Geomorphology of Segmented Alluvial Fans in Western Fresno County, California

GEOLOGICAL SURVEY PROFESSIONAL PAPER 352-E

Prepared in cooperation with the California Department of Water Resources

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By WILLIAM B. BULL

EROSION AND SEDIMENTATION IN SEMIARID ENVIRONMENT

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A study of the interrelations of alluvial-fan morphology, drainage-basin characteristics and tectonic and climatic events

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GLOSSARY

Alluvial fan, a stream deposit whose surface forms a segment of a cone that radiates downslope from the point where the stream channel emerges from a mountainous area.

Apex, the highest point on an alluvial fan, generally where the stream emerges from the mountain front (Drew, 1873, p. 447).

Braided distributary channels, secondary channels that extend downslope from the end of the main stream channel or fanhead trench and are characterized by repeated division and rejoining.

Cross-fan profile, a topographic profile of alluvial fan(s) roughly parallel to the mountain front.

Drainage basin, the area drained by a stream upstream from the fan apex.

Ephemeral stream, a stream, or part of a stream, that flows only briefly in direct response to precipitation.

Fanhead trench, a stream channel entrenched into the upper, and possibly the middle, part of the fan.

Fan segment, a part of an alluvial fan that is bounded by changes in slope.

Intermittent stream, a stream, or part of a stream, that flows only part of the time because it receives water from seasonal sources such as springs and bank storage, as well as from precipitation.

Piedmont plain, a broad sloping plain formed by the coalescence of many alluvial fans.

Radial line, a straight line on the fan surface extending from the apex to the toe.

Radial profile, a topographic profile along a radial line.

Thalweg, the line along the deepest part of the stream channel.

EROSION AND SEDIMENTATION IN A SEMIARID ENVIRONMENT

GEOMORPHOLOGY OF SEGMENTED ALLUVIAL FANS IN WESTERN FRESNO COUNTY, CALIFORNIA

By William B. Bull

ABSTRACT

The alluvial fans fringing the western border of the San Joaquin Valley in Fresno County, Calif., are derived from drainage basins that are generally similar with respect to topography, climate, and tectonic environment but that range in size from 0.2 to 296 square miles and in lithology from predominantly sandstone to predominantly mudstone or shale. Fans derived from mudstone or shale-rich basins are generally 35–75 percent steeper than fans of similar area derived from sandstone-rich basins and roughly twice as large as fans derived from sandstone basins of comparable size.

The radial profiles of the fans are not smooth curves, but, instead, comprise three or four straight-line segments. The surfaces represented by these segments form bands of approximately uniform slope that are, mainly, concentric about the fan apexes. Longitudinal profiles of terraces show that intermittent uplift has changed the stream-channel slope upstream from the fan apexes. The slope of the area of deposition and the slope of the stream channel upstream from it tend to be the same. The segmentation is a result of intermittent uplift that has changed the stream-channel slopes and the succeeding depositional slopes.

Most of the fans are associated with stream channels that have become progressively steeper. Each time the channel was steepened, the succeeding fan deposits formed a new fan-shaped segment of steeper slope that was deposited on the upper part of the pre-existing fan.

The Little Panoche Creek fan, however, has a history that is associated with progressively gentler stream-channel gradients, because the rate of downcutting by the stream has exceeded the average rate of uplift of the reach immediately upstream from the apex. The intermittent character of the uplift resulted in the cutting of a series of paired terraces which preserve a record of the deformation of the mountain front and fan-head areas. With each uplift, the end of the deepened stream channel moved farther down the fan. After each episode of trenching, the lower part of the stream channel and its adjacent area of fan deposition ultimately attained a more gentle gradient than previously.

Fan segmentation is useful for deciphering part of the tectonic history of the area because the fan profiles and the relative ages of the fan segments reflect part of the erosional and tectonic history of the drainage basins.

Two periods of fanhead trenching, apparently unrelated to tectonic activity, have been recorded since 1854 when many fans were receiving deposits near their apexes. One was from about 1875 to 1895 and the other from about 1935 to 1945. Many channels have been deepened 25–40 feet.

Rainfall data from five stations in central California show two periods of much greater than average annual rainfall, which were also periods of high frequency of large daily rainfall. They coincide with the two periods of maximum channel trenching.

INTRODUCTION

PURPOSE AND SCOPE

Alluvial fans are common in the arid and semiarid areas of the world. Ground water in many parts of the Western States is pumped from alluvial-fan deposits and recharge of many ground-water basins is through the alluvial-fan deposits that fringe the basins. Despite the importance of alluvial fans, little detailed work has been done on their sedimentary and geomorphic characteristics until recently.

This report presents data on the geomorphology of alluvial fans collected as part of an investigation of the geology of alluvial fans and their drainage basins in western Fresno County, Calif. The primary purpose of the investigation was to obtain a better understanding of the alluvial fans and their drainage basins so that the causes, magnitude, rate, and duration of near-surface subsidence could be understood better. The sedimentary features of the alluvial-fan deposits and the geomorphic and lithologic characteristics of their drainage basins are described in detail elsewhere (Bull, 1964).

The geomorphology study provided information concerning deposition and erosion of the fans. This information is reported separately in this paper because it did not reveal many criteria that could be used in appraisal of subsidence.

The relations of fan size and slope to drainage-basin area and lithology were studied. The overall shape of the alluvial fans was studied by means of radial and cross-fan profiles, and the different types of stream channels are described. Reasons for the characteristc fan shapes and the history and causes of channel trenching that occurred during the last century are discussed.

The maps used in the study include the following: General Land Office plats and survey notes of 1853–58 and 1879–81; U.S. Geological Survey 7½ minute quadrangles, 1922–31, scale 1:31,680, contour intervals 5 and 25 feet; and U.S. Geological Survey 7½ minute quadrangles, 1955–56, scale 1:24,000, contour intervals 5, 10, 20, and 40 feet.

The investigation was made under the supervision of J. F. Poland, research geologist of the Ground Water Branch, U.S. Geological Survey, in charge of land-subsidence investigations in California, and in co-Resources.

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operation with the California Department of Water

S. N. Davis and G. A. Thompson of Stanford University gave advice on certain aspects of the study. Ranchers, sheepherders, farmers, and other people living in the area gave firsthand accounts of the history of channel trenching. The author also thanks his colleagues in the Geological Survey, C. S. Denny, L. A. Heindl, R. H. Meade, J. F. Poland, F. S. Riley, and W. E. Wilson, for their critical review of the manuscript.

GEOGRAPHIC SETTING

LOCATION AND TOPOGRAPHIC FEATURES

The area discussed in this paper includes about 1,400 square miles of the west side of the San Joaquin Valley and the adjacent Diablo Range in central California (fig. 53). The northern edge of the area is 10 miles south of Los Banos, and the southern boundary is the south side of the drainage basin of Domengine Creek, 12 miles north of Coalinga. The alluvial fans are in western Fresno County and in a small part of Merced County, and the drainage basins of some of the fans extend into San Benito County.

Between the flood plains of the San Joaquin River and Fresno Slough and the foothills to the southwest is a belt of coalescing alluvial fans 12–19 miles wide. The altitude at the base of this piedmont plain ranges from 130 to 175 feet, and the alluvial fans rise to altitudes of about 340–900 feet at their apexes. The slopes of the fans range from about 10 feet per mile near the base of the larger fans to about 150 feet per mile on the upper slopes of some of the smaller fans. The local relief on the fans is generally less than 5 feet, except on the upper parts where the main stream channels are incised as much as 40 feet. Erosional stream channels are not present on the fans except for minor dendritic channels on parts of some older fan surfaces bordering the Panoche Hills.

The Diablo Range in the southwestern part of the area consists of several groups of foothills fringing the San Joaquin Valley and the main range, which is generally about 10–15 miles from the western margin of the valley (pl. 6). The foothills include the Ciervo Hills, whose highest point is about 3,400 feet, and the Panoche Hills, which rise to an altitude of about 2,700 feet. The main Diablo Range has several peaks higher than 5,000 feet. Both the foothill belt and the main Diablo Range are rugged and have many steep canyons. (See pl. 6.)

Most of the geographical features mentioned in this report can be found on plate 6, and the specific drainage basins and their associated alluvial fans are outlined and identified on plate 7. The approximate boundaries of the alluvial fans were determined from aerial photographs and contour maps and by 400 gypsum content determinations. The average gypsum content of fans whose streams head in the foothill belt is five times the gypsum content of fans whose streams head in the main Diablo Range (Bull, 1964, table 12). Plate 7 also shows the section-line grid for all section references.

DRAINAGE

The drainage basins in the foothill belt are generally less than 10 miles long. The lengths of the drainage basins that head in the main Diablo Range and cross the foothill belt—Little Panoche, Panoche, and Cantua Creeks—range from 14 miles for Cantua Creek to 22 miles for Panoche Creek. Plate 7 shows how the larger basins extend around the smaller basins to drain the west side of the foothill belt. In general the streams flow toward the northeast at right angles to the trough of the San Joaquin Valley.

The streams are intermittent or ephemeral. Precipitation is too low and drainage basins are too small to support perennial streams. Little Panoche, Panoche, and Cantua Creeks are intermittent streams that receive enough ground water to flow along the entire length of their drainage basins for a few weeks after most winter rainy seasons. The channels of the ephemeral streams are always above the water table and these streams flow briefly and only in direct response to rainfall.

During the summer and autumn, reaches with flow generally alternate with dry stretches on the intermittent streams, and as the streams approach the San Joaquin Valley, they disappear. During winter floods, several hundred cubic feet per second of water may flow in these streams. Flash floods are not common on the larger streams.

The intermittent streams were described in the 1850's by the surveyors who mapped the area for the General

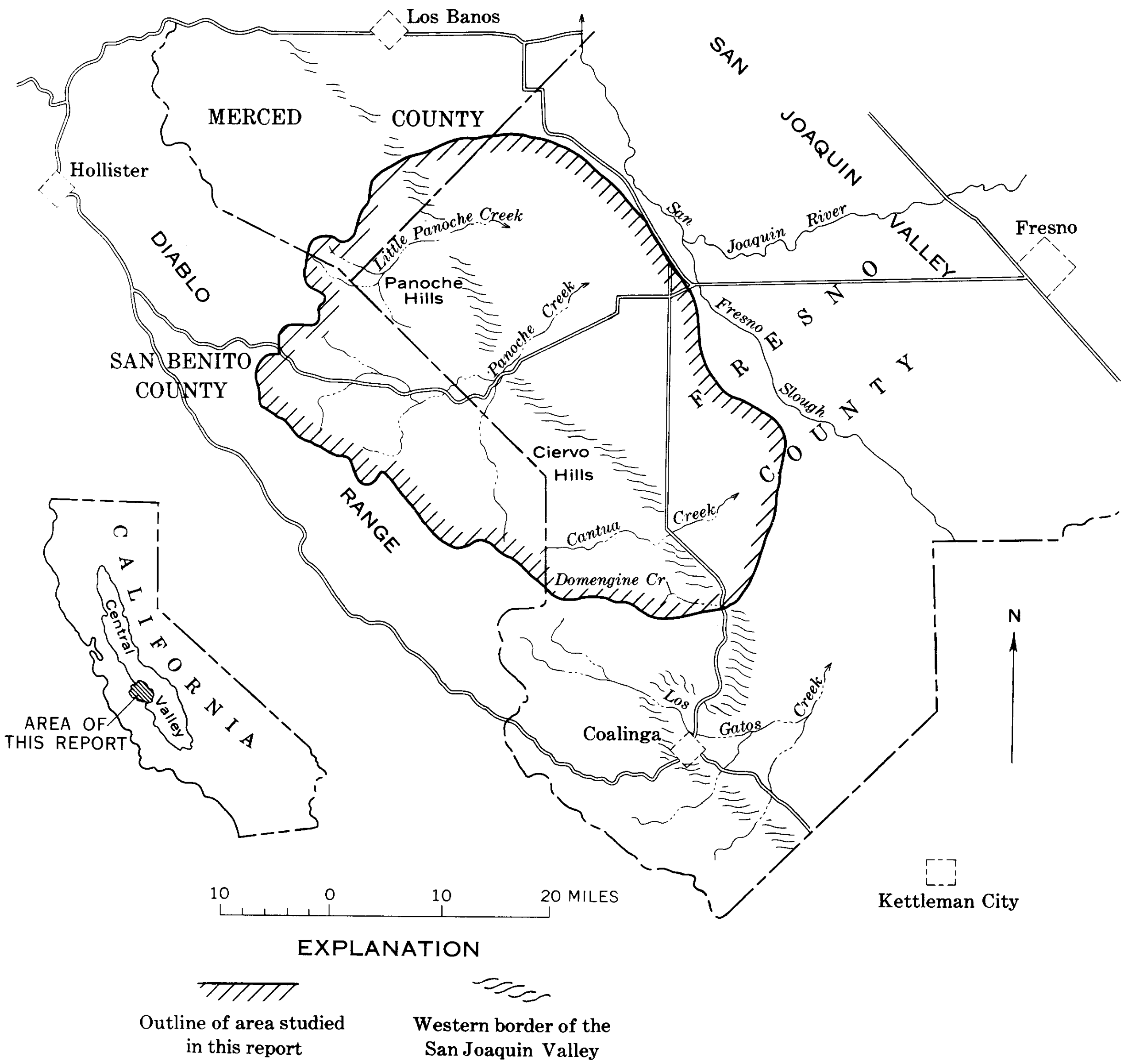

FIGURE 53.—Map of parts of Fresno, Merced, and San Benito Counties, Calif., showing area discussed in this paper.

Land Office. Panoche and Little Panoche Creeks were described in October 1854 by A. McNeill, who noted "* * * the large creek [Panoche Creek] being at this time perfectly dry and never affording any water except in the rainy season." For Little Panoche Creek he remarked that "There is however no timber or water, the creek being dry, and consequently there is little inducement for settlement." J. F. Minturn made the following notes about Cantua Creek in May 1855. "The water in this stream sinks after running about ¾ of a mile into the plains. At the edge of the hills the water runs throughout the year." These descriptions show that the streams were nearly the same 100 years ago as they are today, except that Cantua Creek rarely flows throughout the year now, and Little Panoche Creek has more water than was suggested by McNeill. These descriptions were based partly on conditions at the time of year at which the observations were recorded.

The ephemeral streams have a "flashy type" of flow which ranges from clear water to viscous mud.

CLIMATE AND VEGETATION

Nearly all the precipitation in the area occurs as rain. The average annual rainfall is 15–20 inches for most of the main Diablo Range. The main range creates a rain shadow across the foothill belt and the west side of the San Joaquin Valley. Consequently, the average annual rainfall is about 8–15 inches in the foothills and 6½–8 inches in the valley; it also decreases slightly from north to south. Most of the rainfall comes during the winter. The winter rains are carried by cyclonic storms that move inland across the Pacific coast. The spring and infrequent summer rains result generally from cyclonic storms but also occur as scattered thunderstorms.

This semiarid region is hot in the summer and mild in the winter. The daily temperature range is often 30°–40°F particularly during the summer. The prevailing winds are from the northwest. The lower slopes of the main Diablo Range are brush covered, but oak, pine, and cedar grow at the higher altitudes. The foothills and alluvial fans support shrubs such as shadscale and short grasses such as downy chess and redstem filaree.

The vegetation on the foothills and in the San Joaquin Valley is sparse, particularly during dry years. A more luxuriant growth mantles the flooded parts of alluvial fans and may continue to grow in a dry year following a wet year, if sufficient moisture is left in the ground to support the dense growth. The dryness and hot temperatures discourage the growth of many plants at the low altitudes during the summer.

GENERAL GEOLOGY

REGIONAL SETTING

The Diablo Range is mainly a broad anticline that has smaller folds trending obliquely to the course of the main range. Joaquin Ridge is one of the smaller anticlines, and Cerro Bonito and the Griswold Hills mark the trend of part of the Ciervo anticline. The Vallecitos is a conspicuous syncline to the southwest of the Ciervo anticline. Monoclinal folds are the dominant structures in much of the foothill area.

The core of the Diablo Range consists of deformed and slightly metamorphosed shale and graywacke of the Franciscan Formation of Jurassic to Late Cretaceous Age and of ultrabasic intrusive rocks. The Franciscan Formation is overlain unconformably by predominantly Cretaceous marine rocks, which dip toward the San Joaquin Valley and form the east flank of the Diablo Range. The Cretaceous marine rocks consist mainly of mudstone, sandstone, and shale which are more than 20,000 feet thick. Easily eroded Tertiary marine and unconsolidated continental sediments are exposed mainly along the foothill belt and in basins such as the Vallecitos.

Some of the basic data on selected drainage basins and alluvial fans are in table 1. The total relief of a drainage basin is the difference in altitude between the highest point of the basin and the point where the stream enters the San Joaquin Valley. The mean slope of a drainage basin is the average slope of all the land within the basin and is computed with data from contour maps. Mean slope partly controls the amount and rate of erosion in a drainage basin. The slope values in table 1 are the tangents of average slopes. The lithology and geomorphology of these drainage basins are described in detail elsewhere (Bull, 1964).

TABLE 1.—*Basic data on drainage basins and alluvial fans of selected streams in western Fresno County, Calif.*

Stream	Code letter on plate 7	Drainage basin total relief (feet)	Percentage of mudstone and shale in drainage basin	Approximate mean drainage-basin slope	Drainage-basin area (square miles)	Alluvial-fan area (square miles)	Overall alluvial-fan slope
Laguna Seca Creek	A	1, 270	48	0. 20	11. 1	11. 3	0. 015
Wildcat Canyon	B	1, 140	42	. 16	11. 4	8. 3	. 015
Little Panoche Creek	C	3, 150	35	. 24	104	53. 6	. 0070
Moreno Gulch	D	1, 830	67	. 45	11. 7	20. 6	. 017
Gres Canyon	E	620	57	. 33	. 18	. 36	. 029
Marca Canyon	F	1, 500	60	. 48	1. 9	4. 6	. 025
Chaney Ranch Canyon	G	620	40	. 29	. 53	. 51	. 026
Capita Canyon	H	1, 760	67	. 50	2. 6	5. 9	. 022
Dosados Canyon	I	1, 520	63	. 41	. 93	2. 1	. 023
Escarpado Canyon	J	1, 130	60	. 39	. 56	1. 4	. 029
Panoche Creek	K	4, 550	32	. 27	296	260	. 0035
Unnnamed	L	770	86	. 37	. 49	[1] . 20	. 022
Tumey Gulch	M	2, 590	67	. 30	29. 1	49. 6	. 012
Arroyo Ciervo	N	2, 740	68	. 34	8. 0	10. 3	. 018
Unamed	O	1, 600	51	. 30	1. 7	3. 6	. 022
Arroyo Hondo	P	2, 550	52	. 29	25. 7	54. 6	. 0094
Cantua Creek	Q	4, 610	32	. 35	49. 4	75. 6	. 0047
Salt Creek	R	3, 480	41	. 39	25. 2	28. 2	. 0074
Martinez Creek	S	3, 230	34	. 26	8. 9	7. 1	. 013
Domengine Creek	T	3, 500	38	. 33	11. 2	11. 4	. 011

[1] Small fan area owing to removal of lower part of fan by Panoche Creek.

THE COAST RANGE OROGENY

Alluvial fans are characteristic of structurally disturbed regions (Blackwelder, 1931, p. 136–138). The area discussed in this paper has been subject to intermittent uplift that culminated in the Coast Range orogeny. This orogeny and subsequent periods of uplift determined most of the geomorphic and sedimentary characteristics of the alluvial fans in western Fresno County.

The Coast Range orogeny was preceded by several periods of uplift (Taliaferro, 1943, p. 151–158) one of which resulted in the deposition of the Tulare Formation of Pliocene and Pleistocene(?) age. In western Fresno County, parts of the Tulare consist of coarse fluvial sediments that were eroded from the ancestral Diablo Range to the west. The Tulare to the east of the Panoche Hills contains cobbles of glaucophane schist and other Franciscan rock types such as slaty shale and graywacke. The source area for these rock types was the main Diablo Range and part of Glaucophane Ridge. East of the Ciervo Hills the Tulare Formation includes red chert and serpentine detritus, rock types that are common in the main Diablo Range. Some parts of the Tulare appear similar lithologically to the present-day alluvial fans. For example, the Tulare south of the apex of the Panoche Creek fan may be part of the fan of an ancestral Panoche Creek.

> The deposition of these late Pliocene and early Pleistocene(?) beds [the Tulare Formation] was brought to a close by an even more important and widespread diastropic event [the Coast Range orogeny] than that through which they originated (Taliaferro, 1943, p. 148).

Although the age of the Coast Range orogeny is generally considered to be middle or late Pleistocene (Eaton, 1928; Reed and Hollister, 1936; Stille, 1936; Putnam, 1942; Bailey, 1943; Taliaferro, 1943), within the area studied it can be dated only as post Tulare. The Tulare generally is accepted as being of Pliocene and Pleistocene(?) age, and if this is the age of the Tulare in western Fresno County, then the foothill belt and probably the main Diablo Range were elevated during Pleistocene time.

Middle to late Pleistocene fossils have been found in tilted and folded strata in southern California, and some of these beds have been tilted by minor earth movements since the Coast Range orogeny (Bailey, 1943). Movements younger than the Coast Range orogeny also affected the Diablo Range causing changes in the development of alluvial fans as will be shown later.

Flat-lying beds of the Tulare Formation on the highest parts of the Panoche Hills suggest that during Pliocene and early Pleistocene time these beds probably covered the site of the present foothill belt, which has since been uplifted. Subsequent erosion has separated the remnants of the Tulare from their source areas in the Diablo Range.

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The streams that now head in the main Diablo Range either maintained their original courses through the rising foothill belt, or took new courses around the areas of maximum uplift. Deposition of alluvial fans then took place east of the foothill belt on the older fan deposits of the Tulare Formation.

The streams that now head in the foothill belt did not exist before the Coast Range orogeny. The orogeny formed the foothills and started the deposition of new alluvial fans that are now several hundred feet thick.

The western part of the San Joaquin Valley was uplifted also. A map of the top of a widespread lacustrine clay, the Corcoran Clay Member of the Tulare Formation, shows that the western edge of the Corcoran was uplifted several hundred feet relative to its eastern edge since the end of the pluvial period associated with the clay (R. E. Miller, written communication, 1962). Alluvial-fan deposition has obscured any topographic expression of this folding in the San Joaquin Valley.

