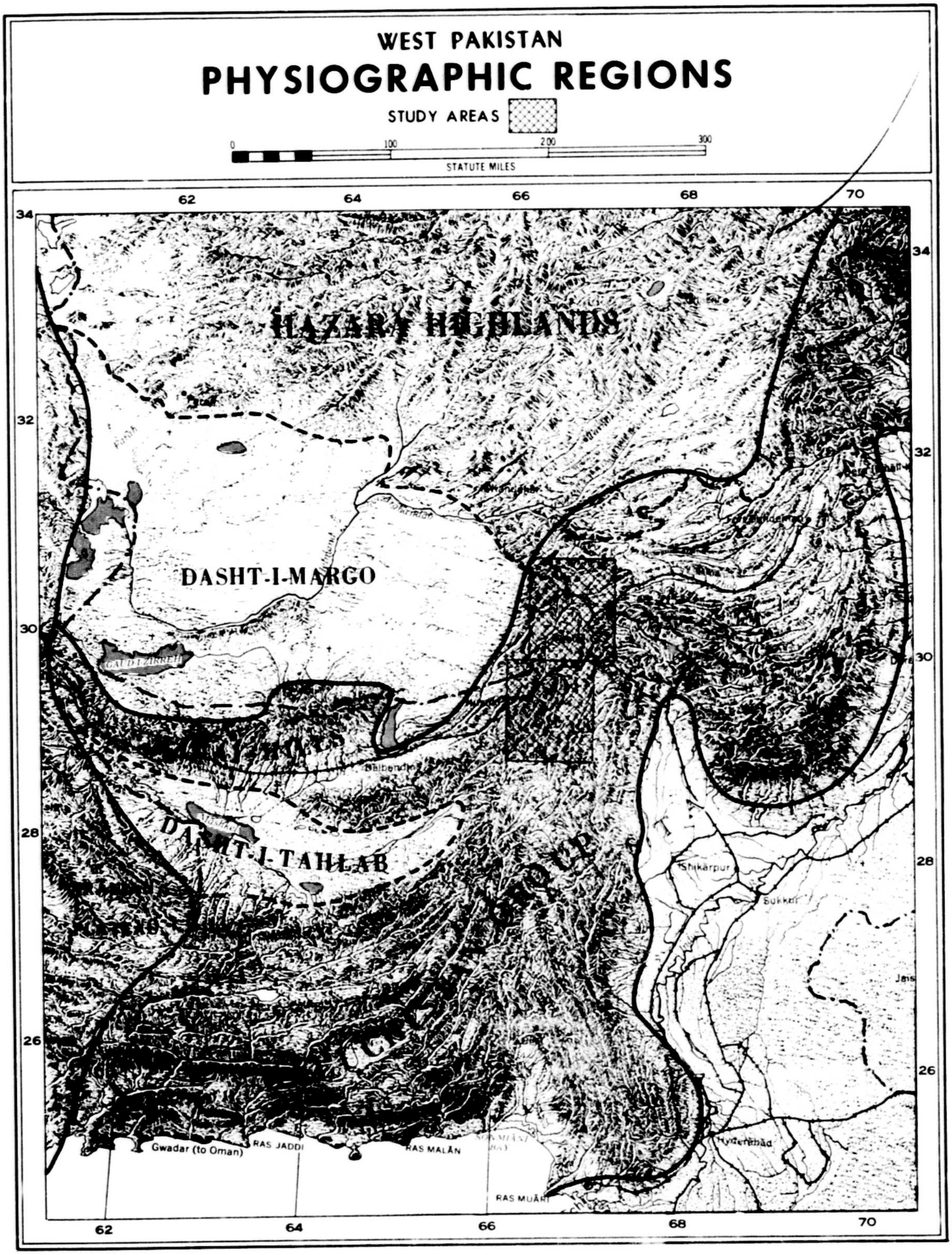

WEST PAKISTAN
PHYSIOGRAPHIC REGIONS
STUDY AREAS
0
100
200
300
STATUTE MILES
62
64
66
68
70
34
32
30
28
26
HAZARA HIGHLANDS
DASHT-I-MARGO
GAUD-I-ZIRREH
Dalbandin
DASHT-I-TAHLAB
Shikārpur
Sukkur
Hyderābād
Gwadar (to Oman)
RAS JADDI
RAS MALĀN
RAS MUĀRI