GEOMORPHOLOGY OF THE ALLUVIAL FANS

DEFINITIONS AND GENERAL FEATURES

An alluvial fan is a stream deposit whose surface forms a segment of a cone that radiates downslope from the point where the stream channel emerges from a mountainous area. The deposit may consist of water-laid sediments or mudflow deposits; the alluvial fans in western Fresno County are made up of both. A radiating surface gives a fan the distinctive shape of a segment of a cone. The channel may contain either a perennial, intermittent, or ephemeral stream. In western Fresno County the source areas range from low, rolling hills to steep, rugged mountains.

Stream channels are commonly entrenched into the fanheads, the area close to the apex, and Eckis' (1928, p. 240) term "fanhead trench" gives a good description of this feature. Downslope from the end of the fanhead trench most of the stream channels divide into several braided distributary channels which are about 1–3 feet deep and commonly change position during floods.

A piedmont plain is a broad sloping plain formed by the coalescence of many alluvial fans. The terms "compound alluvial fan" and "bajada" (Tolman, 1909, p. 142; Blackwelder, 1931, p. 136) have the same meaning. Blackwelder noted that "parallel to the mountain front the convexities of the component fans impart to the bajada an undulating surface."

FAN SIZE AND SLOPE

Alluvial fans and their drainage basins or source areas act as open systems because changes in drainage-basin conditions cause changes in fan characteristics. The area and slope of a fan are related to the size and lithology of its drainage basin. The fan slope used in computing quantitative relations is the average overall slope from the fan apex to the outer margin where the fan coalesces with another fan or with the river deposits in the trough of the San Joaquin Valley. Radial profiles drawn near the middle of a fan from apex to toe were used to help locate the lower end of the slope to be measured. The boundaries shown on plate 7 were used to determine most of the fan areas.

In general, "* * * large deep canyons have broad fans of low gradient; short ravines have small steeply sloping fans" (Blackwelder, 1931, p. 136). This general relation is true for fans in western Fresno County, as is shown by figure 54.

Statistical-fitting procedures were not used in drawing the lines, but the set of equations for each lithologic group was checked by inserting terms from the equations of figures 54*A* and 54*B* in the equations of figure 54*C*.

Overall fan size is controlled mainly by drainage-basin features, such as size, slope, rainfall, and erodibility of the exposed rocks. The fans studied range in size from 0.4 to 260 square miles. Figure 54*A* shows that all the fans derived from basins underlain mainly by mudstone and shale, and half the fans derived from basins underlain mainly by sandstone, are larger than their basins. The plotted points scatter moderately about straight lines described by the equations shown on the figure. On the logarithmic graph the slopes of the lines (0.88) are equal and show that fan area increases in about the same exponential manner as drainage-basin area increases, despite appreciable differences in lithology. The coefficients of the equations (1.3 and 2.4) show that, on the average, fans derived from drainage basins characterized mainly by mudstone and shale are roughly twice as large as the fans derived from drainage basins of comparable size characterized mainly by sandstone.

The fans studied range in overall slope from 0.0035 (0°12′) to 0.029 (1°40′). Figure 54*B* shows that the overall fan slope decreases with an increase in drainage-basin size. In drainage basins of comparable size, all but the smallest fans of mudstone and shale basins slope more steeply than fans of sandstone basins.

The relation of fan area to fan slope is shown in figure 54*C*. In general, fan slope decreases with increasing fan area. Fans derived from mudstone and shale drainage basins are larger than fans of similar slope that are derived from sandstone basins; and fans (in the size range 1–100 square miles) that are derived from mudstone and shale basins are 35–75 percent steeper than fans of similar area that are derived from sandstone basins.

The apexes of fans of mudstone and shale drainage basins are, on the average, 520 feet above the trough of the San Joaquin Valley, whereas the apexes of fans of sandstone drainage basins have an average height of 400 feet above the valley trough. The relative heights of the fan apexes, and the relations shown by figure 54, show that for drainage areas of comparable size fans derived from mudstone and shale are not only larger, but also are thicker than fans derived from sandstone. Presumably, these differences in fan volume can be attributed largely to the greater erodibility of the mudstone and shale.

In the area studied, downcutting of the stream channels in the mountains has not kept pace with uplift. The effect of uplift on stream gradients is described in the section "Tectonic hypothesis." The relations between fan slope, fan area, and drainage-basin area and lithology may be different in areas where downcutting by streams has exceeded uplift of the mountains, and erosion of part of the fan has occurred.

RADIAL PROFILES OF ALLUVIAL FANS

The radial profiles of an alluvial fan reflect its depositional history, which is controlled partly by erosional and tectonic changes in the drainage basin upstream from the fan. The radii of a fan are restricted by adjacent fans, and by stream deposits at the toe of the fan if the fan is built into a narrow valley.

The overall radial profiles of most alluvial fans are gently concave upward. Most investigators have reported that the slopes of alluvial fans decrease gradually away from the mountain front. Blissenbach (1954, p. 176) said that "from the apex of the fan the surface dips towards the base in which direction the angles of dip gradually become flatter." Trowbridge (1911, p. 714) stated that "The slope of the piedmont plain away from the mountains varies rather uniformly with distance away from the mountains." Krumbein (1937, p. 588–590), in his studies of the San Antonio Canyon fan in southern California, concluded that the slope of the profile decreases at such a constant rate that the slope can be expressed as a negative exponential function.

The slopes of the fans in western Fresno County do not decrease gradually away from the mountain front. All the fans have distinct breaks in slope, which give their radial profiles a segmented appearance. The fan segments generally have a constant slope and appear

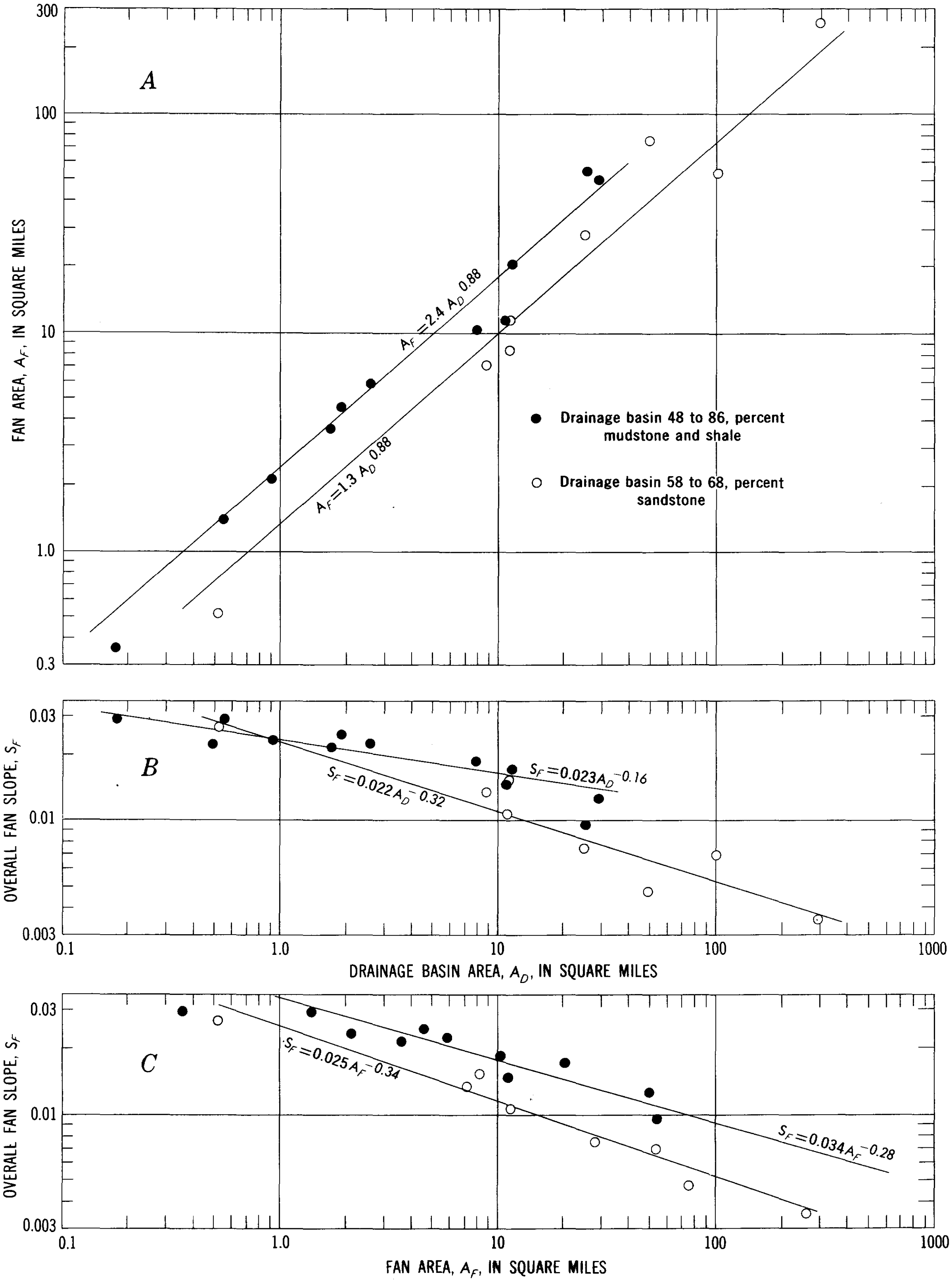

FIGURE 54.—Relations of fan area and slope to drainage-basin area and lithology. *A*, Relation of fan area to drainage-basin area. *B*, Relation of fan slope to drainage-basin area. *C*, Relation of fan slope to fan area.

as straight lines on a radial profile. The fans of Little Panoche Creek and Cantua Creek, however, each have a segment that is concave in addition to their straight-line segments (fig. 59).

The uniform slopes of straight-line segments of the radial profiles are not merely the result of interpolation between widely spaced survey control points. Maps made 30 years apart by somewhat different techniques, show consistent fan shapes, except in areas that have been affected by intense land subsidence. For example, the fan segmentation of the upper part of the Tumey Gulch fan (figs. 56, 57) was studied by using data from the Monocline Ridge quadrangle which was mapped by planetable methods in 1923 (1:31,680, 5-ft contour interval) and 1955 (1:24,000, 10-ft contour interval). According to authorities at the Pacific Area Office of the Topographic Division of the U.S. Geological Survey (oral communication), some interpolation was necessary for the 1923 map, which was based partly on surveyed profile lines spaced 1,000 feet apart. No interpolation was used on the 1955 map because the individual contour lines were surveyed in this part of the quadrangle. The radial profiles obtained from both maps are the same, and show that the fan segments have constant slopes for several miles.

A survey of topographic maps of other areas in California and in Nevada has also shown that segmented alluvial fans in western Fresno County are by no means unique. Slopes of many other California fans are segmented also as is illustrated in figure 55 which shows some common types of radial profiles. The dots represent altitudes from topographic maps. The profile of the San Antonio Canyon fan was drawn on the same radial line used by Krumbein (1937, fig. 5). Most of the profile of the fan was prepared from a topographic map with a 5-foot contour interval whereas Krumbein used a map with a 50-foot contour interval. The upper and lower segments are straight, but the middle segment is concave as is shown by the chord and the extended lines of the straight segments. The upper seg-

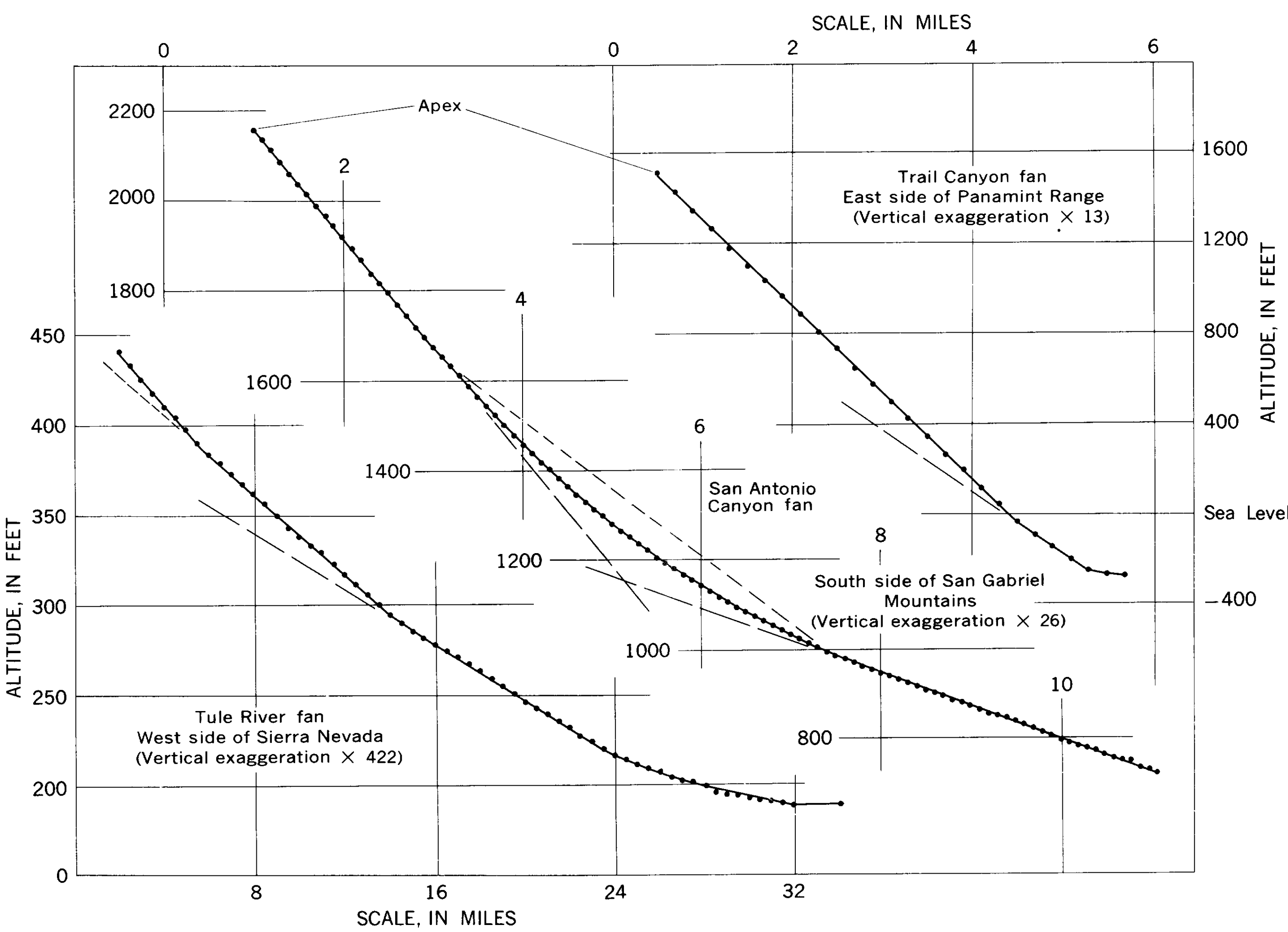

FIGURE 55.—Types of radial profiles of alluvial fans in California.

ment of the San Antonio Canyon fan has a gradient that is constant through a decrease in altitude of 500 feet in 2 miles. The base of the fan merges with other alluvial deposits near the Puente Hills. The Trail Canyon fan has a radial profile that is virtually a straight line except for a small straight-line segment of lesser slope near the toe of the fan, which merges with the old lakebed of Death Valley. The radial profile of the Tule River fan consists mainly of straight-line segments also, but the lowest part of the fan, where it merges with the deposits of Tulare Lake, has a concave profile. The angular relation between any two adjacent straight segments is indicated by extending the trace of the lower segment upslope; the curvature of the curving segment is indicated by a chord.

The profiles are subjective to the extent that different people will draw slightly different lines through the same set of control points. The author has tried to keep the profiles simple by not breaking curves into a large number of short straight segments and by averaging gently undulating slopes with straight lines rather than depicting them in detail as a series of convex and concave curves.

Vertical exaggeration is necessary to show clearly the segmented shape of the radial profiles. Steep fans such as the Trail Canyon fan require little exaggeration (13 times), but gentle fans such as the Tule River fan require much exaggeration (422 times).

A detailed study of the Tumey Gulch fan in western Fresno County shows that the angular relations and the length of the segments vary from one side of the fan to the other but that the overall profiles are very similar. Eight radial profiles of this fan are shown in figure 56 and the locations of the profiles are shown in figure 57. Each profile has three straight-line segments, and the angle between the upper and middle segments is larger than the angle between the middle and lower segments.

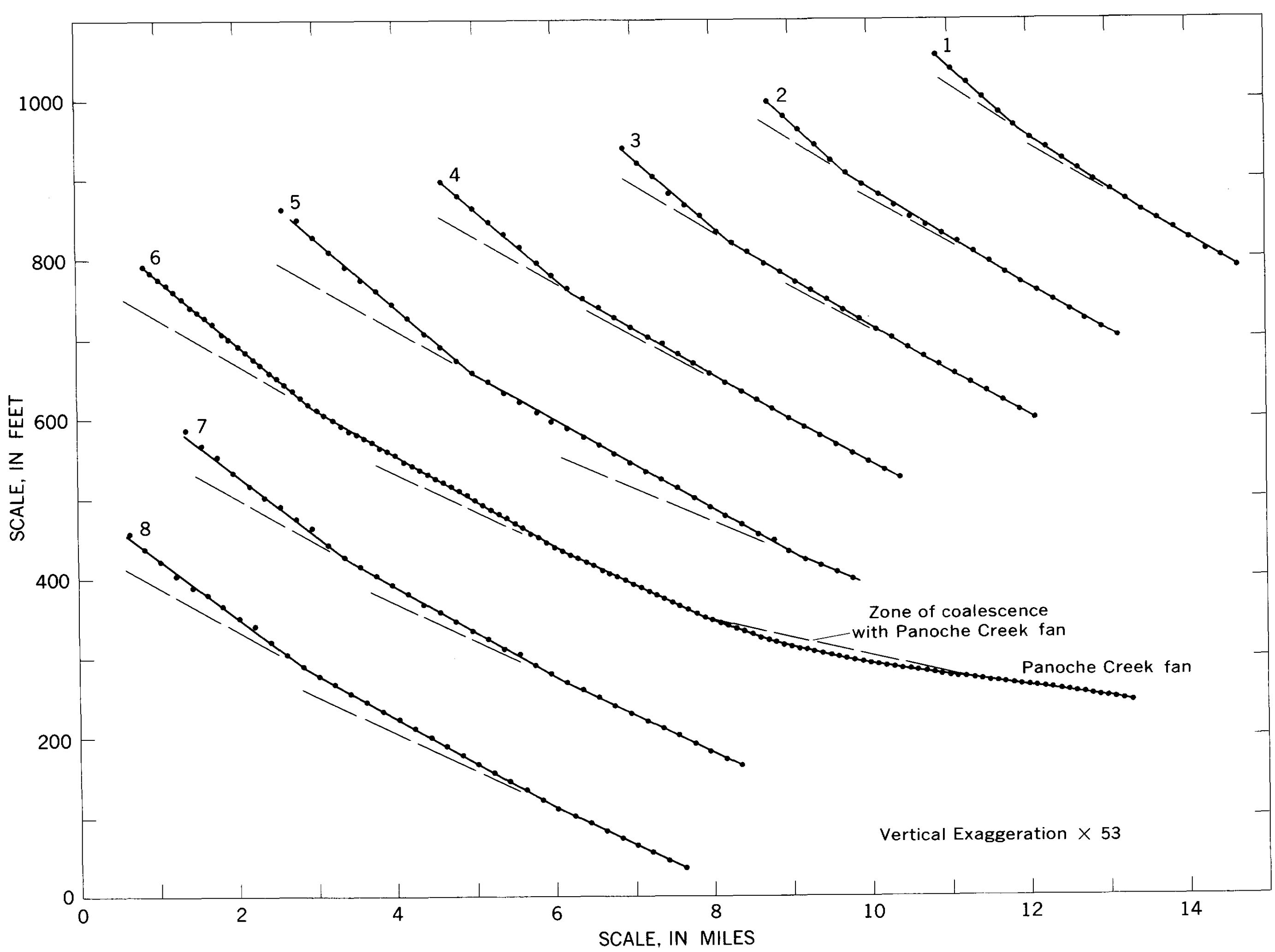

FIGURE 56.—Radial profiles of the Tumey Gulch fan.

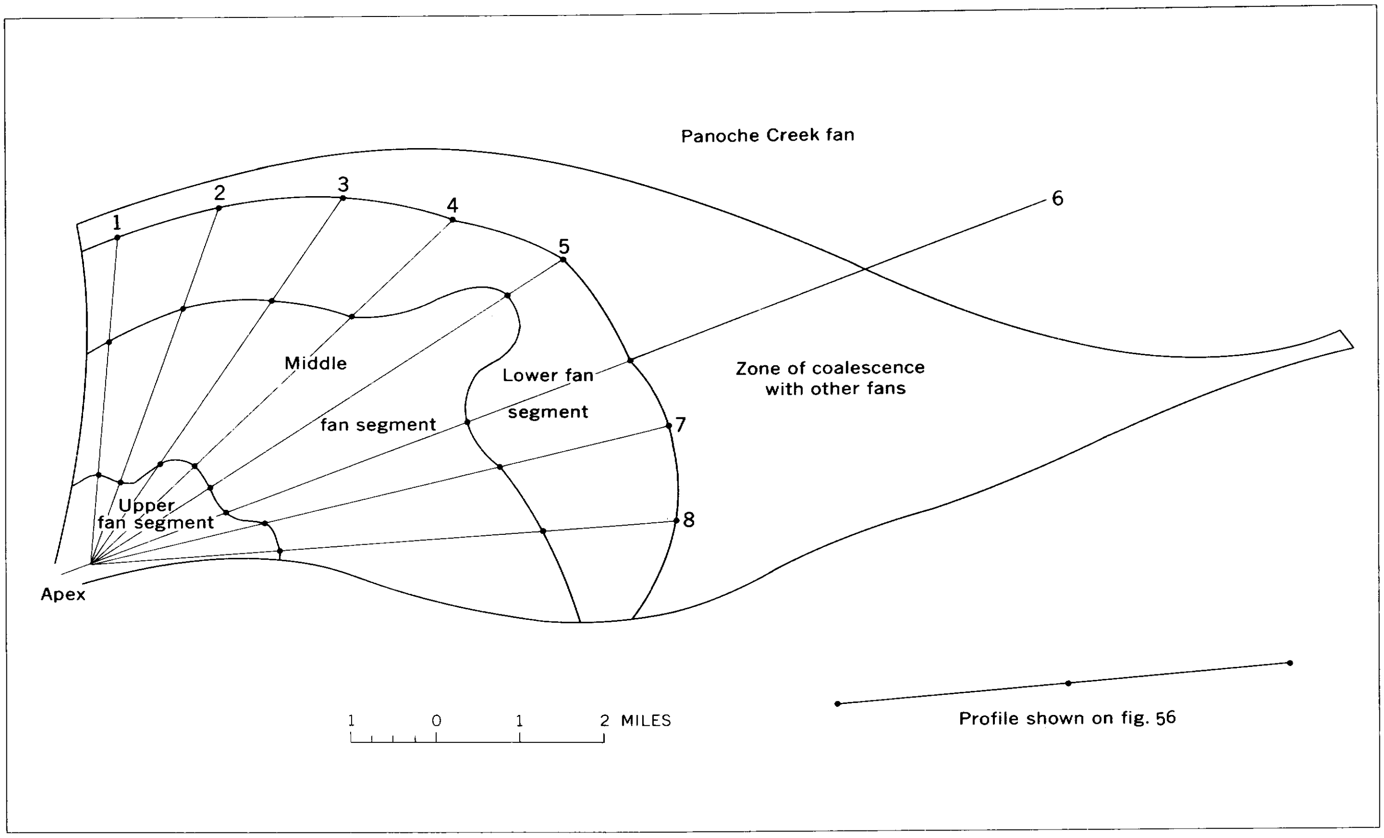

FIGURE 57.—Segments of the Tumey Gulch fan.

Profile 6 has been extended onto the Panoche Creek fan. The zone of coalescence between the Tumey Gulch and Panoche Creek fans for profile 6 is concave, but the profiles of the coalescence zone for half of the radial profiles (not shown in fig. 56) are straight. Most of the radial profiles in this paper show the topographic profile of a specific alluvial fan but not the profiles of zones of coalescence of two alluvial fans.

The radial profiles of figure 56 show two dimensions of the fan segments and the map of the Tumey Gulch fan in figure 57 shows the third dimension of the three fan segments. The general shape of the boundaries between the fan segments is concave toward the apex, and the upper segments have lobate tongues extending downslope.

The boundaries between the fan segments of the Capita Canyon fan (fig. 72) show that the same general features exist for this small fan. The boundaries between the fan segments cross the contour lines at a large angle, and the lobate tongue of the upper fan segment centers about the present-day stream channel.

If the upper fan segment of the Capita Canyon fan continues to spread downslope, the adjacent lower fan segment may be overlapped. Part of the lower fan segment of the Tumey Gulch fan was almost overlapped by the middle segment in the vicinity of profile 5 (figs. 56, 57).

Radial profiles near medial radial lines were drawn for 12 fans whose streams head in the foothill belt, all were found to have three straight-line segments. Radial profiles for six of these fans are shown in figure 58. (See pl. 7 for location.) Only a half or one-third of the control points are shown for most of the profiles. The average slope of the upper segments is 1°14′ (range 0°55′–1°46′); the average slope of the middle segments is 0°48′ (range 0°32′–1°14′); and the average slope of the lower segments is 0°37′ (range 0°22′–0°51′). The average angular difference between the upper and middle segments is 0°26′ (range 0°14′–0°44′); the average angular difference between the middle and lower segments is 0°11′ (range 0°4′–0°24′). The drainage-basin areas of the fans shown in figure 58 range from 2.6 square miles for Capita Canyon to 29 square miles for Tumey Gulch. Lengths of segments vary, but the lower segment of most fans is short.

The radial profile of each fan is distinct, but the fans whose drainage basins are adjacent to each other generally have roughly similar radial profiles. An example shown in figure 58 is the profiles of the Arroyo Ciervo and Arroyo Hondo fans. Other adjacent fans

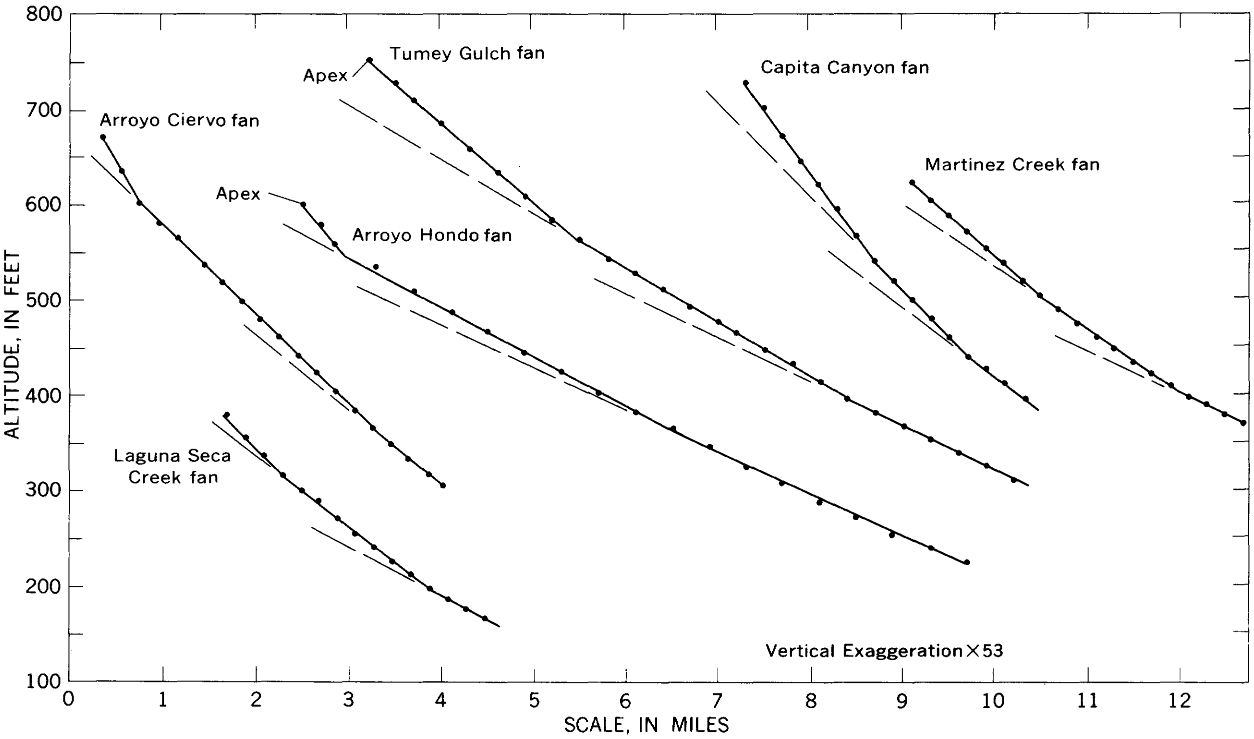

FIGURE 58.—Radial profiles of six fans whose streams head in the foothill belt.

with similar profiles, not shown in the figure, are the Martinez Creek and Domengine Creek fans, and the Capita Canyon fan and the adjacent fans to the north and south of it.

The upper segments of most of the fans are the youngest. Maps made a century ago by the General Land Office show that the stream channels were not entrenched into the upper segments of some fans. Aerial photographs show a fresh pattern of braided distributary channels on the upper fan segments as well as on the middle and lower segments, which indicates that deposition has occurred recently on most upper fan segments. The degree of soil-profile development is about the same on the upper and middle parts of most fans and cannot be used to differentiate the ages of these fan surfaces. Patches of older soils occur on the lower parts of some fans, and locally at the mountain front, where fan deposits have been warped by uplift. Charcoal from 10.5 feet below the surface of the upper fan segment of the Arroyo Hondo fan (pl. 7) gave a radiocarbon age determination of 1,040±200 years before the present time (Rubin and Alexander, 1960, p. 156). The total thickness of deposits of the fan segment at this locality is estimated, by extending the slope of the adjacent fan segment, to be 24 feet. If the rate of deposition for the 24 feet is assumed to be constant, the segment has been growing for only 2,000–3,000 years.

Radial profiles of fans whose streams head in the main part of the Diablo Range have a different number of fan segments. (Compare figs. 58 and 59.) Each of the three fans has four distinct segments. The segments of the Panoche Creek fan are straight, but the uppermost segments of the Cantua Creek and Little Panoche Creek fans are slightly concave.

The Little Panoche Creek fan has two anomalous features. First, it has a steeper slope than the Cantua Creek fan, although its drainage area is twice that of Cantua Creek. Second, unlike other fans, the surface of the uppermost fan segment of the Little Panoche Creek fan is underlain by old soils that indicate that deposition has not occurred on the upper fan segment during Recent time. The history of the Little Panoche Creek fan is discussed in detail on pages 106–109.

The Panoche Creek fan, whose basin drains 296 square miles of the Coast Ranges, is the most gently sloping fan in the area studied. The slope ranges from 0°17′24″ on the uppermost fan segment to 0°8′14″ on the lowest fan segment.

Drainage-basin characteristics such as lithology and mean slope (table 1) do not seem to be related to the segmentation of a radial profile. For example, the Capita Canyon basin (67 percent mudstone, mean slope 0.50) is the source area of a fan whose radial profile (fig. 58) is similar in shape to the radial profiles (fig. 58) of the fans of the Martinez Creek basin (34 per-

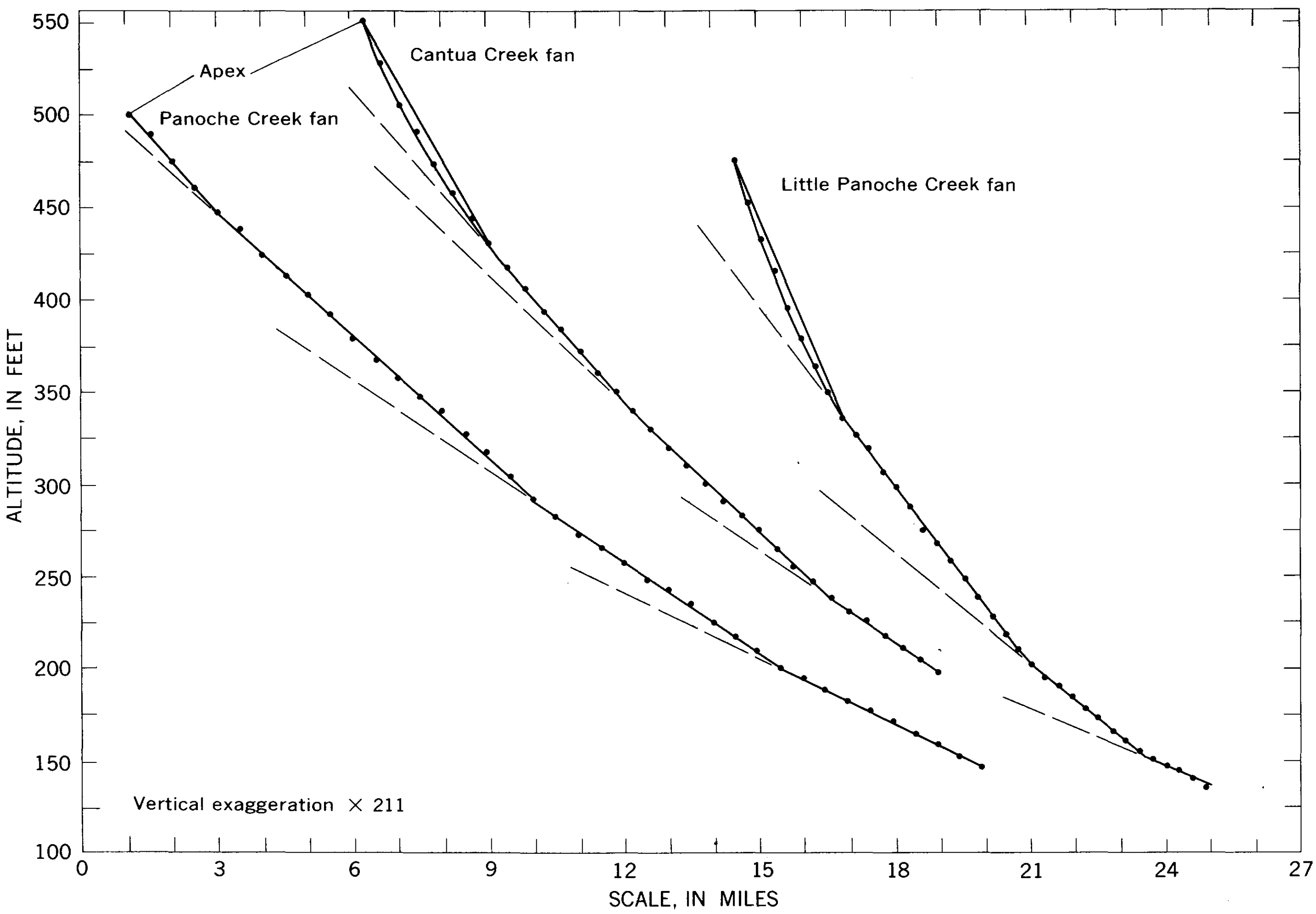

FIGURE 59.—Radial profiles of fans whose streams head in the Diablo Range.

cent mudstone and shale) and the Laguna Seca Creek basin (mean slope 0.20).

No consistent relation between the grain-size distribution of the fan deposits and fan segmentation has been found. Grain-size analyses of 200 surface and subsurface samples show a general decrease in maximum and median grain sizes and an increase in clay content in the downslope direction (Bull, 1964). The grain-size distribution of a particular area of a fan is influenced greatly by the periods of fanhead trenching that allow deposition to start from various points on the upper and middle parts of the fan.

RELATION OF STREAM AND FAN-SEGMENT GRADIENTS

Alluvial fans and their drainage basins are hydrologic units that function as open systems, and climatic or tectonic changes in the drainage basins affect the rate, mode, and locus of deposition on the fans. The gradient of a stream and of its fan tend to attain a steady state or equilibrium, and are sensitive to changes in the drainage basin. This tendency is important in considering the possible causes of fan segmentation.

In the area studied, steep fans form at the mouths of canyons having steep longitudinal profiles, and the gently sloping fans form at the mouths of valleys having gentle longitudinal profiles. This general relation also occurs in the White Mountains of California and Nevada where Kesseli and Beaty (1959, p. 10) have noted that "* * * the steepness of the alluvial fans is in direct relation to the steepness of the mountain canyons providing the debris out of which they are constructed."

In western Fresno County, the slope of the valley floor upstream from the apex of a fan and the upper fan segment are virtually the same. In fact, the upper fan segments and the valleys for a distance of ½–1 mile upstream from the apex have the same general slope. Of 10 valleys, 5 of them have slightly lower gradients above their apexes than their upper fan segments and 5 have slightly higher gradients than the upper fan segments. The average difference in slope is 0°10′ (range in difference, 0°3′–0°17′), which is only half the average difference in slope between the uppermost and the adjoining downslope segments of the same fans.

On most fans the slope of the upper fan segment and of the valley upstream from it are similar even where the underlying rock type is not the same (fig. 60). The stream channel of Capita Canyon is in Cretaceous and Tertiary marine rocks and slopes slightly more than the adjacent fan segment. The stream channel of Laguna Seca Creek is in Recent alluvium and slopes slightly less than the adjacent fan segment. These two stream channels were formed after the deposition of the upper fan segments. On the other hand, the terrace deposits of an unnamed stream and Arroyo Ciervo probably were deposited during the same interval as the surficial deposits of their upper fan segments, because the fans and low terraces have the same gradients. Maps made by the General Land Office show that the terrace cutting of both these streams occurred since 1858.

The previously discussed evidence shows that near the apex of most fans, deposits have accumulated that have the same general slope as the valleys upstream from the fans. Erosion predominates in the valleys before the fans have attained the same gradients as the valleys.

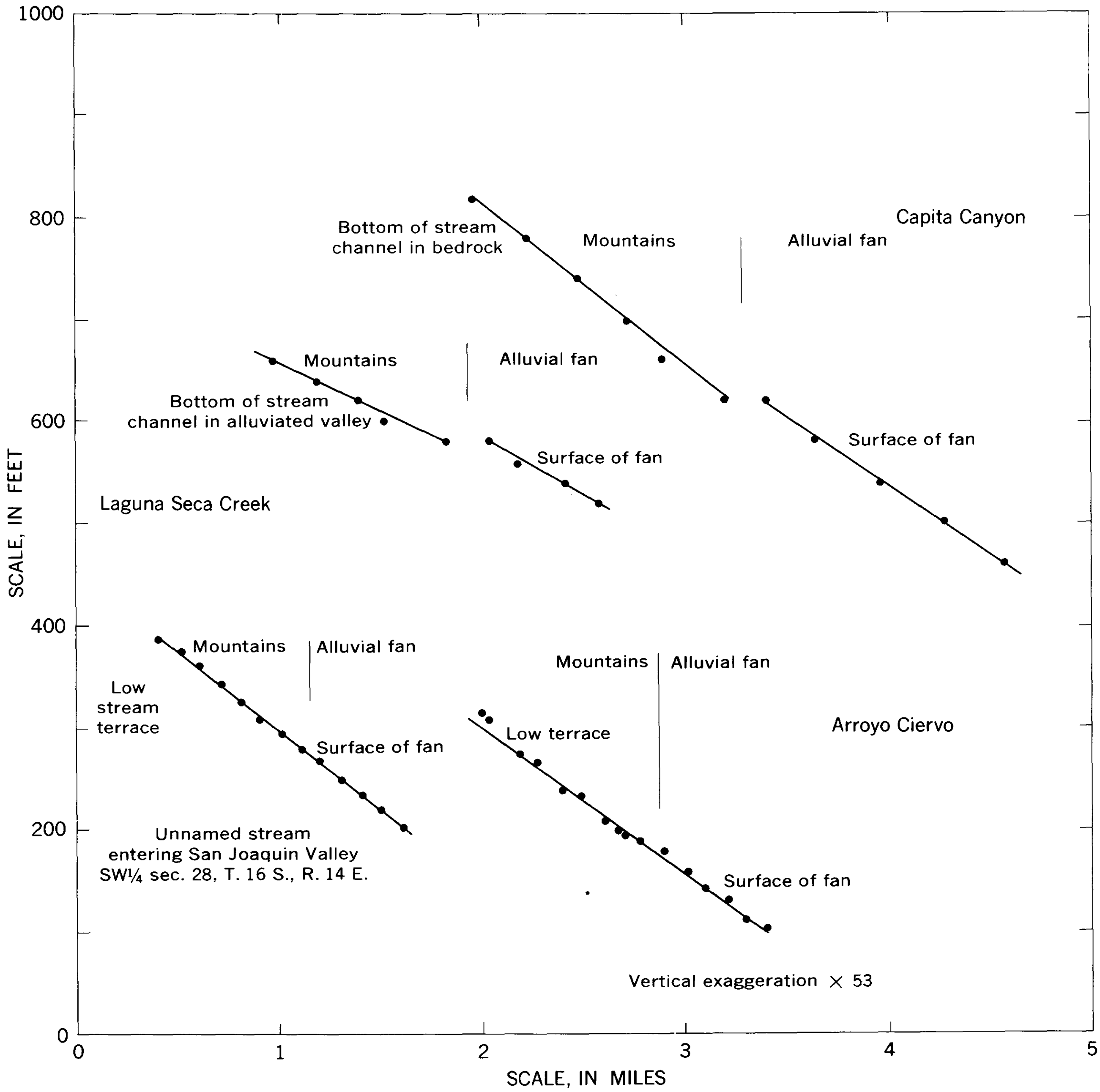

FIGURE 60.—Longitudinal profiles of two streams and two low terraces and the surface of the upper part of their alluvial fans.

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After the same gradient has been attained, aggradation of the upper fan surface and stream valley maintains this common gradient—examples are the unnamed stream and Arroyo Ciervo of figure 60.

The fanhead trenches also tend to be cut down to the same gradients as adjacent lower fan segments. This adjustment of stream gradients to depositional gradients is illustrated by the gradient relations of some fanhead trenches shown in figure 61, and the same relation probably existed for the streams when the main channel ended at the top of the upper fan segment. Part of the fanhead trenches of the streams shown in figure 61 have been cut down to the same gradient as that of the adjacent lower fan segment. About a mile of the Tumey Gulch and Moreno Gulch fanhead trenches now have the same gradients as their adjacent lower fan segments, and about 5 miles of the Panoche Creek fanhead trench now has the same gradient as its adjacent lower fan segment. Most of this adjustment has occurred in the last century (fig. 77). Streams probably tend to backfill if cut to a gradient less than their adjacent lower fan segment.

The relation of the stream and fan-segment gradients is significant because it shows that the area of deposition and the stream channel upslope from it tend to maintain a uniform and common gradient. Therefore, the fan segments probably are the result of changes in stream-channel gradient that cause deposition on steeper or gentler slopes.