Figure 14

BLANK PAGE

00 — Sheet number

(00) — Total per sheet

NUMBER OF ALLUVIAL FANS BALUCHISTAN GROUP

30°N 66°E — 67°E 30°N

K-1 (7)	K-5 (3)	K-9 (17)	K-13 (22)
K-2 (10)	K-6 (10)	K-10 (38)	K-14 (12)
K-3 (3)	K-7 (11)	K-11 (23)	K-15 (5)
K-4 (0)	K-8 (17)	K-12 (14)	K-16 (6)

29°N 66°E — 67°E 29°N

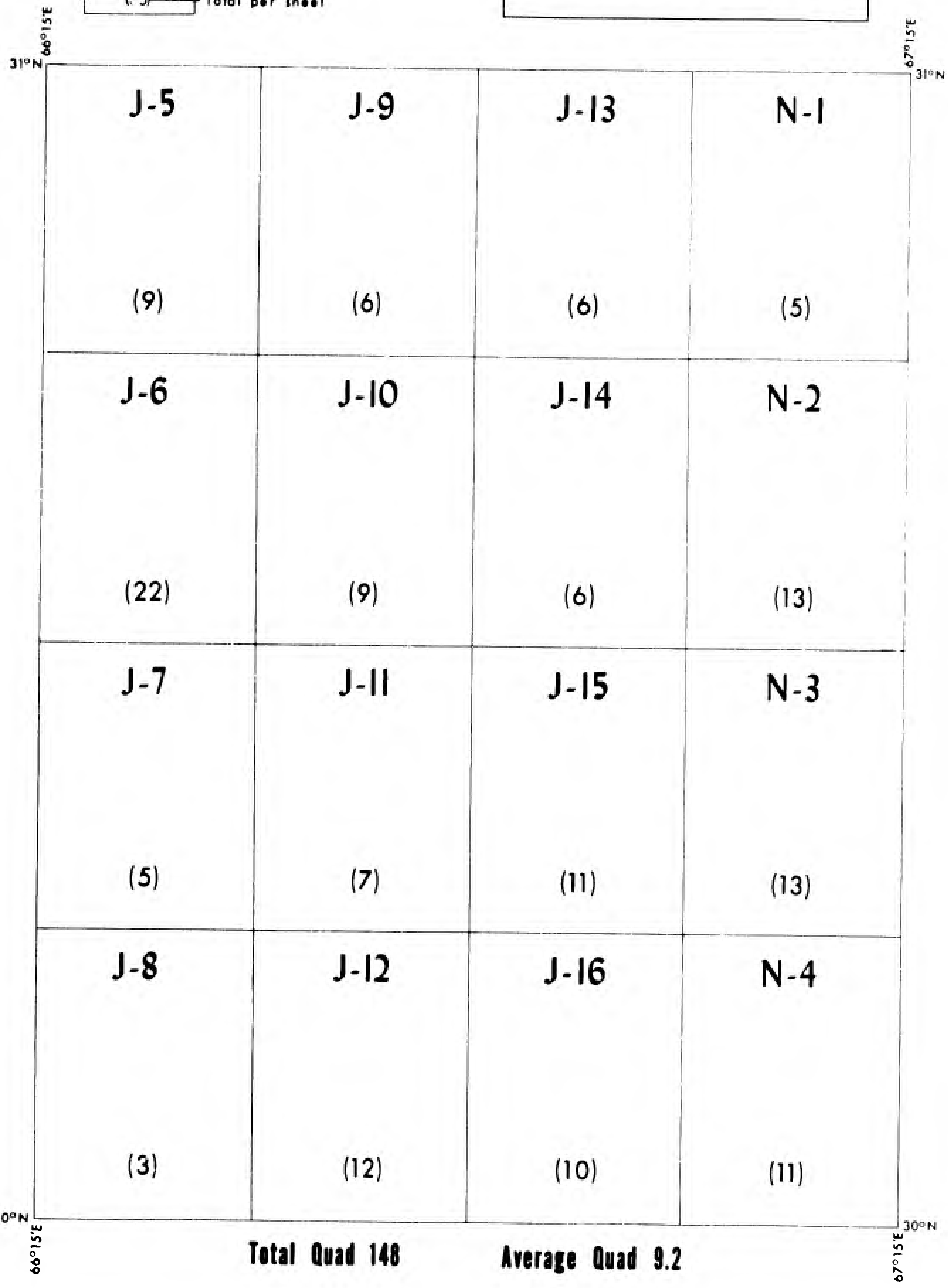
Total Quad 19 **Average Quad 12.38**

Figure 15a

00 — Sheet number

(00) — Total per sheet

NUMBER OF ALLUVIAL FANS
BALUCHISTAN GROUP

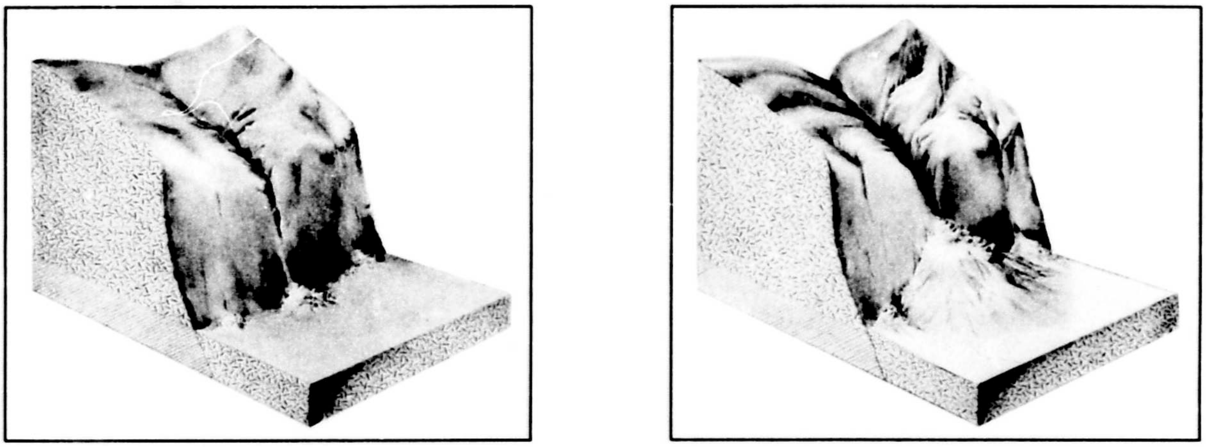


J-5 (9)	J-9 (6)	J-13 (6)	N-1 (5)
J-6 (22)	J-10 (9)	J-14 (6)	N-2 (13)
J-7 (5)	J-11 (7)	J-15 (11)	N-3 (13)
J-8 (3)	J-12 (12)	J-16 (10)	N-4 (11)