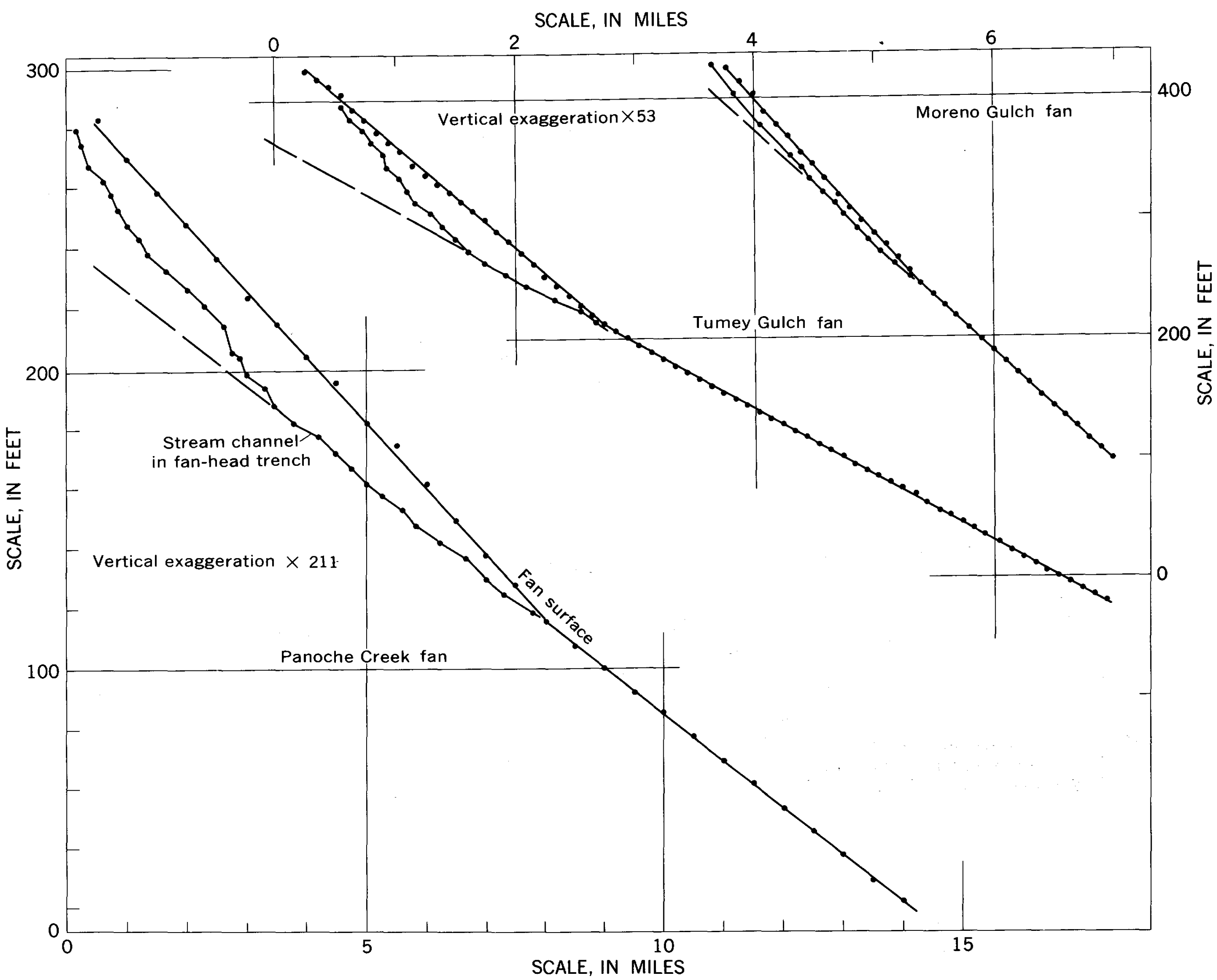

FIGURE 61.—Relation of the gradients of fanhead trenches to the gradients of their adjacent lower fan segments.

POSSIBLE CAUSES OF FAN SEGMENTATION

An explanation for the formation of segmented fans is essential to the understanding of their depositional history. Alluvial fans in western Fresno County have three to four segments which appear as straight, or rarely as slightly curving, lines on the radial profiles of the fans. The fan deposits accumulate on surfaces that have about the same gradient as the stream channel upstream from the area of deposition. Therefore, changes in the gradient of the stream channel probably have caused changes in the slope of succeeding fan segments. First, the evidence for changes in the environment of deposition will be presented, and then the possible causes of fan segmentation will be discussed.

The prominent paired, or matched, terraces of western Fresno County (Arnold and Anderson, 1910, p. 155, pl. IV–A; Anderson and Pack, 1915, p. 104–106) reflect changes in the erosional history of the drainage basins. The terraces are classified in this paper as high and low terraces. High terraces generally are more and low terraces generally less than 30 feet above the present-day stream channels. Two high terraces and one low terrace are shown in figure 62*A*. Figure 62*B* shows one pair of terraces about 100 feet above Arroyo Ciervo and a second pair of terraces, less distinct than the first, about 300 feet above the valley floor. The lower pair of terraces and the present valley floor diverge downstream. The area pictured is upstream from a zone of pronounced monoclinal folding. Paired, or matching, terraces, have a two-phase origin: first, the surface is formed by beveling or deposition; and second, the surface is entrenched by accelerated erosion. The several levels of paired terraces along the valleys indicate that the area has been rejuvenated repeatedly.

The terraces show that erosional and depositional rates have varied from time to time in western Fresno County. Changes in erosional conditions probably changed the stream gradients and the slopes of the adjacent fan deposits. The accelerated erosion that causes terracing may be due to either uplift or climatic fluctuations, or both (Bryan, 1923, p. 21–25), or to changes in base level. The entrenchment that caused the formation of many of the low terraces was caused mainly by climatic changes during the last century. (See section on "Causes of the Fanhead Trenching.") The high terraces, on the other hand, reflect tectonic changes. This is discussed on pages 106, 107.

The number of fan segments seems to be related to the number of terraces. For example, the Arroyo Ciervo fan has three segments separated by two changes in fan slope, and the drainage basin has two paired high terraces. Little Panoche Creek has four segments separated by three changes in fan slope, and the drainage basin has three paired terraces. In the following discussion, climatic, base-level, and tectonic changes will be examined as possible causes of the terracing and fan segmentation.

The alluvial fans in western Fresno County are of Quaternary age. Therefore climatic changes that affected the erosional and depositional conditions probably occurred during the formation of the fans. Extensive glaciation occurred in the Sierra Nevada during Pleistocene time, but this part of the Coast Ranges was not glaciated.

A

B

FIGURE 62.—Terraces in the foothill belt of western Fresno County. *A*, Terraces along Cantua Creek. Looking southeast from NE¼SE¼ sec. 35, T. 17 S., R. 14 E. The fence is on a low terrace and two high terraces occur between it and the skyline. *B*, Paired high terraces along Arroyo Ciervo. Looking southwest from NW¼NE¼ sec. 36, T. 16 S., R. 13 E. Arrows mark location of upper terrace.

The moisture content of some of the fan deposits, as shown by tests of core samples, provides evidence concerning possible precipitation changes in the area during fan deposition. Irrigation has produced extensive near-surface subsidence on certain fans in western Fresno County; about 125 square miles have subsided or probably would subside if irrigated. This settling of the land surface is caused by the compaction of deposits by the overburden load as the clay bond supporting the voids is weakened by water percolating through the deposits for the first time (Bull, 1964). Prior to irrigation the moisture content of these compactible deposits while in the root zone is below field capacity because plants and air remove much of the soil moisture during the hot, dry summers, reducing the moisture content to the wilting coefficient. Moisture tests (fig. 63) and the presence of near-surface subsidence indicate that these deposits continue to be moisture deficient after burial below the root zone, thus proving that water from succeeding winter rains and floods does not percolate below the root zone. The native moisture contents of these deposits represent moisture conditions that have not changed appreciably since burial below the root zone.

For example, moisture content for two 300-foot core holes in the Arroyo Hondo and Arroyo Ciervo fans are shown in figure 63. Grain-size analyses indicate that there are no major changes in lithology in the 300-foot sections. The moisture content fluctuates with depth partly because of variations in the clay content of the samples. Moisture-equivalent tests of samples from the same core holes indicate that the moisture condition of the upper 120 feet of deposits is roughly 50 percent of field capacity—about at wilting-coefficient conditions. A sharp increase in the moisture content of the Arroyo Ciervo fan deposits at about 130 feet indicates deposition under slightly wetter conditions than at present, but the deposits are still much drier than field-capacity conditions. The deficient moisture condition of these fan deposits indicates that major changes in the amount of precipitation and stream flow have not occurred during the deposition of the upper 100–200 feet of deposits, which span the time of formation of the fan segments.

An explanation of fan segmentation based on climatic change would require thick valley fills upstream from fans on which the upper segment is the youngest. In figure 64, the initial fan profile is shown (for simplicity) as a single straight line. Diagram *A* shows a fan and a stream channel upstream that have developed a common gradient. As the result of a hypothetical climatic change the stream deposits material on its bed and on the fan steepening the gradient of both surfaces (diagram *B*). In order to maintain similar fan and stream gradients, a large amount of valley filling would have to occur in conjunction with the steepened fan surface. Such a process would require more than 100 feet of valley fill less than a mile upstream from the apexes of fans such as those of Arroyo Ciervo and Tumey Gulch. The valley fill along Arroyo Ciervo is less than 20 feet thick and, along other streams that head in the foothill belt, the fill does not appear thick.

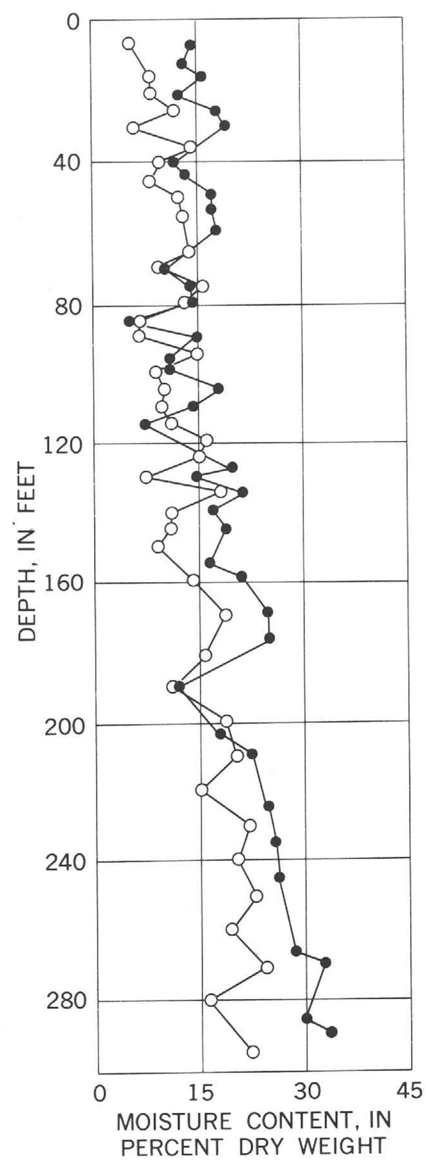

FIGURE 63.—Moisture content for core holes on the unirrigated parts of the Arroyo Hondo (o) and Arroyo Ciervo (•) fans.

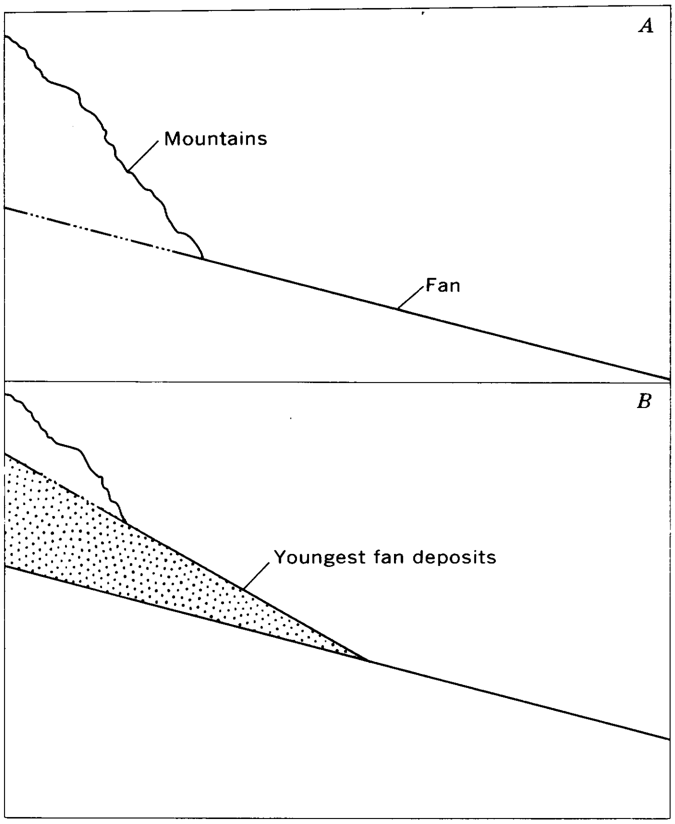

FIGURE 64.—Diagrammatic sketches showing the steepening of stream gradients due to a hypothetical climatic change.

If segmentation is caused by climatic changes, then fans with similar and adjacent drainage basins should have similar shapes. However, this is not true of fans in the area studied. The upper segment of the Tumey Gulch fan is much larger than the upper segment of the Arroyo Hondo fan. The drainage basins of the two fans have a similar size, lithology, mean slope, vegetation, and rainfall distribution. These facts indicate a similar rate of deposition and suggest that the upper segment of the Tumey Gulch fan started to form much sooner than the upper fan segment of the Arroyo Hondo fan. This, in turn, suggests that the causes of the fan segmentation did not necessarily occur over large regions at the same time.

Both regional and local base-level changes should be considered as possible causes of fan segmentation. Pleistocene lowering of sea level probably caused entrenchment of the San Joaquin River. This regional change in base level should have caused entrenchment of the streams into the fans along the west side of the San Joaquin Valley if the streams were perennial at that time. Entrenchment would steepen the stream gradients, but entrenchment also would prevent deposition on the fan. Thus, regional base-level changes apparently did not affect the development of fan segmentation.

Evidences of intermittent local base-level changes are common and are described in the next section.

TECTONIC HYPOTHESIS

The third possibility is that fan segmentation is caused mainly by tectonic changes. Parts of the mountains probably were uplifted more than 2,000 feet during and since the Coast Range orogeny. The abrupt breaks in slope between the fan segments cannot represent tectonic hinge points, however, because the segment boundaries are strongly concave toward the apexes of the fans (figs. 57, 72). This concentric distribution shows that the fan segments are depositional features instead of purely tectonic forms.

The following explanation is in accordance with the facts available from western Fresno County at the present time. In brief, terrace cutting caused by uplift of the mountains formed a steeper stream gradient, and subsequent deposition on the fan built a new fan segment at a new gradient. Repeated periods of uplift produced additional terraces and fan segments.

This explanation applies to two types of fan-segment history in western Fresno County. All the drainage basins have been uplifted, but the location of the area of maximum differential uplift (generally the mountain front) with respect to the fan apex partly determines the locus of successive stages of fan deposition. Most of the fan apexes are immediately downstream from the area of maximum differential uplift, and the stream-channel gradient upstream from the apex has become progressively steeper because downcutting has not kept pace with the uplift. Intermittent uplift associated with progressively steeper stream gradients causes fan segmentation in which the uppermost segment is the youngest, as in figure 65*A*. The second type of fan segmentation occurs where the fan apex is several miles downstream from the area of maximum differential uplift, and the stream-channel gradient upstream from the area of deposition has become progressively gentler, because the downcutting by the stream has exceeded the minor uplift in the reach immediately upstream from the apex. Intermittent uplift, or possibly climatic change, associated with progressively gentler stream gradients, causes fan segmentation in which the lowest segment is the youngest, as in figure 65*B*.

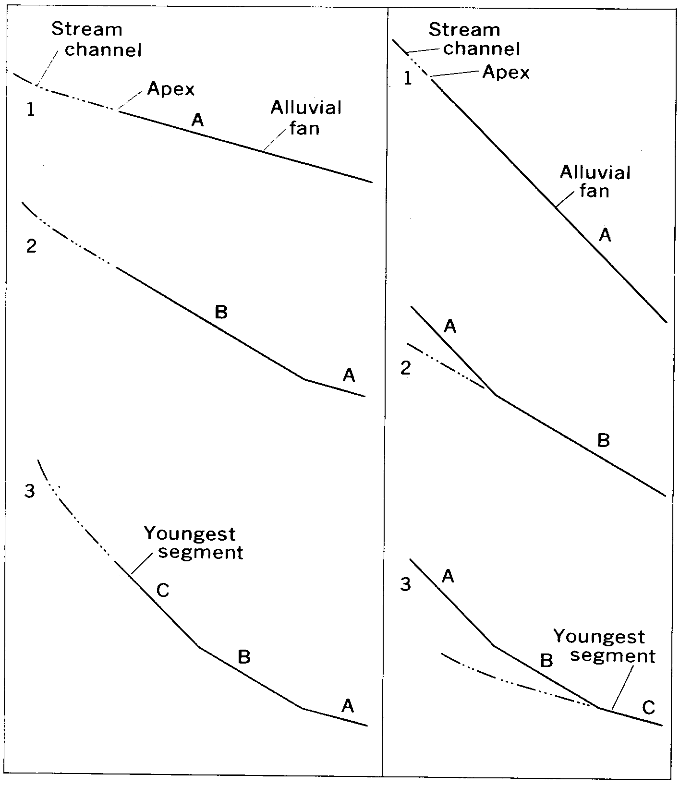

FIGURE 65.—Diagrammatic sketches showing two types of alluvial-fan and stream-gradient history. Fan associated with (*A*) has progressively steeper stream gradients and (*B*) progressively gentler stream gradients. Successive alluvial-fan surfaces A–C are shown in alphabetical order.

FANS ASSOCIATED WITH PROGRESSIVELY GENTLER STREAM GRADIENTS

Little Panoche Creek and Wildcat Canyon have fans whose uppermost segment is the oldest and whose younger segments are associated with progressively gentler stream gradients. For purposes of discussion, the Little Panoche Creek fan includes a small area near the mountain front on which some erosion has occurred. These two fans do not represent the usual occurrence in western Fresno County, because on most fans the upper segment is the youngest and because most of the fans have a history of progressively steeper gradients upstream from their apexes. Little Panoche Creek is the only stream in the area, however, that had broad terraces for which topographic maps of sufficient detail are available to allow accurate plotting of longitudinal terrace profiles. These profiles are shown in figure 66 to illustrate the relations between tectonic environment and stages of alluvial-fan deposition. A direct relation between terraces and fan segments can be shown for this type of fan.

Three prominent paired terraces occur near the mouth of Little Panoche Creek. All three are underlain by a 2- to 20-foot veneer of sand and gravel that was deposited on truncated deformed Tulare sediments. The upper terrace is dissected and much of the soil that formed in the surficial deposits has been removed by erosion. Two to four feet of caliche-cemented gravel, representing the Cca horizon (U.S. Dept. Agriculture, 1960) of a well-developed soil, commonly is found at or near the surface. The middle terrace is not extensively dissected and a moderately well developed soil has formed on the surficial deposits. The soil profile consists of 2 feet of red clayey sand and gravel that is underlain by weakly cemented calcareous material. The lower terrace is not dissected, and visible soil-profile development has not occurred. Examination of fossils[1] collected by the author from a ledge several feet beneath the Tulare dip slope (fig. 66) suggests that this part of the Tulare Formation is of Pleistocene Age. The distribution and stage of development of the terrace soils suggest that the upper and middle terraces are of late Pleistocene age and that the lower terrace is of Recent age.

Part of the tectonic history of the Little Panoche Creek drainage basin is revealed by the various surfaces shown in figure 66. Deposition of the Tulare Formation ceased in this area when the Coast Range orogeny uplifted this part of the Panoche Hills. The dip slope of the upper, or possibly the uppermost, Tulare shows a pronounced decrease in gradient near the mountain front, where gently folded Tulare beds can be seen in roadcuts.

Little Panoche Creek cut a wide valley through the hills. A period of uplift caused the stream to cut down leaving parts of the former valley floor as the upper terrace. The upper part of the fan was upwarped slightly causing it to be abandoned by Little Panoche Creek. The profile of the upper terrace (fig. 66) shows that minor anticlinal folds were superimposed on the warped surface near the mountain front where the differential uplift was greatest. Little Panoche Creek continued to cut down and then laterally during a period of little or no tectonic activity. A second period of uplift during which a narrow band of monoclinal folding occurred along the mountain front caused another stream rejuvenation, which resulted in the formation of the middle terrace. The relations of the folded and unfolded parts of the terraces indicate a differential uplift at the mountain front of 20–30 feet during each of these periods of folding.

A period of regional uplift, or possibly a climatic change, then caused the formation of the lower terrace whose smooth profile indicates that differential uplift at the mountain front did not occur. The lower terrace

[1] Examination made by D. W. Taylor. U.S. Geol. Survey Cenozoic fossil loc. 22692.

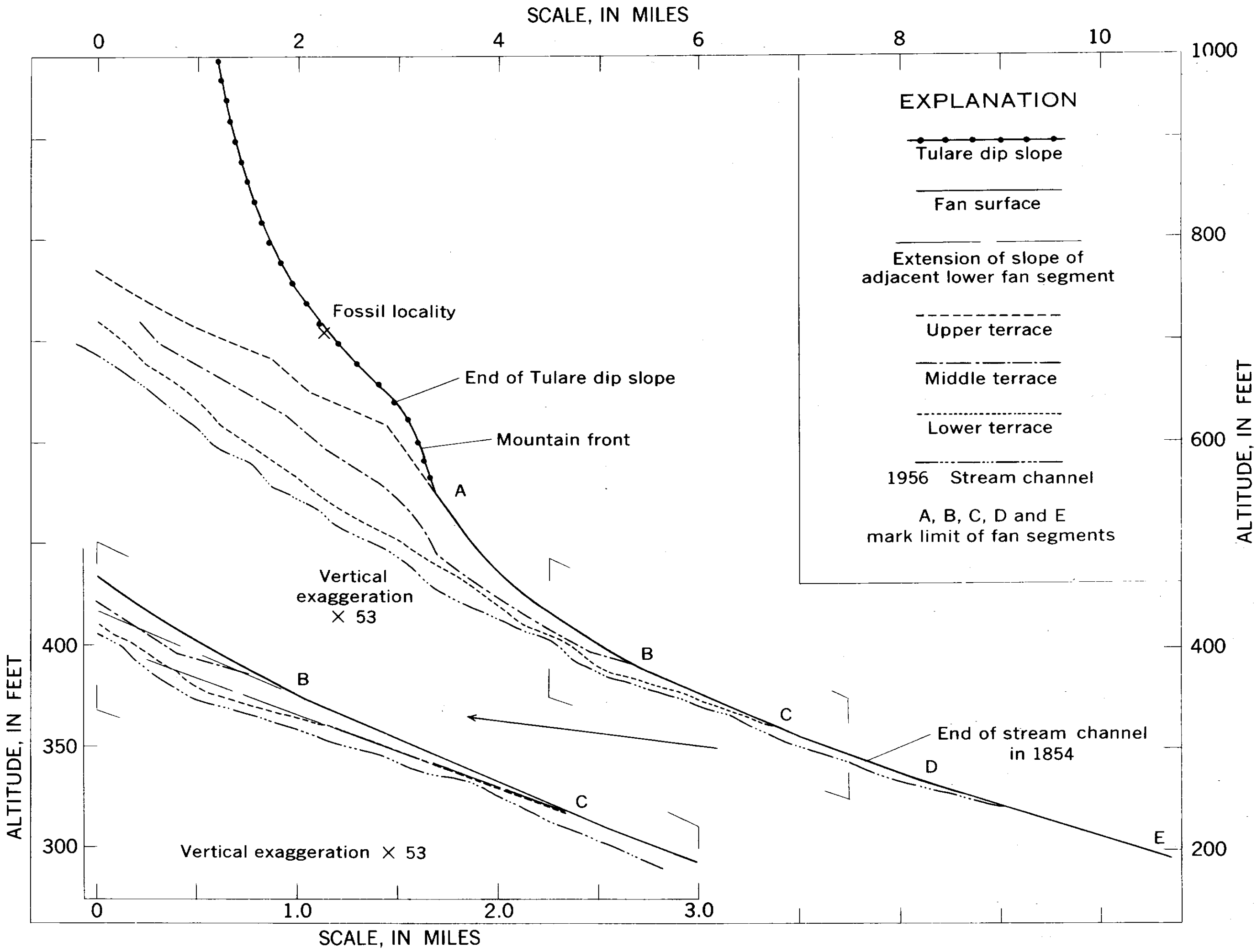

FIGURE 66.—Relation of stream terraces to fan segments for Little Panoche Creek.

converges with the stream channel downstream. Most of the convergence may be due to channel trenching caused by fluctuations in rainfall during the past century.