Total Quad 148 **Average Quad 9.2**

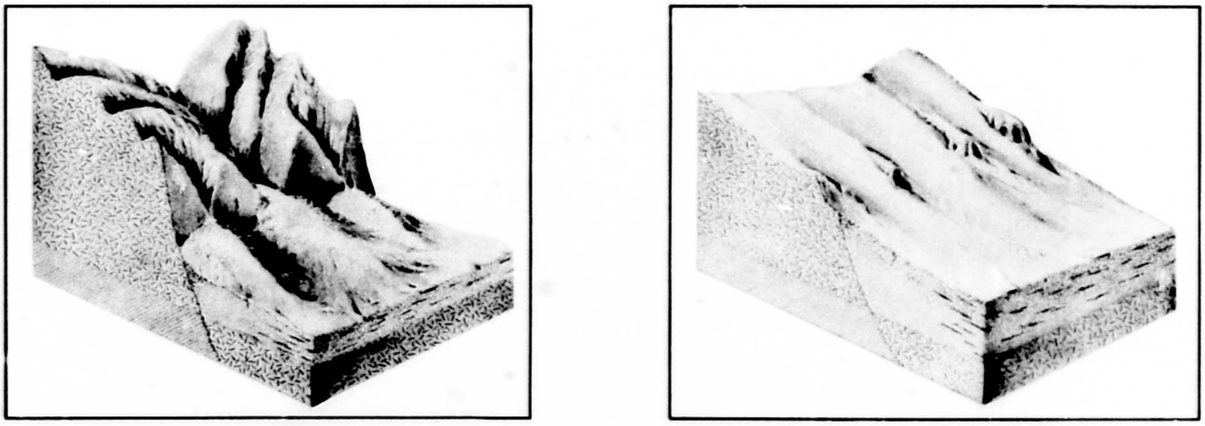
Figure 15b

BLOCK DIAGRAMS OF ALLUVIAL FAN SEQUENCE MORPHOLOGY



a. New Talus Cone

b. Initial Development of Fan



c. Initial Coalescence of Fans

d. Old Coalesced Fan

Figure 16

BLANK PAGE

Figure 17. Fanhead trench at mouth of Corkscrew Canyon. Note the stratification of the diluvial beds which stand as remnants on either side of the present trench. The age of recent erosion can be appreciated by the size of the vegetation on the floor of the wash.

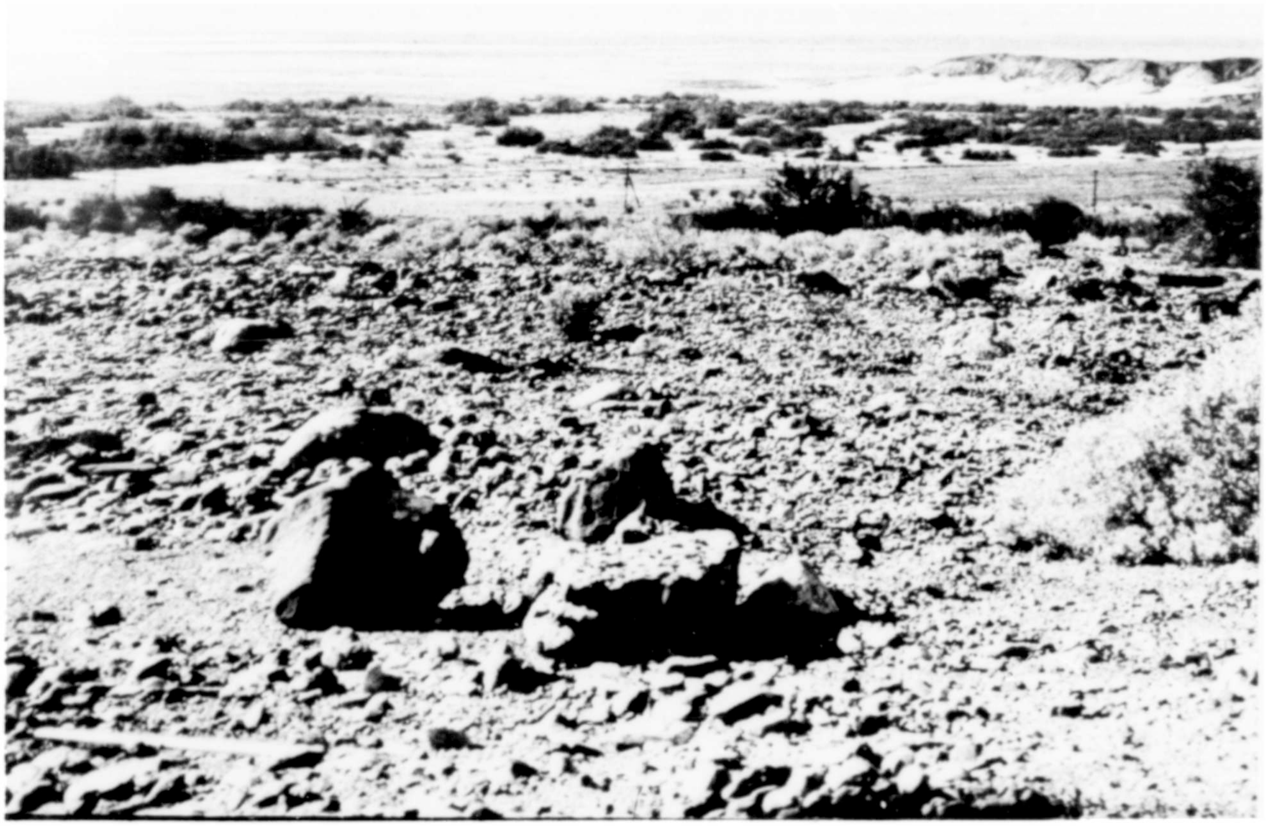


Figure 18. Boulders transported by flood water on the alluvial fan near Furnace Creek. Note the fresh appearance of the vegetation at the base of the fan.

Figure 19. Litter-strewn flood wash near the hangar at Furnace Creek Airport. The light colored streaks are clay deposits.

Figure 20. Clay wash on the alluvial fan near Furnace Creek California. This area received only a very light flood.

Figure 21. Alluvial fans near the Amargosa River at Saratoga Spring. Small alluvial fans and talus cones are shown in the lower center of this aerial photograph. A deeply dissected middle size fan is shown in the right center, and an old age coalesced fan is shown in the upper left of the photograph.

BLANK PAGE

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)*
U. S. Army Natick Laboratories

2a. REPORT SECURITY CLASSIFICATION
Unclassified

2b. GROUP

3. REPORT TITLE
PHYSICAL CHARACTERISTICS OF ALLUVIAL FANS

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

5. AUTHOR(S) *(Last name, first name, initial)*
ANSTEY, ROBERT L.

6. REPORT DATE
December 1965

7a. TOTAL NO. OF PAGES
109

7b. NO. OF REFS
46

8a. CONTRACT OR GRANT NO.

b. PROJECT NO.
1L013001A91A

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)
ES-20

9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10. AVAILABILITY/LIMITATION NOTICES
Distribution of this document is unlimited.
Release to CFSTI is authorized.

11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY
Earth Sciences Division
U.S. Army Natick Laboratories
Natick, Massachusetts

13. ABSTRACT

In this study a new technique is developed for analyzing available world maps and aerial photographs in terms of frequency of occurrence of terrain obstacles as related to capabilities of various types of military vehicles. Employing this technique, an areal quantification of the geometry of alluvial fans was completed for a total of seven 1-degree quadrangles (1 degree Latitude x 1 degree Longitude) of representative desert terrain in the United States and West Pakistan.

The greatest development of alluvial fans is associated with mountainous desert regions having wide valleys. Alluvial fans are not related to high mountainous areas or to areas where the mountain mass has been deeply dissected by steep, narrow valleys. Within desert regions it was noted that landform data in one physiographic province were very similar to those in the same type of province (such as a golded-faulted type) and climate elsewhere. Except for similar provinces the agreement was not close.

Approximately 70 percent of all alluvial fans studied were 1 to 5 miles in length and had total slope gradients of 1 to 5 degrees. Gradients up to 600 feet per mile have been measured on the upper slopes of small alluvial fans. Nearly all alluvial fans have deep washes with vertical walls which may be located near their apices or their aprons.

DD FORM 1 JAN 64 1473

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Measurement	8		8			
Area	8					
Geometry	8					
Surfaces	8					
Terrain	9		8			
Deserts	9		9			
Analysis	10					
Maps	10					
Aerial photographs	10					
Armed Forces transportation	4					
Tables			8			
United States			9			
Pakistan			9			

INSTRUCTIONS

1. **ORIGINATING ACTIVITY:** Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization *(corporate author)* issuing the report.

2*a*. **REPORT SECURITY CLASSIFICATION:** Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2*b*. **GROUP:** Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. **REPORT TITLE:** Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. **DESCRIPTIVE NOTES:** If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. **AUTHOR(S):** Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. **REPORT DATE:** Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7*a*. **TOTAL NUMBER OF [illegible]ES:** The total page count should follow normal pagi[illegible]n procedures, i.e., enter the number of pages containing information.

7*b*. **NUMBER OF REFERENCES:** Enter the total number of references cited in the report.

8*a*. **CONTRACT OR GRANT NUMBER:** If appropriate, enter the applicable number of the contract or grant under which the report was written.

8*b*, 8*c*, & 8*d*. **PROJECT NUMBER:** Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9*a*. **ORIGINATOR'S REPORT NUMBER(S):** Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9*b*. **OTHER REPORT NUMBER(S):** If the report has been assigned any other report numbers *(either by the originator or by the sponsor)*, also enter this number(s).

10. **AVAILABILITY/LIMITATION NOTICES:** Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through
_______________________________________."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through
_______________________________________."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through
_______________________________________."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. **SUPPLEMENTARY NOTES:** Use for additional explanatory notes.

12. **SPONSORING MILITARY ACTIVITY:** Enter the name of the departmental project office or laboratory sponsoring *(paying for)* the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS)*, *(S)*, *(C)*, or *(U)*.

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Idenfiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.