The longitudinal profiles in figure 66 show both divergent and convergent patterns in the downstream direction. The upper and lower terraces diverge downstream 50 feet in the first 3 miles. The divergence indicates steepening of the stream gradient by headward erosion, as the mountain front was uplifted intermittently by anticlinal and monoclinal folding.

Terrace divergence occurs upstream from the zone of maximum differential uplift, and terrace convergence occurs downstream from the zone of maximum differential uplift. Most of the terrace convergence occurs within 2 miles of the folded zone at the mountain front.

The uplifts accelerated the deepening of the stream channel, but the channel downstream from the mountain front was not uplifted appreciably. The net effect in this reach was trenching of the stream channel and extension of the end of the channel farther out on the fan. Each time this happened the area of deposition and the stream channel upstream from it developed a more gentle gradient than previously.

The slopes of the terraces are continuous with the slopes of the fan segments. The slope of the upper terrace continues onto segment A–B (fig. 66). The old mouth of Little Panoche Creek has been preserved because of an overall lateral migration to the south of this part of Little Panoche Creek. The middle terrace ends at the upslope end of fan segment B–C, and the lower terrace ends at the upslope end of the fan segment C–D. The gradient of the lower part of each terrace approximates the gradient of the adjacent lower fan segment. (See insert, fig. 66.) The soil-profile development on the fan segments and the terrace profiles both confirm that the segment nearest the mountains was formed first and that the two adjacent lower segments are younger.

The present-day stream channel ends on the upper part of the lowest fan segment (D–E), and maps made by the General Land Office show that the end of the channel in 1854 was just upslope from the upper end of this lowest segment. Thus most deposition is occurring on the lowest segment on the south side of the fan, but the stream channel is shallow and narrow enough to permit major floods to flow over the banks and deposit material on parts of the three lower segments.

Fan-segment boundaries, soil types, and selected contour lines reveal part of the history of the Little Panoche Creek fan (fig. 67). The positions of the concentric contour lines indicate that the present fan apex is 2–3 miles downslope from the mountain front (see pl. 7 for complete outline of fan) and that the old alluvial slope upstream from the apex was mainly an erosional surface. The soils data indicate a general decrease in grain size in the downslope direction. The fan-segment boundaries and the distribution of the younger alluvium (particularly the conspicuous lobes of sandy deposits) both show that most of the deposition of the younger alluvium has occurred on the north and east sides of the fan and that little deposition has occurred in the central part of the fan, where older soils and clayey younger soils predominate. The fan-segment boundaries and the areal distribution of the older and younger alluvium also indicate that the overall amount of deposition of the younger alluvium was small compared to the other fans in western Fresno County. The small amount of deposition may be due partly to the fact that the Little Panoche Creek drainage basin is the only source area studied that is underlain by a large amount of resistant Franciscan rocks.

The information shown in figures 66 and 67 can be used to reconstruct the history of the Little Panoche Creek fan. A fan-shaped alluvial slope was formed after the initial deformation of the Tulare Formation. The upper part of the slope was a small narrow erosional area, and the lower part of the slope was a large broad depositional area. The slope of the valley floor represented by the upper terrace was continuous with the upper part of the alluvial slope. Remnants of the alluvial slope are represented in figure 67 by the areas of older alluvium. The uppermost (A–B) and lowest (D–E) segments (fig. 66) were formed at this time. The uplift that caused the cutting of the upper terrace warped the uppermost segment (A–B) and determined the location of the present fan apex. The uplift also caused accelerated erosion that ultimately decreased the stream gradients in the reach upstream from the area of deposition. The fan segment B–C was deposited. Erosion that accompanied the cutting of the middle terrace caused another decrease in stream gradient in the reach upstream from the area of deposition, and the fan segment C–D was deposited at a lower gradient than that of the fan segment B–C. The segment C–D occurs on both sides of the fan which means that the stream changed position on the fan and cut through the segment B–C. Change in the position of the entrenched stream is plausible because the present-day stream channel is shallow and narrow enough at the apex to allow floods to top its banks, as it did during a flood in September, 1958, and to form natural levees such as those indicated by the 350-foot contour line of figure 67. During the deposition of the fan segments B–C and C–D, slight amounts of deposition partly covered the older alluvium on the fan segment D–E. Areas of older alluvium, however, are not exposed on the downslope part of the east side of the fan, which has been the area of principal deposition for more than a century. A new fan segment whose slope is gentler than the segment C–D and whose slope is partly controlled by the gradient of the present stream, probably is forming on this part of the fan.

The segment B–C probably had a larger areal extent formerly. Before deposition of the segment C–D, B–C would have intersected the surface of the old alluvial slope (D–E) at a point between C and D. Subsequent deposition of the fan segment C–D made an area of active deposition that probably encroached both upslope and downslope from the area where the former slopes intersected. The D fan-segment boundary line has a lobate shape that indicates downslope expansion of the fan segment. The C fan-segment boundary line, however, does not have a shape that suggests progressive overlapping by the adjacent lower fan segment.

The Little Panoche Creek fan is representative of fans whose segmentation is associated with progressively gentler stream gradients during their history. Although intermittent uplift steepened the stream gradient upstream from the mountain front, the fan apex was 2–3 miles downslope from the mountain front, and the successive areas of deposition were downstream from reaches of progressively gentler stream gradients. Each new stage of fan deposition was farther downslope and on a more gentle gradient than the previous stage.

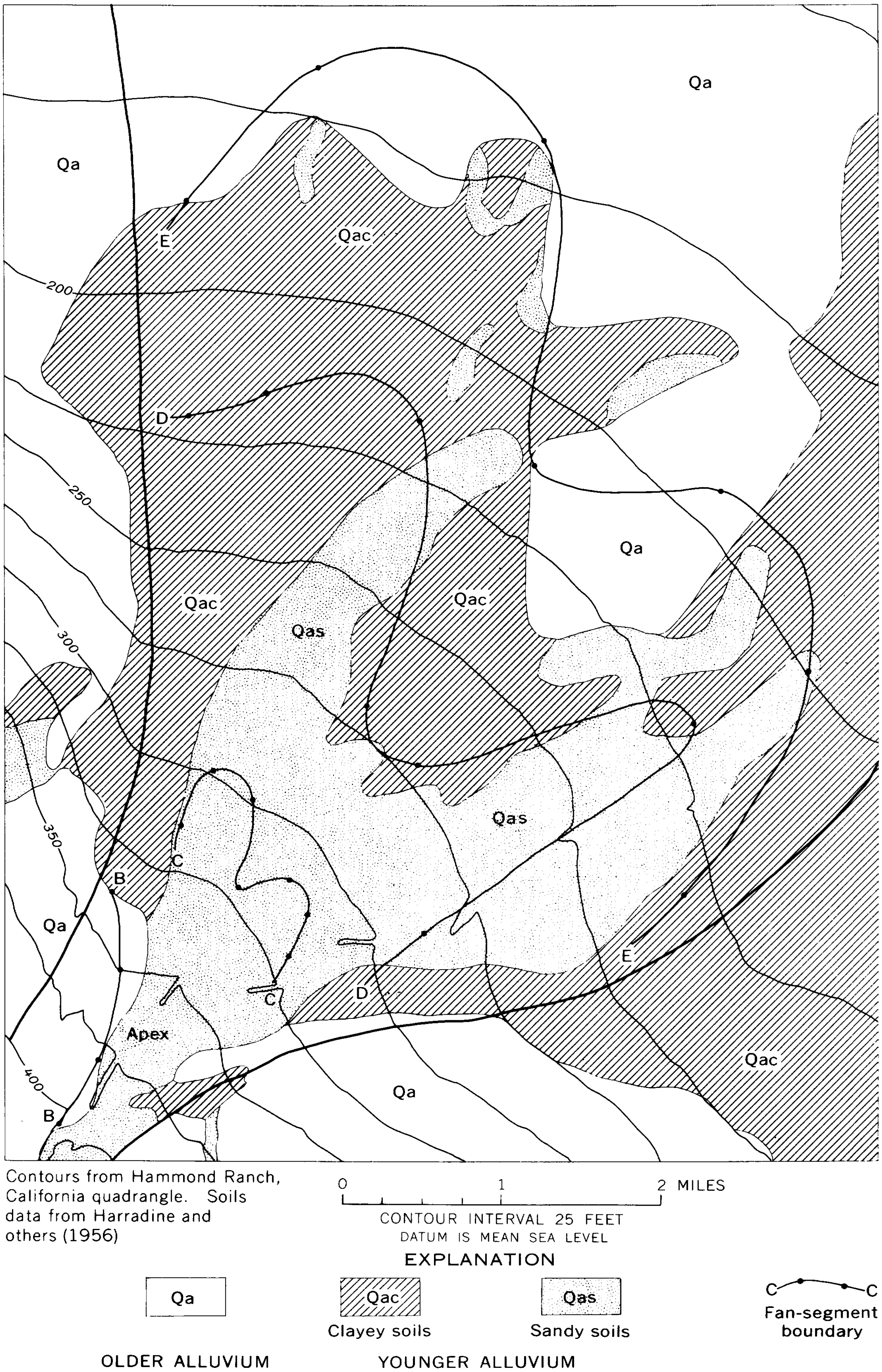

FIGURE 67.—Soils and fan-segment boundaries of the Little Panoche Creek fan.

FANS ASSOCIATED WITH PROGRESSIVELY STEEPER STREAM GRADIENTS

Most of the fans studied show a sequence of fan-segment development that is reversed from the Little Panoche Creek fan—their uppermost segments are the youngest and their lowest segments are the oldest. The youngest terrace (or stream channel of a century ago) has a slope that is continuous with the upper fan segment (fig. 60). Before the current period of fan-head trenching, the areas of most active deposition were just downstream from the mountain front. The tectonic history of most of the drainage basins is similar to that of the Little Panoche Creek basin, except that the upper parts of the fans have not been warped appreciably. The gradients of the streams above the apexes have become progressively steeper, as is shown by the downstream terrace-gradient divergence upstream from the mountain front in figure 66. In contrast, the apex of the Little Panoche Creek fan is 2–3 miles downslope from the mountain front, and the reach upstream from the area of deposition has been intermittently decreased in gradient.

Figure 68 shows diagrammatically four successive stages in the development of a single fan segment, for a fan whose upper segment is the youngest. In profile A the fan and stream channel for a short distance upstream from the apex have developed a common gradient. This equilibrium then is destroyed by rapid monoclinal folding along the mountain front, which raises the valley bottom about 40 feet, steepening the stream gradient (profile A′). The deformation induces trenching headward from the mountain front (profile B) leaving parts of the uplifted stream channel as paired terraces. The terraces probably were continuous with prior fan surfaces which have since been buried by the deposits of younger fan segments. A substantial increase in the rates of erosion and deposition results in the rapid accumulation of sediments on the fan, particularly on its upper part, where the emergent stream enters a reach characterized by a reduction in gradient. In profile C, erosion has deepened the valley and deposition raised the fan surface until a common gradient has again been attained. The fan surface now has two segments which appear as straight lines on the radial profile. Deposition continues on the fan, and the valley upstream from the apex is aggraded in order to maintain a common gradient (profile D). The upper fan segment is extended farther onto the fan, and the change in slope moves from Y to Z. Most of the deposition has occurred on the upper fan segment, but enough deposition occurs on the rest of the fan to prevent the formation of well developed soil profiles.

The above discussion postulates that a fan segment that appears as a straight line on a radial profile may be the result of rapid uplift of the drainage basin followed by a time of little or no uplift, during which the stream channel and fan attain a common slope. A fan segment that appears concave may represent the case in which a fan surface has not had sufficient time to develop a constant slope after a period of rapid uplift. (See profile B, fig. 68). A concave surface also could be the result of a period of gradual continuing uplift. During a period of continuous uplift the stream gradient would gradually steepen and the depositional slope of the fan also would become progressively steeper.

The segmented fans of western Fresno County indicate at least three or four episodes of uplift of the different parts of the Diablo Range rather than continuous uplift of the entire range. The profiles differ a little from fan to fan, indicating differences in the times and amounts of uplift and rates of erosion in their respective structural areas and drainage basins. Part of the uplift probably occurred in the last 3,000 years, as is indicated by the Arroyo Hondo radiocarbon date.

Alluvial fans whose drainage basins are in a different tectonic setting than that of western Fresno County are those along the southern border of the San Joaquin Valley, about 100 miles to the southeast of the area studied. Figure 69 shows the strikingly similar radial profiles of two large alluvial fans whose drainage basins head in the San Emigdio Mountains. These two profiles are markedly different from the radial profiles of western Fresno County fans because they have pronounced concave middle segments. The geologic environment of the two areas is similar in many respects. Both have similar climate and drainage-basin characteristics.[2] The Santiago Creek drainage basin has a total relief of 5,080 feet, and the rocks exposed in the drainage basin consist of 90 percent sedimentary rocks and 10 percent metamorphic and plutonic rocks. The San Emigdio Creek basin has a total relief of 7,330 feet, and the rocks exposed in the drainage basin consist of 40 percent sedimentary rocks and 60 percent metamorphic and plutonic rocks. Terraces that diverge downstream are common upstream from the mountain front (McGill, 1951, pl. 2).

The major difference between the San Emigdio Mountains and the Diablo Range is in their structural history and tectonic setting. The Diablo Range has been formed by anticlinal and monoclinal folding, and by minor faulting. The main part of the San Emigdio

[2] Drainage basin information for the fans heading in the San Emigdio Mountains from J. M. Parsons, Calif. Dept. Water Resources (oral communication, July 1961).

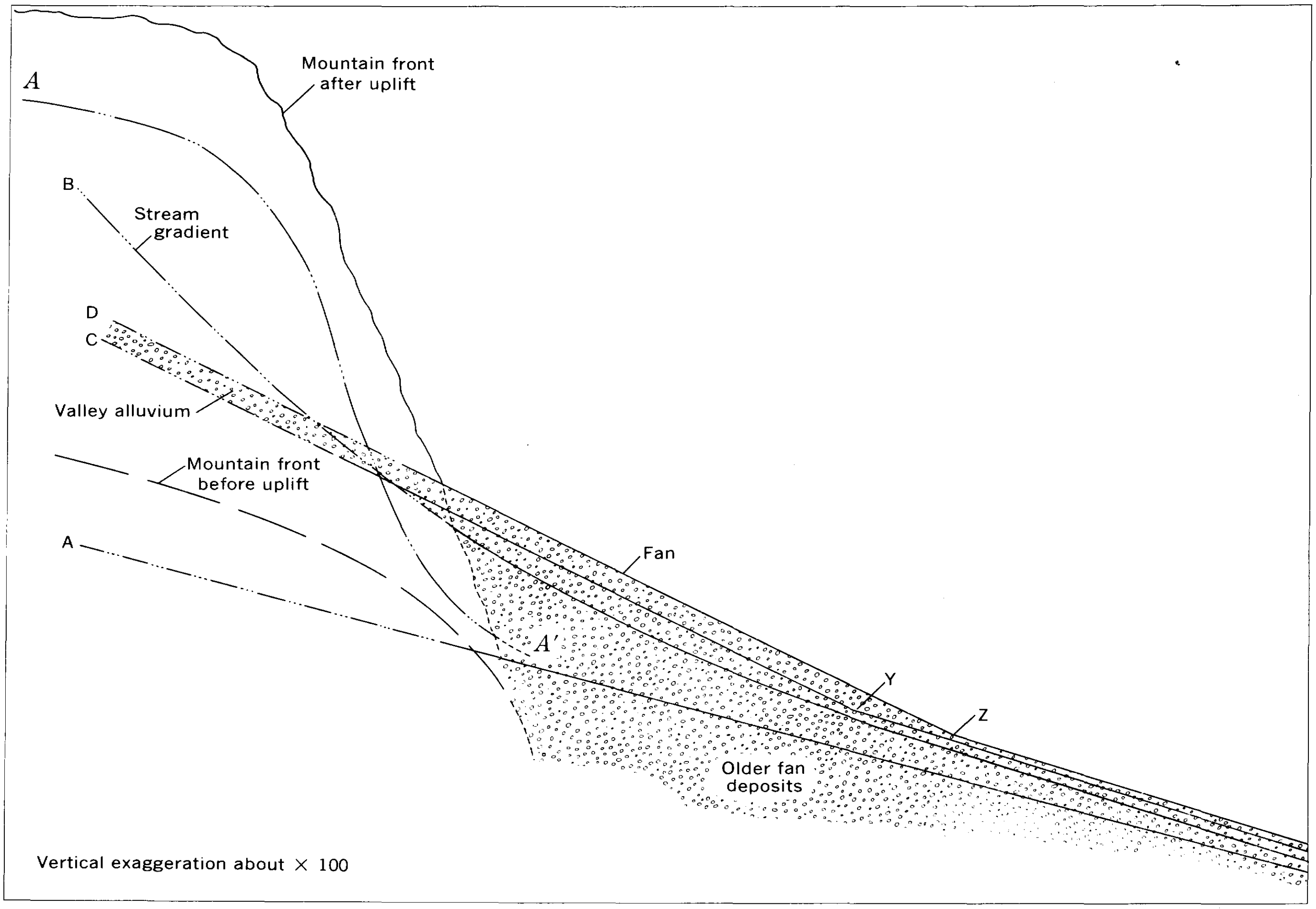

FIGURE 68.—Diagrammatic sketch showing stages of fan-segment development.

Mountains is characterized by thrust faulting and tight asymmetric folds that lean toward the San Joaquin Valley. The marked difference in radial profiles of the two fans on the northern side of the San Emigdio Mountains as compared to those for fans in western Fresno County is ascribed by the author to the different tectonic history of the two source areas.

Large changes in slope between fan segments presumably indicate greater uplift and steepening of the valley upstream from the apex than do small changes in fan slope. Uplift in western Fresno County has been mainly as monoclinal and anticlinal folding. The valley slopes could not have been made much steeper than the fan slopes if there had been a similar fault-block tilting of the mountains and fans; such fans there would have little or no segmentation. An example is the Trail Canyon fan (fig. 55) on the east side of the Panamint Range. Eastward tilting of this part of the Panamint Range and Death Valley has been described by Greene and Hunt (1960). On the west side of the Panamint Range, by contrast, some of the valley slopes have been steepened more than the fan slopes, and the segmentation of these fans is more pronounced.

Some stages of alluvial-fan development for fans whose upper segment is the youngest are summarized in figure 70. A stream channel and fan have developed a common gradient as shown in diagram 1, figure 70. Uplift steepens the stream gradient and the new fan deposits are laid down with a steeper gradient. The stream channel gradient may have been steeper after the uplift, but the slopes in diagram 2 represent equilibrium conditions near the end of the stage. Another period of uplift makes the third segment, completing a three-segment fan. Deposition continues on the fan and the stream channel upstream from the fan apex maintains the same slope as the fan by aggrading slightly (diagram 4). A temporary period of channel trenching occurs (diagram 5) and the low terrace and upper fan segment have a common slope. The downstream end of the fanhead trench has the same gradient as the adjacent lower fan segment. Valley alluviation and stream entrenchment (diagrams 4 and 5) may occur several times during the development of a fan as is

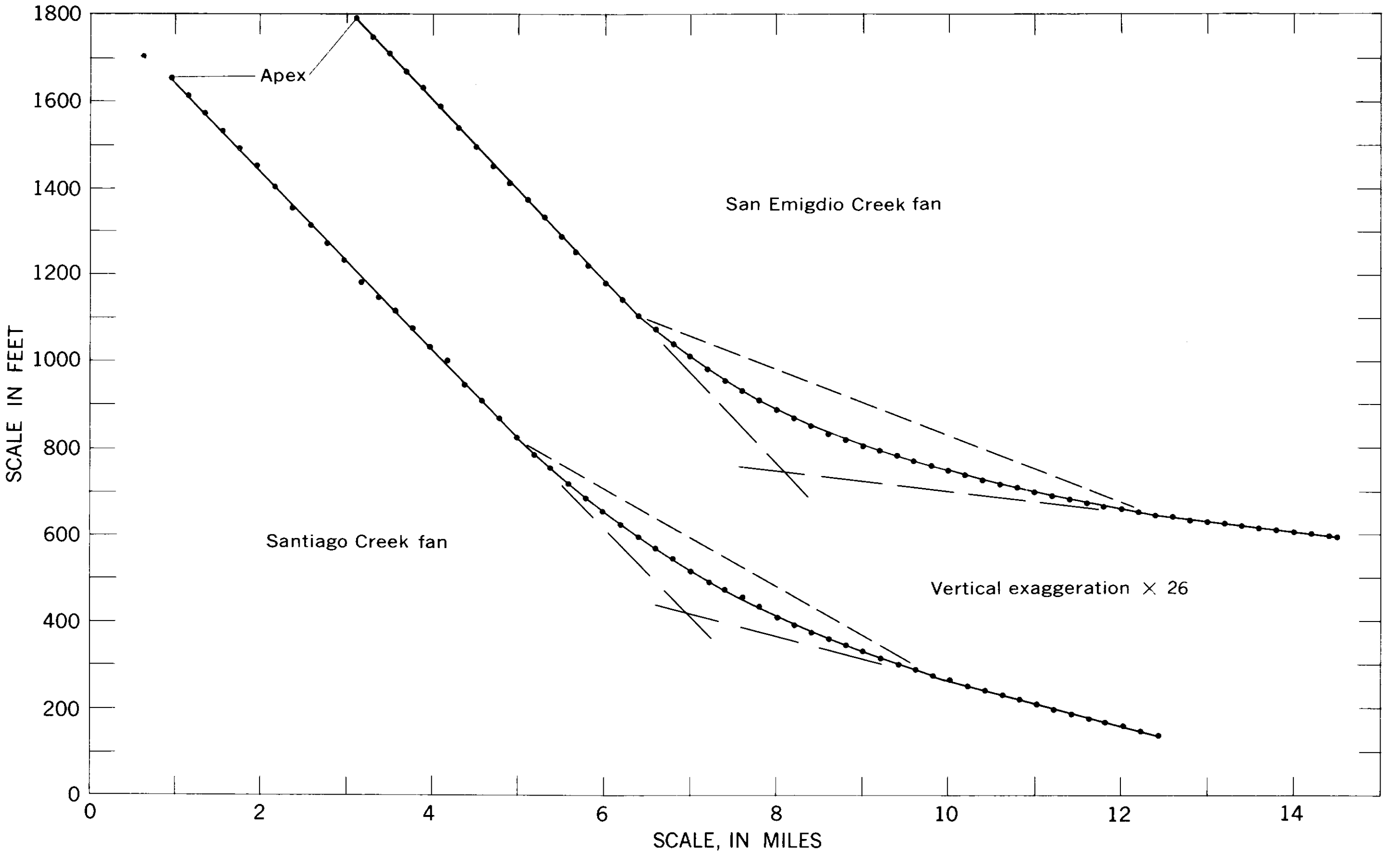

FIGURE 69.—Radial profiles of the San Emigdio Creek and Santiago Creek fans.

shown by old terrace and channel patterns on aerial photographs. Deposition probably was occurring mainly on the upper segment a century ago, but channel trenching then caused deposition to occur mainly on the middle segment as the end of the channel moved downslope (diagram 5). Present-day deposition is restricted to the area downslope from the first or second fan segment of most fans.

When an area becomes tectonically stable, permanent trenching of the fans occurs as the mountains are eroded and the streams cut below the fan apexes. Erosion gradually removes the deposits that are higher than the main channels, and the fans become alluviated slopes that are characterized by large areas of erosion as well as areas of deposition. Such slopes are common in the Basin and Range Province of California and Nevada.

Fan segmentation should be helpful in deciphering part of the tectonic and erosional history of the drainage basins of other mountain ranges. Fans are formed adjacent to a mountain front after uplift, and renewed uplift that causes progressive steepening of the stream gradients will keep the principal loci of deposition close to the mountain front. Segmentation on such fans can be attributed chiefly to tectonic causes and the youngest fan segment will be adjacent to the mountain front. If renewed uplift does not occur the stream will cut downward establishing progressively gentler gradients, and the locus of principal deposition will be progressively farther downslope from the fan apex. If it is not segmented the fan may have a smooth concave profile. Fan segmentation associated with progressively gentler stream gradients is common, however, and can be attributed to climatic as well as tectonic causes. In western Fresno County this type of fan history (Little Panoche Creek fan) can be shown to have been caused chiefly by uplift of the mountains several miles upstream from the present fan apex. However, many segmented fans in the Basin and Range Province of California and Nevada also have surficial deposits that are older near the mountains and younger near the base of the fan. Climatic changes during fan deposition should be considered as a possible dominant cause of the progressive decrease in stream gradient and associated segmentation of many of the basin and range fans.

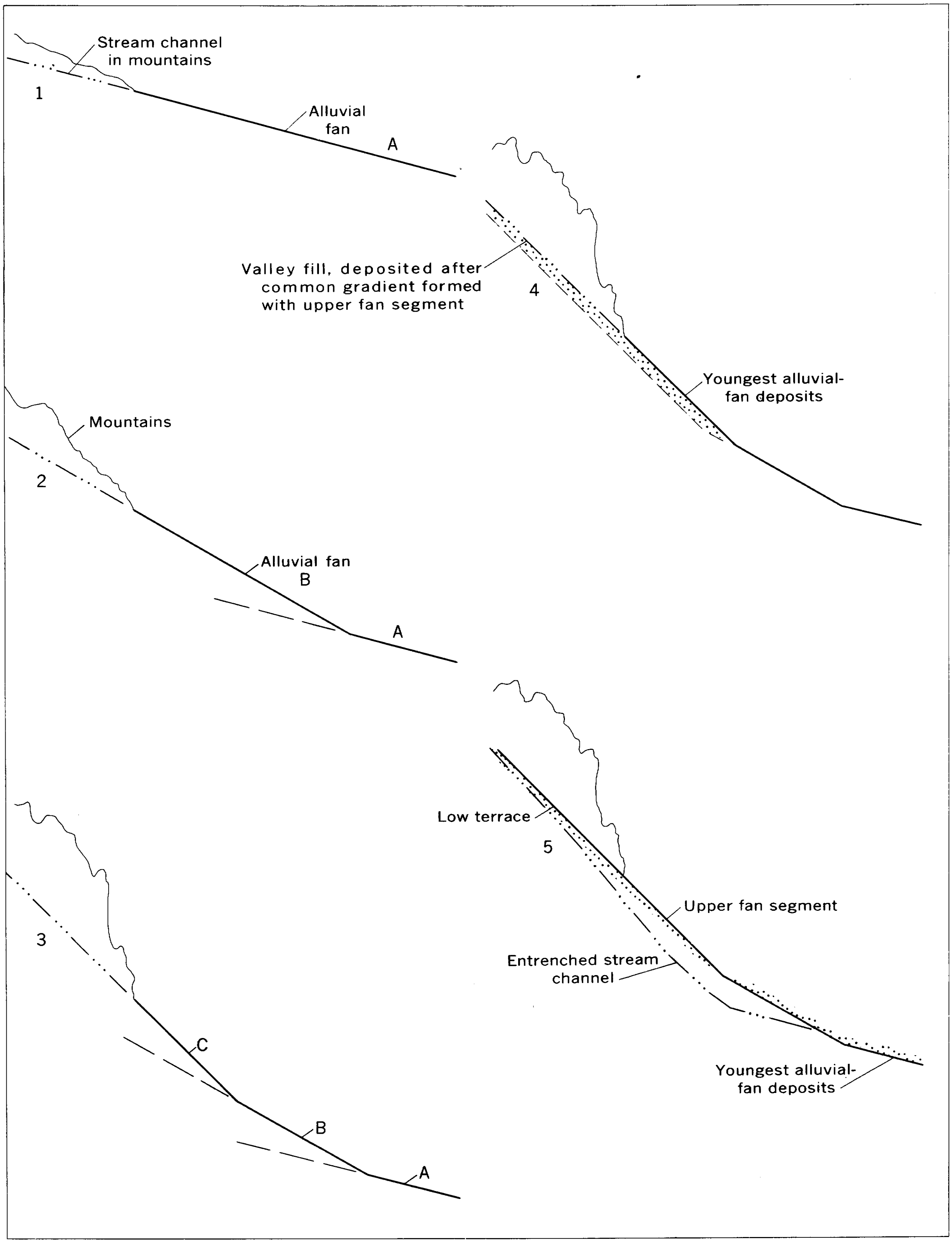

FIGURE 70.—Diagrammatic sketches showing stages of alluvial-fan development. Successive alluvial-fan surfaces A–C are shown in alphabetical order.

CROSS-FAN PROFILES

Cross-fan profiles parallel to the mountain front show the convexities of the alluvial fans (figs. 73, 74). The amount of convexity depends on where the profile is drawn and on the coalescing of adjacent fans. The convex shape of a series of cross-fan profiles shows that an alluvial fan is part of a gently sloping cone. The central part of the fan generally is higher than the sides because of greater deposition on the central part.

Stream channels control the place of deposition, and the present-day channel deviation from the medial position on the fanheads of 75 fans is shown in figure 71. The distribution of channel deviation is fairly uniform from the medial position to a deviation of about 50°, but two-thirds of the channels are within 30° of the medial position. Only three channels have a deviation of more than 50°. Thirty-nine streams have an average deviation toward the northwest of 26°, and 35 streams have an average deviation toward the southeast of 23° The predominance of stream channels within 30° of the medial position implies that more deposition occurs there than in areas farther from the medial position which are not frequented as often by streams.

CHANGE IN SHAPE DOWNSLOPE

The progressive downslope decrease in the convexity of cross-fan profiles is well illustrated in the area. The fans of Capita, Chaney Ranch, and Marca Canyons are described as examples (figs. 72 and 73). The respective drainage areas for these fans are 2.6, 0.53, and 1.9 square miles. The fan of Chaney Ranch Canyon is small and coalesces with the other fans within 2 miles of the mountain front.

The Capita Canyon fan excellently displays features characteristic of many fans whose streams head in the foothill belt. The convexity of the upper part of the fan (downslope to profile *D–D′*) stands out clearly, as shown by the conspicuous curvature of the contour lines. The downslope decrease in convexity is well shown by the progressive straightening of the contour lines toward the base of the fan. The depth of the fanhead trench decreases markedly downslope from the upper fan segment and the stream channel becomes a distributary channel that is about 2 feet deep.

The six cross-fan profile lines *A–A′* through *G–G′* are spaced at half-mile intervals except for the quarter-mile spacing between *A–A′* and *B–B′* (figs. 72 and 73). The profiles across the lower parts of the fans are flat compared to the profiles across the upper parts of the fans. The decrease in the convexity of the cross-fan profiles progressively farther from the mountain front occurs much as would be expected in a series of profiles drawn progressively farther from the apex of part of a true cone.

STREAM CHANNELS

Leopold and Wolman (1957) described three characteristic channel patterns of rivers: braided, meandering and straight. A braided channel is characterized by the repeated division of the channel around islands of alluvium; a meandering stream has a series of regular looplike bends; a straight channel has little or no curvature.

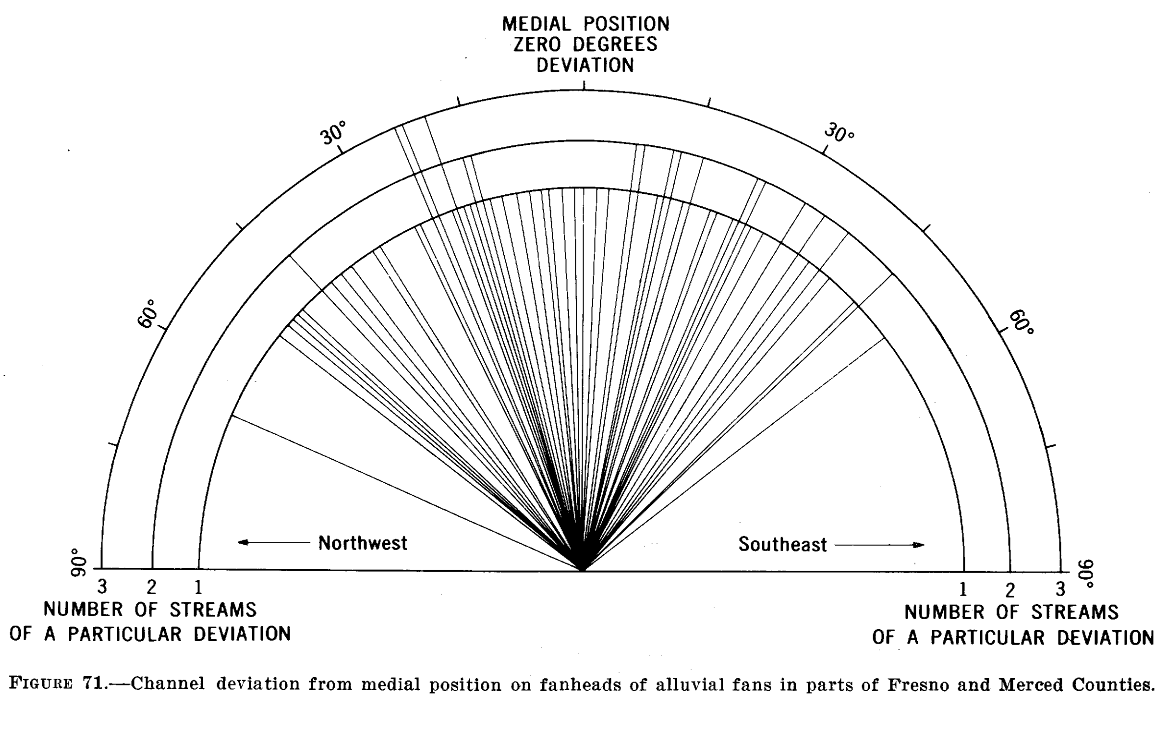

FIGURE 71.—Channel deviation from medial position on fanheads of alluvial fans in parts of Fresno and Merced Counties.

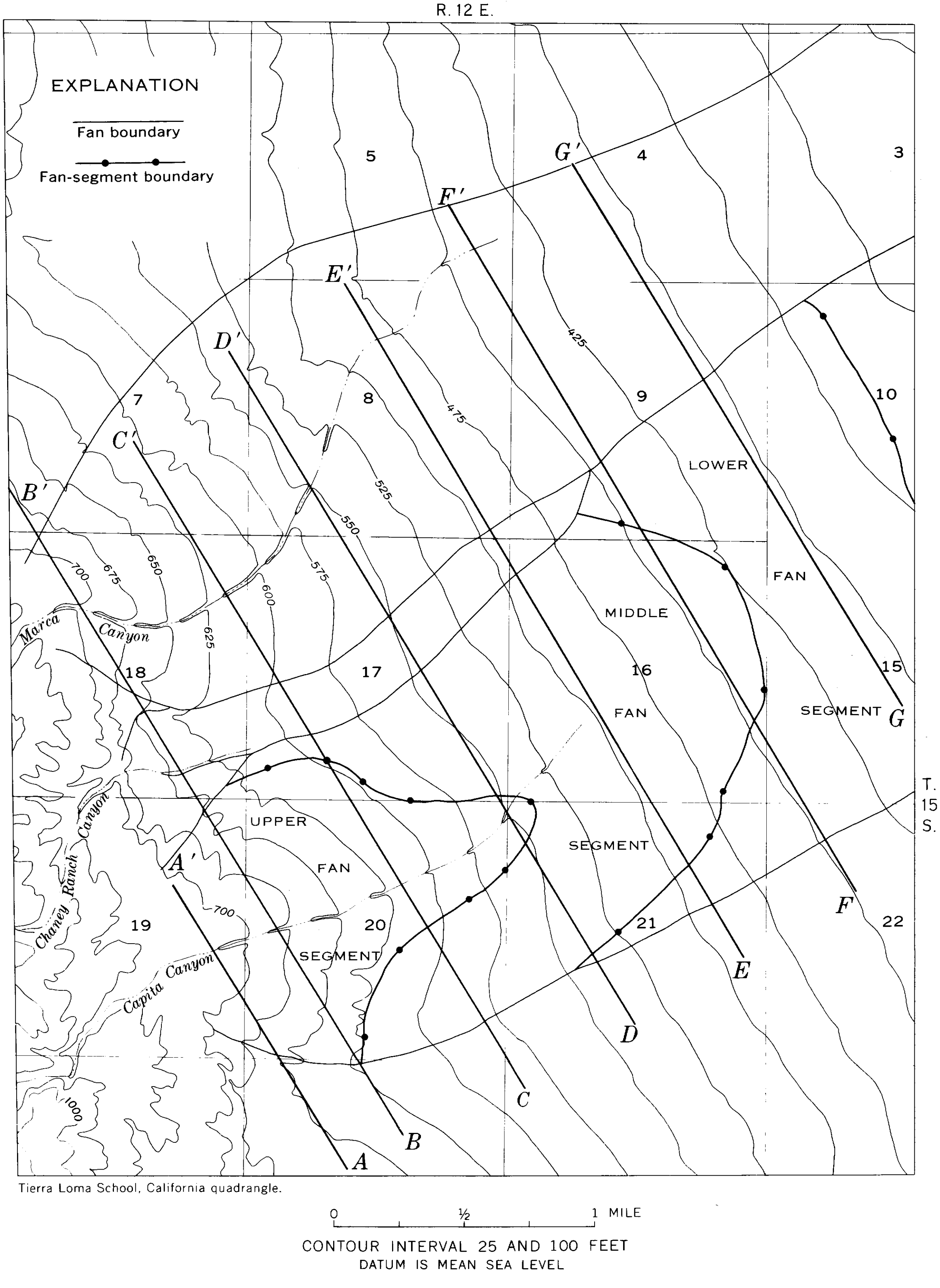

FIGURE 72.—Topographic map of the alluvial fans of Capita Canyon, Chaney Ranch Canyon, and Marca Canyon. Profiles *A–A'* to *F–F'* are shown in figure 73.

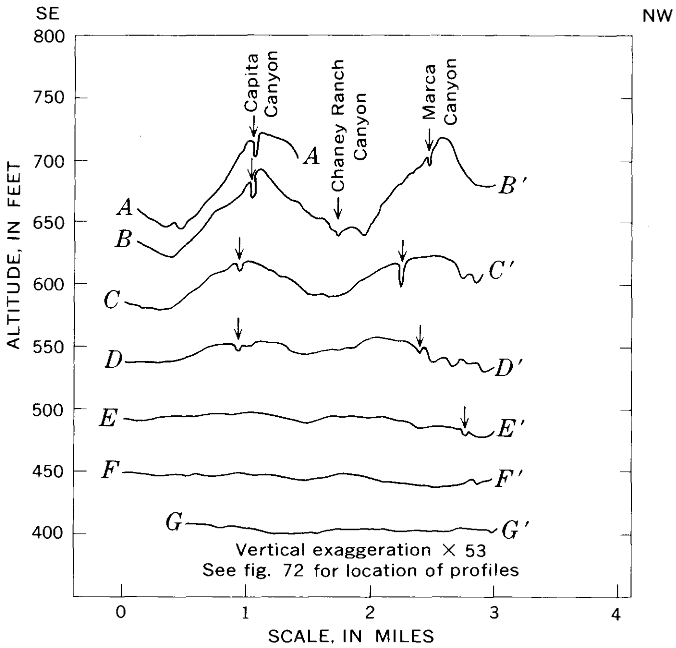

FIGURE 73.—Cross-fan profiles of Capita Canyon, Chaney Ranch Canyon, and Marca Canyon fans. Vertical exaggeration × 53. See figure 72 for location of profiles.

All three of these channel patterns are common on the fans in western Fresno County. The most common channel pattern of the fanhead trenches is the meandering type, as illustrated by Panoche Creek. (See fig. 79.) Panoche Creek also has some relatively straight sections of channel, and straight channels are common on the alluvial fans of ephemeral streams. (See Capita Canyon, fig. 72). In the straight sections, the thalweg, or the deepest part of the channel, generally weaves back and forth between the channel banks. This also occurs on straight stretches of perennial streams (Leopold and Wolman, 1957, p. 53–55). The braided channel pattern is characteristic of the distributary channels downslope from the end of the fanhead trenches but is not present in the fanhead trenches themselves.

A cross-fan profile drawn about parallel to the east edge of the Panoche Hills, and less than a mile from the hills, is show in figure 74. The stream channels are commonly on the highest parts of the fans, but they may be on any other part of a fan, as shown by the arrows in figure 74. Streams, such as the one occupying Gres Canyon, deposit so little material that they remain at the bottom of the trough formed by two adjacent large fans. The fans have a variety of cross-sectional shapes, many of which reflect the influence of the size and shape of adjacent fans. The profile between mileage markers 1–4 on the line of the section is representative of an area where several fans have coalesced.

The main channels of some of the streams do not flow at right angles to the contours of the fan. The stream channels of Marca Canyon (fig. 72, secs. 17, 18) and part of the channel of Arroyo Hondo are examples of these streams. Arroyo Hondo apparently is migrating sideways toward the downslope side of the channel; at the present time the downslope bank is 7–12 feet high in contrast to the 2- to 4-foot bank on the upslope side from which the channel has moved. These anomalous positions of stream channels may have been started by the entrenchment of a minor channel. Once such an entrenchment is started, natural levees tend to be concentrated on the lower side of the channel. The entrenchment of the channel and the formation of natural levees temporarily prevent the stream from breaking out of its channel and flowing directly down the slope. Natural levees of this type are shown by the contour lines along parts of the stream of the Marca Canyon fan (fig. 72, secs. 8, 17).

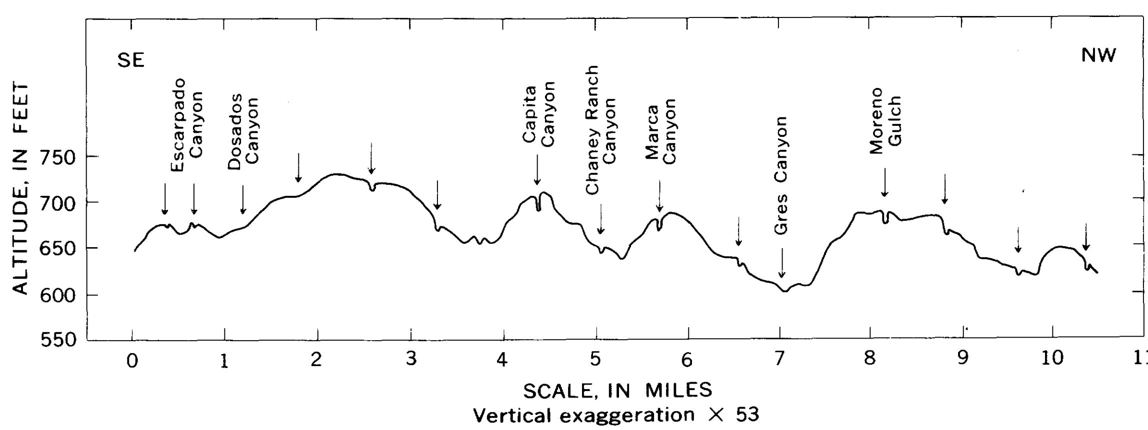

FIGURE 74.—Position of stream channels on the fanheads of the piedmont plain east of the Panoche Hills.

Natural levees are a common feature on most fans in the area. Many natural levees were formed before the recent entrenchment of the streams, and natural levees are being made along the shallow reaches of the channels at the present time. Figure 75 shows mudflow deposits on the natural levees of Arroyo Hondo. The channel was shallow enough for the mudflow to flow over the banks and spread out to add another increment to the natural levees. Bushes helped to keep the deposition within 100 feet of the channel in most places. Natural levees along the intermittent streams are made of water-laid sediments that probably were deposited as the velocity of flow decreased after the stream left the main channel. Natural levees about 3–5 feet high are shown in figure 79 along the downslope part of Panoche Creek in the NW¼ sec. 10 and the NE¼ sec. 20, T. 14 S., R. 13 E.

FANHEAD TRENCHES

The stream channel of almost every fan in the area is entrenched into the upper part of the fan. The fanhead trenches of the ephemeral streams are narrow and the fanhead trenches of the intermittent streams are wide. The sides of these incised channels in many places are nearly vertical walls. The depth of the fanhead trenches decreases away from the mountains, and eventually the channel splits into several distributary channels.

Fanhead trenches are a natural feature of alluvial fans, and traces of abandoned trenches can be found on several fans. The present cycle of arroyo cutting already had started on some fans when the first land survey was made in the early 1850's. Later surveys and the accounts of some of the first settlers show that channel trenching started on other fans in the period between 1875 and 1885. This date is about the same as the time of the channel trenching in parts of Arizona, Utah, Colorado, and New Mexico (Bryan, 1925). Cattlemen and sheepherders who have lived 30–40 years in the area agree that much of the deepening of these channels has occurred since about 1935, although the channels on most of the fans had their present areal extent by 1930.

Many of the fanhead trenches are terraced. Tumey Gulch has scattered remnants of paired terraces 7–20 feet above the present channel, and Arroyo Hondo has 3- to 5-foot terraces, which are paired in some places. Paired terraces are excellently preserved in the fanhead trench of Arroyo Ciervo, where a narrow slot about 8–15 feet wide has been cut 5–9 feet deep into the bottom of the first-stage fanhead trench to form the terrace. The channels of the large intermittent streams are flanked by broad terraces 3–10 feet above present stream grade. Most fanhead terraces have been formed since about 1935.

The fanhead trench of Tumey Gulch a mile from the edge of the foothills is shown in figure 76. At this point the channel is 37 feet below the surface of the fan. The bushes along one side of the channel indicate the location of a narrow terrace remnant. The original land surveys show that Tumey Gulch had the same extent and position in 1854 as it does today, but in 1854 the channel was shallow enough for the surveyors to walk across as they chained the section lines.

FIGURE 75.—Mudflow deposits on the natural levees of Arroyo Hondo. Arrow marks outer edge of mudflow. View northwest from the SW¼SE¼ sec. 2, T. 17 S., R. 14 E.

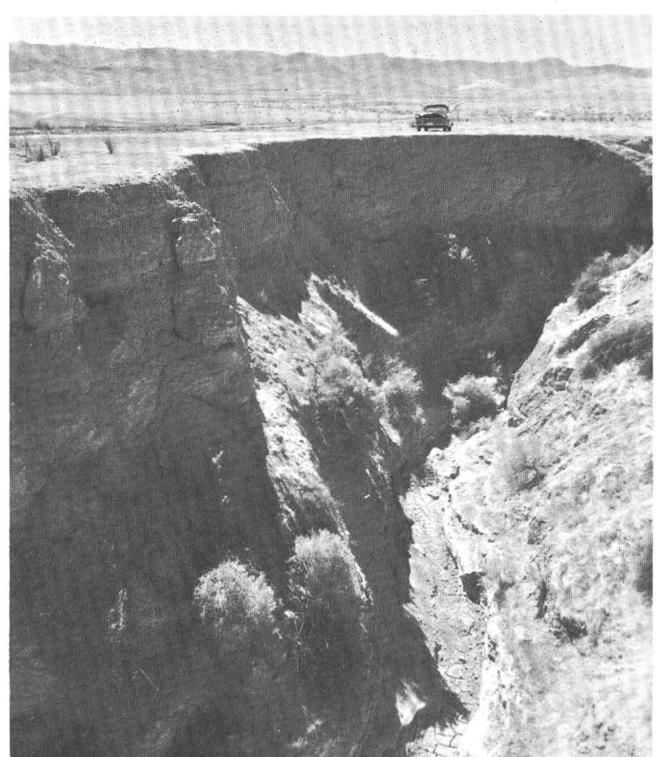

FIGURE 76.—The fanhead trench of Tumey Gulch looking upstream from SW¼SW¼ sec. 29, T. 15 S., R. 13 E.

The changes in the depth of Tumey Gulch between 1921 and 1955, based on data from topographic maps, are shown in figure 77. The fanhead trench terminates at the downslope end of the upper fan segment. The shallow channel shown in the middle fan segment is one of several distributary channels. In 1921 the fanhead trench was as much as 20 feet deep. By 1955 the upslope part of the trench was partly filled, but in places the trench was deeper than 30 feet and the deepest part was moving upstream. More than a mile of the downslope end of the 1955 trench is a continuation of the slope of the middle fan segment. Similar fanhead-trench and fan-gradient relations exist for other fans (fig. 61).

Figure 78 shows the changes in the depth of the fanhead trench of Arroyo Ciervo between 1921 and 1956. The 1858 maps do not show a gully, but the 1880 mapping reveals that a gully extended to the downslope end of the upper fan segment. Topographic maps show the 1921 channel to be 4–6 feet deep and the 1955 channel to be as much as 26 feet deep. Most of the channel deepening between 1921 and 1956 occurred within the upper fan segment and, like the channeling in Tumey Gulch, the deepening increases upstream. The channel entrenched in the Arroyo Ciervo fan differs from that in the Tumey Gulch fan because it extends downslope past the upper segment.

Unlike the channel widths of ephemeral streams, which apparently have not changed much since first reported, the channel widths of the intermittent streams have increased from about 20 to several hundred feet during the past 100 years. The pairs of numbers in figure 79 show changes in the width of Panoche Creek between 1854 and 1959. Many sections of the channel are from two to six times wider than they were in 1854. The lines of measurement along which the width was measured generally are not perpendicular to the stream channel because the surveyors in 1854 noted the channel widths between section corners; therefore the 1959 measurements also were made along section lines.

The length and depth of the channel of Panoche Creek also have changed since 1854. The fanhead trench was 5 miles long in 1854 and 10 miles long in 1959, and the channel has been deepened by erosion in some places as much as 25 feet.

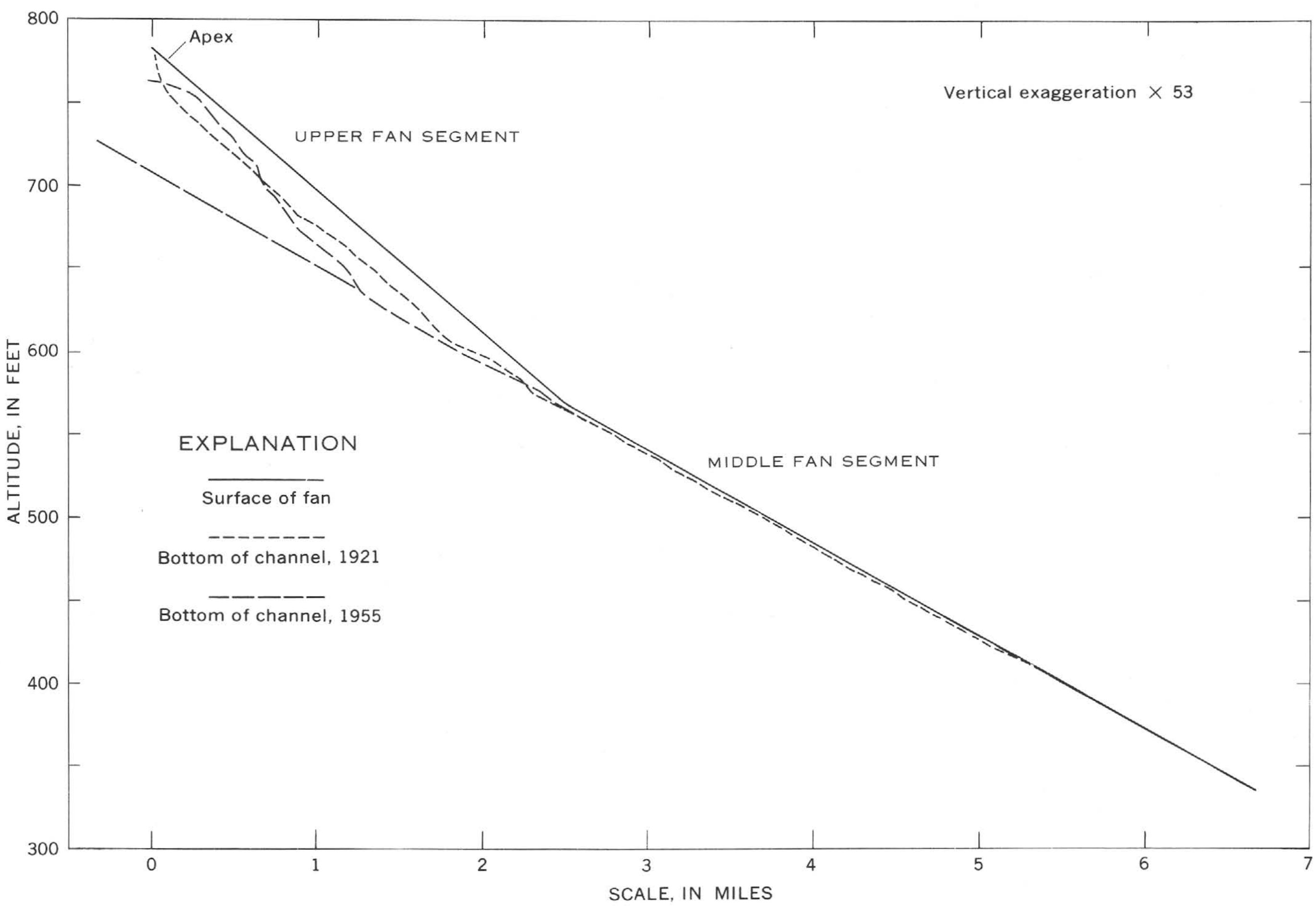

FIGURE 77.—Changes in the depth of the Tumey Gulch fanhead trench, 1921–55.

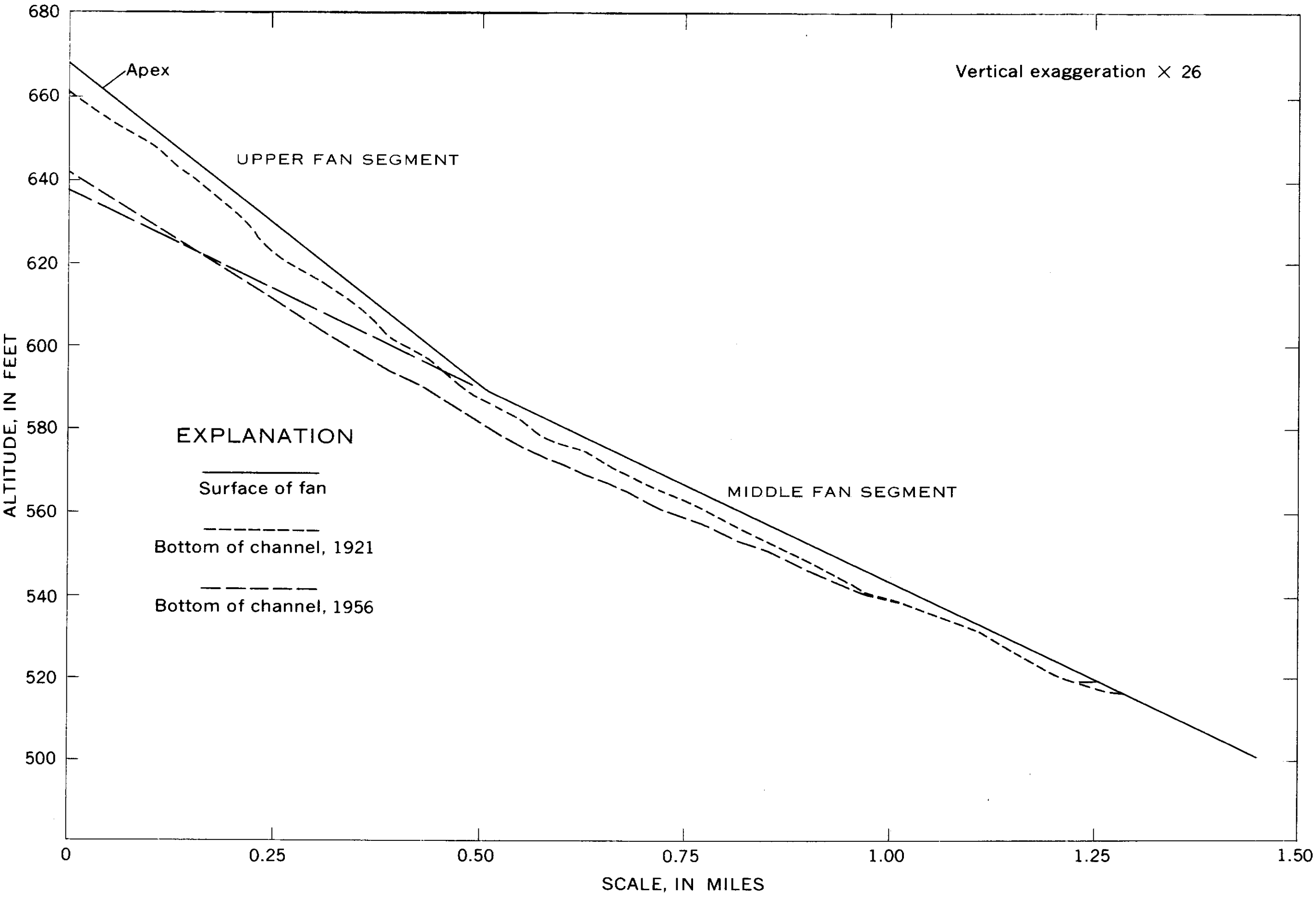

FIGURE 78.—Changes in the depth of the Arroyo Ciervo fanhead trench, 1921–56.

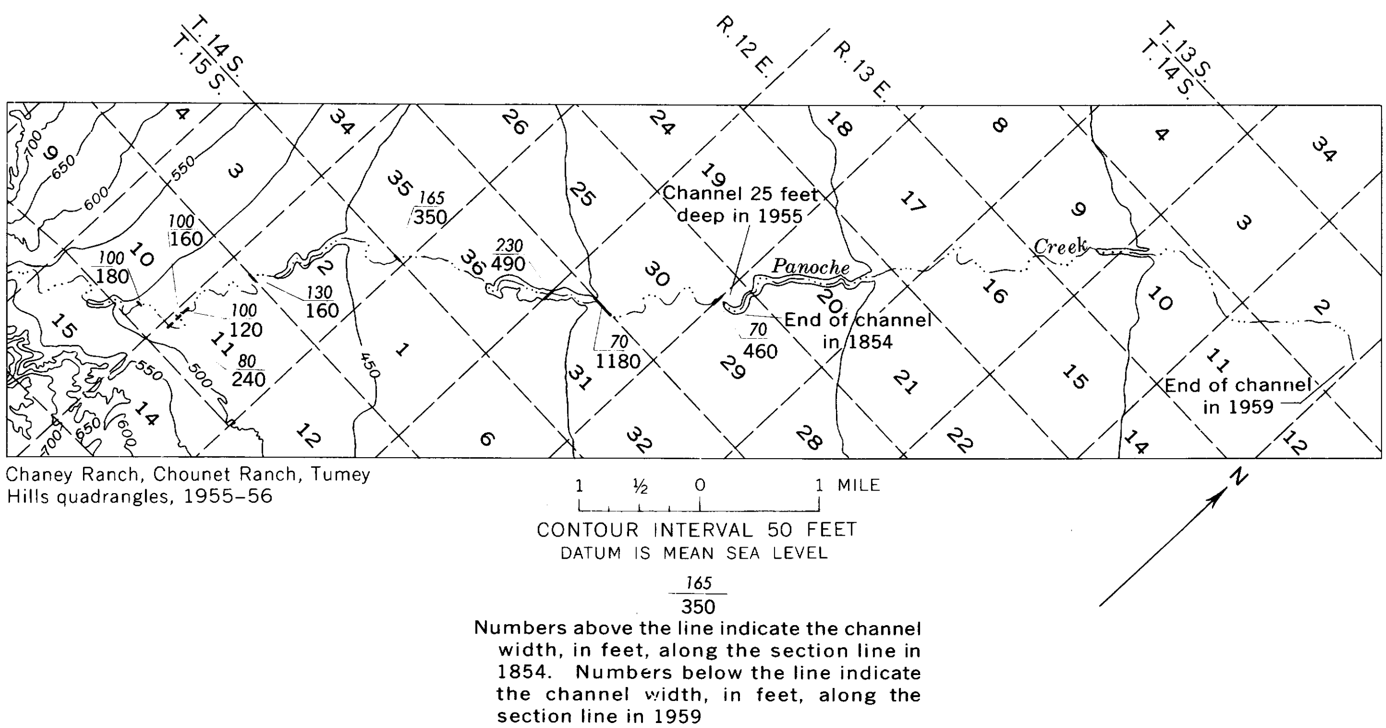

FIGURE 79.—Changes in the width and length of the Panoche Creek fanhead trench, 1854–1959.

The changes in the channel of Panoche Creek are less noticeable on the uppermost fan segment than on the second fan segment away from the hills. The average depth of the channel on the uppermost segment is less than on the second segment, and the width of the channel on the uppermost segment has increased

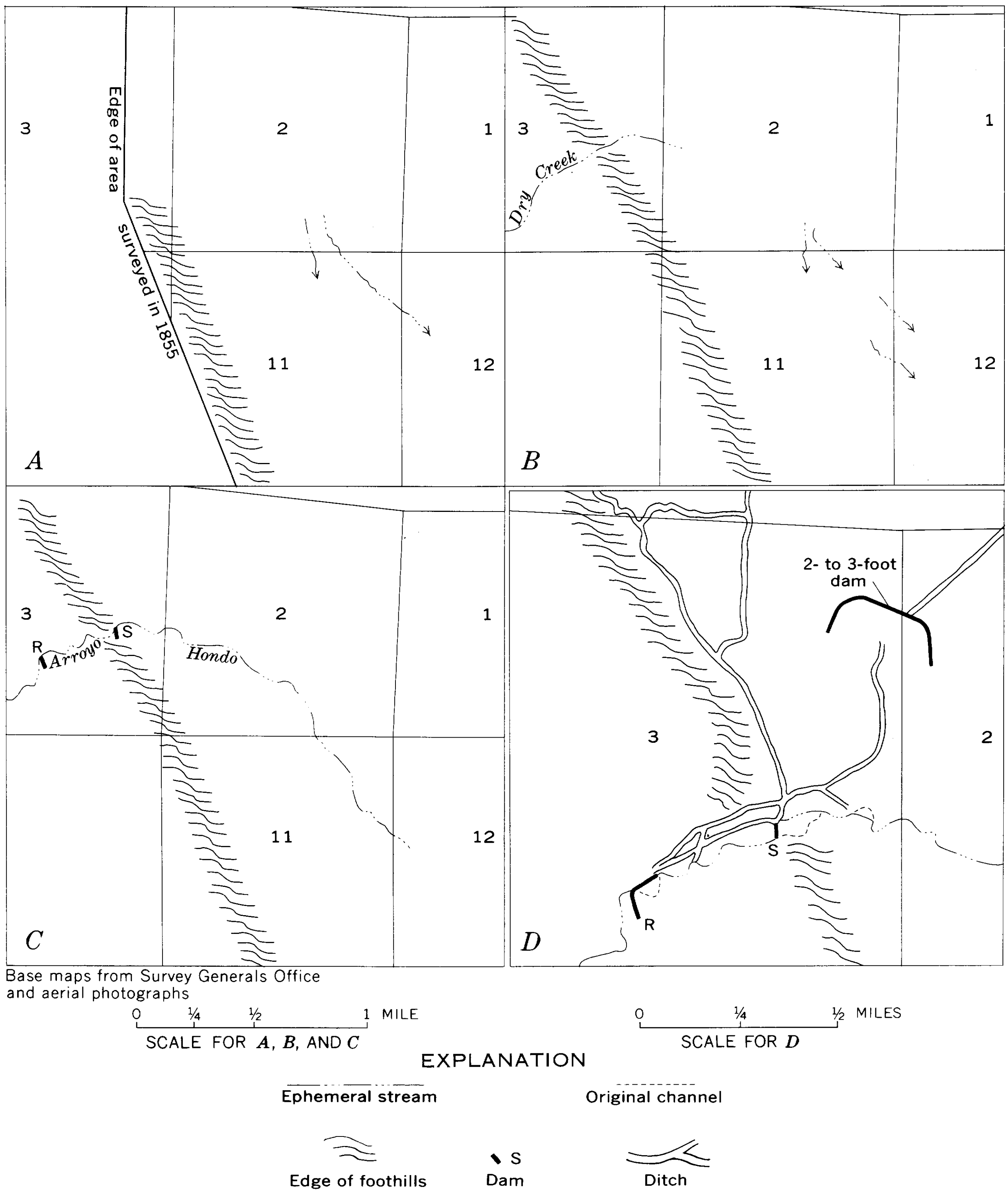

FIGURE 80.—Changes in the channel configuration of Arroyo Hondo, 1855–1954. *A*, 1855; *B*, 1881; *C*, 1924 and 1954; *D*, 1954.

from about one to three times the 1854 width, but the channel width on the second segment has increased from about 2.0 to 17 times the 1854 width.

Some of the changes in Arroyo Hondo (Dry Creek on the 1881 map) since 1855, based on maps made in 1855, 1881, 1924, and 1954, are shown in figure 80. Sometime between 1890 and 1924 the name "Dry Creek" was changed to Arroyo Hondo, which is Spanish for "deep stream," possibly because the channel had been deepened, not only on the alluvial fan but also along the valley in the foothills. In 1855 the entrenched stream either did not exist or it did not extend more than one-quarter of a mile into the valley. Figure 80*A* shows two channels on the Arroyo Hondo fan. These may have been deep parts of some braided distributary channels on the fanhead rather than principal channels. By 1881 a more noticeable channel had formed along the valley of Arroyo Hondo and this channel extended about 0.4 mile onto the fanhead. The distributary channels are still present, but now one is shown to be discontinuous and the other apparently has a new downstream extension. The stream channel had its present position in 1924 and appears to be an extension of the channel near the foothills to the distributary channels farther downslope.

The letters R and S in figure 80*C* and 80*D* mark the location of dams built in 1890 and 1907 respectively. The dams diverted the flow of the stream into ditches which were used by the early settlers to carry water out to the valley. The original channel downstream from these dams is preserved; immediately downstream from dam R it is about 9 feet deep and downstream from dam S about 16 feet deep. In 1959 the channel was 27 feet deep adjacent to dam R and 25 feet deep adjacent to dam S showing that the stream channel had deepened 18 feet adjacent to dam R since 1890 and deepened 9 feet adjacent to dam S since 1907.

Aerial photographs of the fan of Moreno Gulch taken in 1940 showed three deep discontinuous gullies, apparently similar to those on the Arroyo Hondo fan in 1881. Small fans were at the downslope end of the three gullies and at the end of the main channel of Moreno Gulch. Farming of the land prevented the discontinuous gullies from becoming a continuous channel. Entrenched streams apparently have formed from discontinuous gullies in other semiarid regions (Bryan, 1928, p. 279–281; Leopold and Miller, 1956, p. 29–33; Schumm and Hadley, 1957).

CAUSES OF THE FANHEAD TRENCHING

Channel trenching has been ascribed by most authors to periods of increased runoff during which floods deepened stream channels. The increased runoff has been attributed to the removal of vegetation by overgrazing and to climatic fluctuations.

Accelerated erosion in the southwestern States was ascribed to overgrazing by Rich (1911), Bailey (1935), and Thornthwaite, Sharpe, and Dosch (1942). On the other hand, Gregory (1917, p. 132) said that some parts of Arizona not used for grazing present the same features as the areas that were overgrazed. Leopold (1951a) studied the vegetation of several areas in the southwest that had been photographed between 1895 and 1903 and again between 1937 and 1946. He concluded that better quality forage might have been available in some spots at the turn of the century, but his general impression was that there has been little change in the volume of growth during the 50-year interval and therefore that grazing was not a primary cause of arroyo cutting.

It is unlikely that overgrazing was the dominant factor in starting the channel trenching in western Fresno County, because traces of older gullies on some fans indicate that fanhead trenches existed before sheep were brought into California in 1853 and before large-scale cattle ranching was introduced in western Fresno County. Adolph Domengine (oral communication, August 1959), a rancher, said that there are more stock now than in the 19th century because feed and water can be brought in now to support the herds during dry years.

Severe reduction in vegetation might increase the runoff to the streams and perhaps Bryan (1928, p. 281) was close to the truth when he said that "* * * the introduction of livestock and the ensuing overgrazing should be regarded as a mere trigger pull which timed a change about to take place."

Variation in the intensity and amount of rainfall is the most likely regional cause for the fanhead trenches. Richardson (1945, p. 17) and Antevs (1952, p. 382) stated that vegetation is the immediate factor controlling erosion which in turn is controlled by precipitation.

The precipitation records of five U.S. Weather Bureau stations were examined to determine if trends in the amount of rainfall coincided with the times of fanhead trenching. These weather stations are: New Idria in the Diablo Range; Coalinga in a sheltered valley adjacent to the San Joaquin Valley; Mendota Dam station in the trough of the San Joaquin Valley; Fresno on the east side of the San Joaquin Valley; and Sacramento in the southern Sacramento Valley. Their locations and altitudes are shown in figure 81.

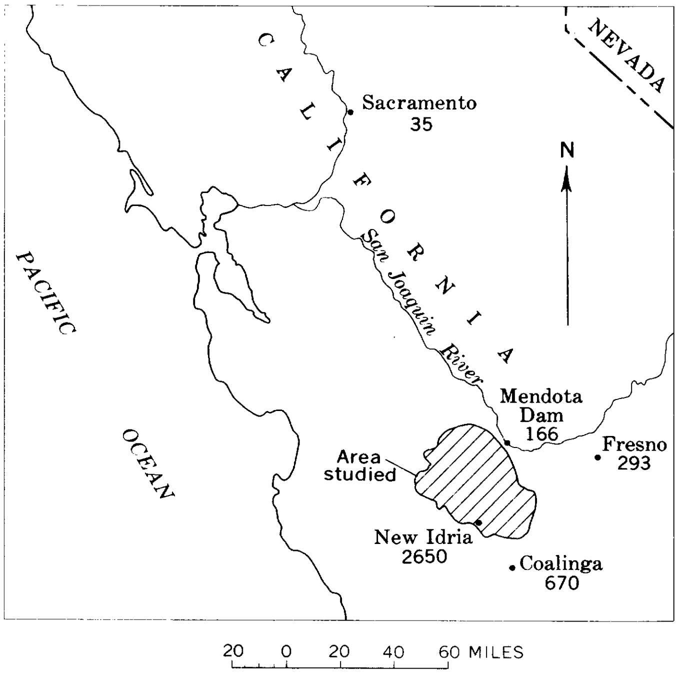

FIGURE 81.—Index map of central California showing location and altitude, in feet, of weather stations referred to in this report.

The trends of the annual rainfall (Weather Bureau climatic year July 1–June 30) at the five stations are shown in figure 82; second order moving averages were used to remove minor irregularities in the curves. The patterns of rainfall at the stations are similar despite the variety of physiographic settings and the distances between stations. This similarity suggests that cyclonic storms that move southeastward across the Pacific coast are a common source of rainfall for all the stations. Annual rainfall decreases generally from north to south and increases with an increase in altitude. The New Idria station, at an altitude of 2,650 feet, receives only slightly less rain than the Sacramento station 150 miles to the north at an altitude of 35 feet.

The period of highest rainfall, well defined at all the stations, was between 1935 and 1945. Although several peaks of excessive rainfall between 1850 and 1910 are shown on the Sacramento record, the broadest highest peak occurred in the general period 1875–95. The Fresno record shows highs during the same time interval. The 1875–95 and 1935–45 intervals coincide with the two periods of fanhead trenching reported since 1854. This conclusion contrasts with the work of Thornthwaite, Sharpe, and Dosch (1942) and Leopold (1951b) who, in their discussions of accelerated erosion in the southwest, suggested that there is no significant relation between annual precipitation and periods of arroyo cutting.

Leopold (1951b) pointed out that the New Mexico records show significant trends in the number of rains of a given size group. He showed that between 1850 and 1870 there was a decrease in the annual number of rains of 0.01–0.49 inch in a day, and he pointed out that this decrease would weaken protective vegetation such as summer grasses. This, combined with a high frequency of large rains at some stations, apparently contributed to the accelerated erosion. The trends of the daily rainfall size classes of California stations were analyzed in about the same way as Leopold treated the New Mexico data.

Figure 83 shows the trends of some daily rainfall size classes at Sacramento. Rainfall of 0.01–0.24 inch per day would promote the growth of grasses but would provide little runoff. The number of rains in this size class was at its lowest level for the years between 1881 and 1900 and about average between 1935 and 1945. Between 1875–95 and 1935–45 the number of days of rainfall of more than 0.50 inch were among the highest on record. These heavy rains would produce above-normal runoff to erode the stream channels. Again, the years that had a high frequency of large daily rainfall coincide with the times of known arroyo cutting in western Fresno County. A comparison of figures 82 and 83 shows that periods of large annual rainfall were also periods of more than the usual number of large daily rainfalls. This suggests that in this region years of high annual rainfall coincide with years of abnormally large numbers of large daily rainfalls.

Mendota Dam is the only station in western Fresno County for which daily rainfall records are available as far back as 1900. The trend in the amounts of daily rainfall are shown in figure 84. Daily rainfalls greater than 0.50 inch are not as common at Mendota Dam as at Sacramento. The period between 1930 and 1945 shows the same general characteristics as the Sacramento record except that there was a high frequency of daily rainfalls in the 0.01–0.24-inch-size class as well as a marked increase in the 0.50–0.99-size class. The pronounced peak in the 0.50–0.99-size class coincides with the period of high annual rainfall and with the time at which channel deepening was known to have occurred.

The rainfall analyses offer a reason for the arroyo cutting that began on some streams about 1880. The periods of most of the arroyo cutting (1875–95, 1935–45) also were periods of above-normal daily and annual rainfall. A combination of a high frequency of the large rainfalls and a low frequency of the small rainfalls coincided to produce above-normal runoff and less vegetation, thus allowing the above-normal runoff to erode the stream channels. Once started, channels probably became semipermanent although they may

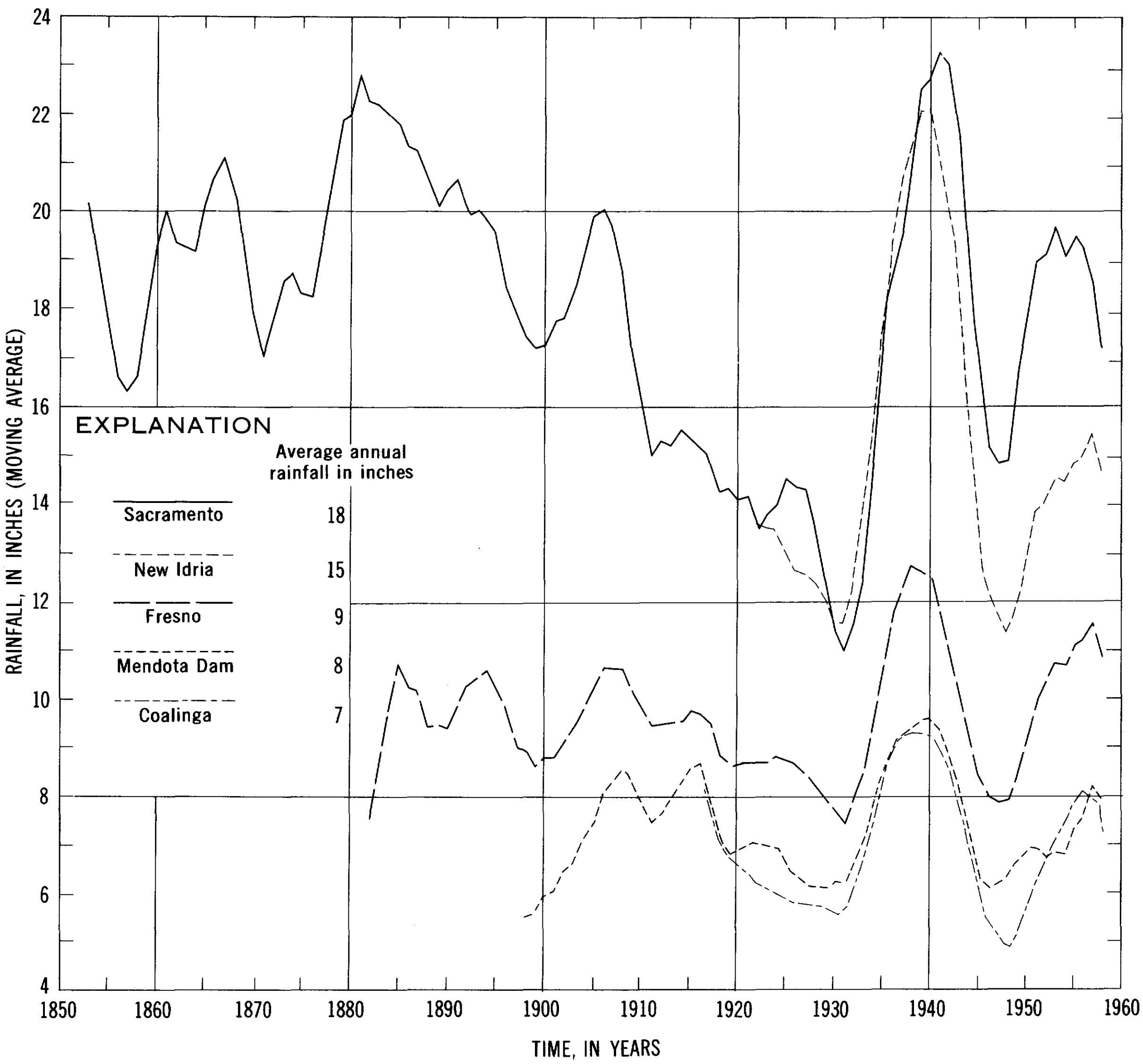

FIGURE 82.—Trends of annual rainfall for five stations in California, 1853–1958.

have been partly filled with deposits during dry periods such as 1920–35 and 1945–52. Figures 83 and 84 show a low frequency of large rainfalls during dry-year periods and therefore few large runoffs to keep the channels scoured of the material deposited in them by small amounts of runoff. About 1935 the channels began to be deepened again, coincident with another period of high frequency of large daily rainfalls. Renewal of channel entrenchment resulted in the terraces within the fanhead trenches.

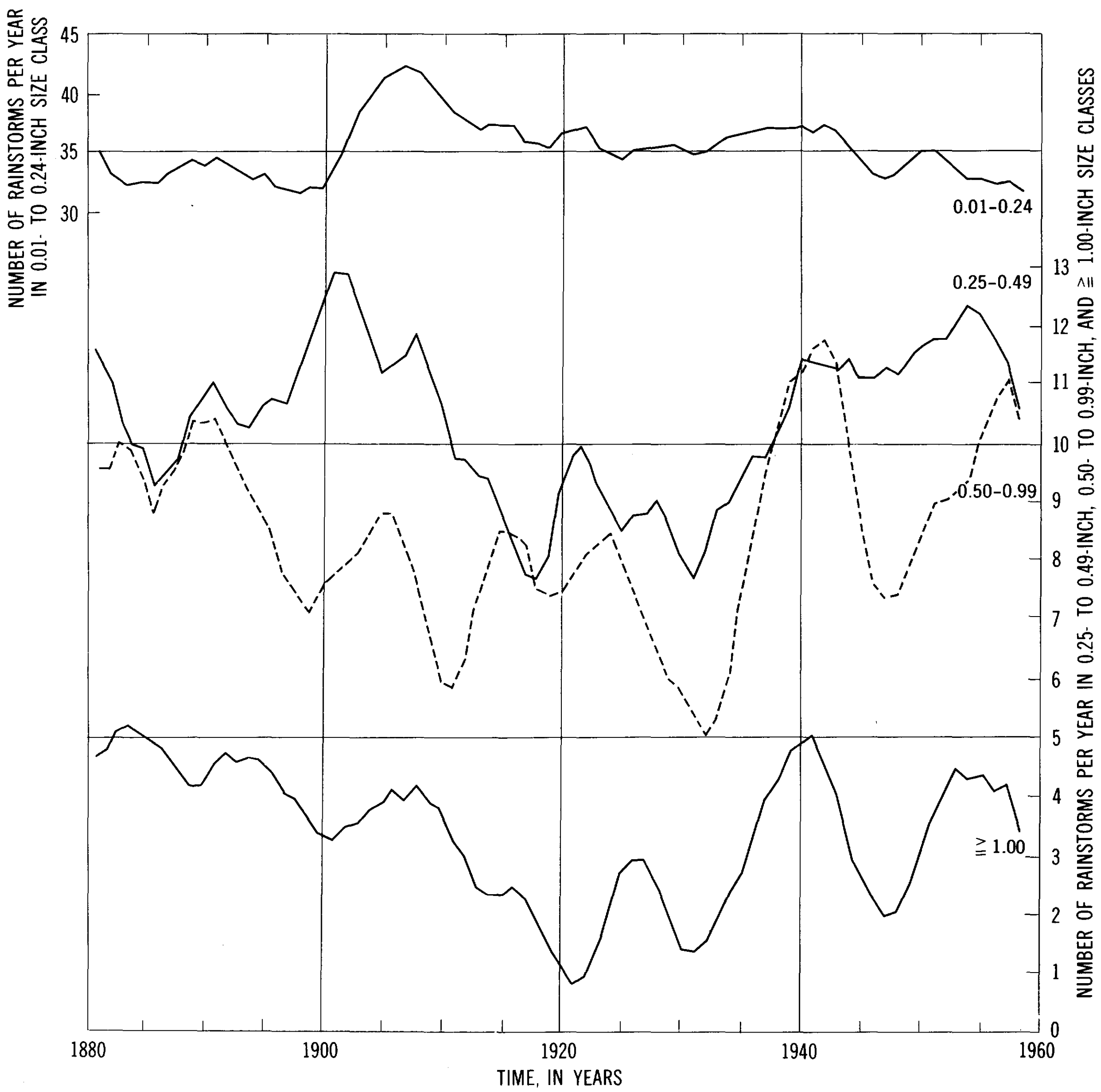

FIGURE 83.—Trends of daily rainfall size classes, 1881–1958, Sacramento, Calif.

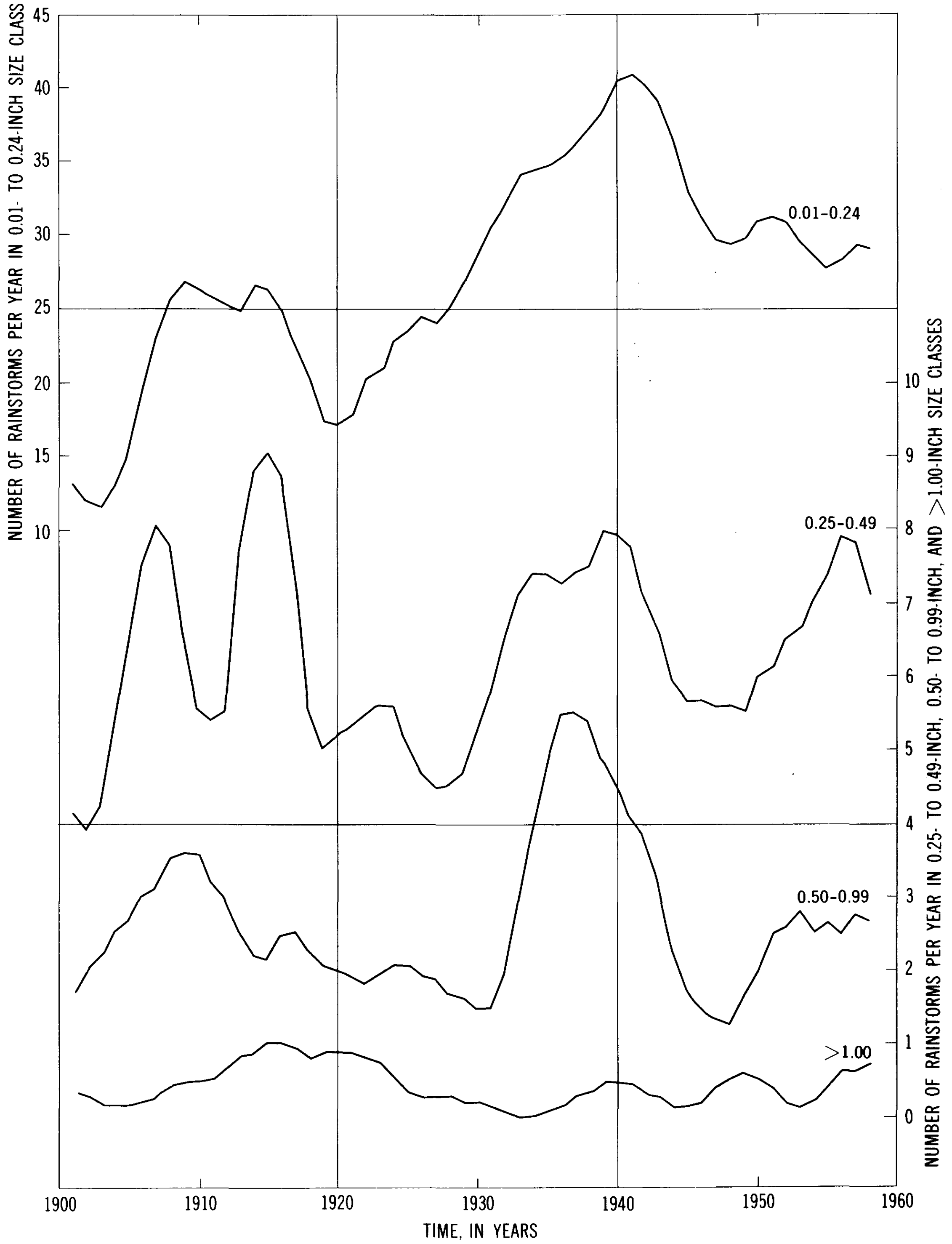

FIGURE 84.—Trends of daily rainfall size classes, 1901–58, Mendota Dam, Calif.

SUMMARY AND CONCLUSIONS

Between the trough of the San Joaquin Valley and the Diablo Range in western Fresno County is a belt of coalescing alluvial fans 12–19 miles wide. The shapes, areas, slopes, and histories of deposition of the individual fans reflect a tendency toward a state of equilibrium, or balance, among a complex set of controlling factors, which include the area, lithology, mean slope, and vegetative cover of the drainage basin; slope of the stream channel; climatic and tectonic environment; and the geometry of the adjacent fans and the depositional basin itself. Changes in one or more of these factors will tend to cause a readjustment of the fan morphology.

The fans are derived from drainage basins that are generally similar with respect to topography, climate, and tectonic environment but that range in size from 0.2 to 296 square miles and in lithology from predominantly sandstone to predominantly mudstone or shale. The fan slopes range from 10 feet per mile near the base of the larger fans to 150 feet per mile near the apexes of some small fans. Fans derived from mudstone or shale-rich basins are generally 35–75 percent steeper than fans of similar area derived from sandstone-rich basins, and roughly twice as large as fans derived from sandstone basins of comparable size. These facts indicate that the volume of fan deposits derived from the two rock types differs; presumably the difference can be attributed mainly to the greater erodibility of the mudstone and shale.

The equations expressing these relations between fan area, A_f, drainage-basin area, A_d, and fan slope, S_f, are as follows. Drainage basins underlain by 48–86 percent mudstone and shale:

$$A_f = 2.4A_d^{0.88}$$
$$S_f = 0.023A_d^{-0.16}$$
$$S_f = 0.034A_f^{-0.28}$$

Drainage basins underlain by 58–68 percent sandstone:

$$A_f = 1.3A_d^{0.88}$$
$$S_f = 0.022A_d^{-0.32}$$
$$S_f = 0.025A_f^{-0.34}$$

The overall radial profiles of the alluvial fans are gently concave, but the slopes do not decrease at a uniform rate downslope from the apexes. Instead, the radial profiles of most of the fans consist of several straight-line segments. The surfaces represented by these segments form bands of approximately uniform slope that are, in most cases, concentric about the fan apexes. The fans whose streams head in the foothill belt have three segments, each of which has a constant slope. The fans of streams that head in the main Diablo Range have four segments. The three lower segments have constant slopes, but two fans have uppermost segments that are concave.

The changes in fan slope are associated with changes that have occurred in the slope of the stream channel upstream from the fan apex. Longitudinal profiles of terraces show that intermittent uplift has changed the slope of the stream channels upstream for most fan apexes. The slope of the area of deposition and the slope of the stream channel upstream from it tend to be the same. Therefore, changes in the stream-channel slope caused by intermittent uplift have caused changes in the slope of the succeeding depositional surfaces and thus have produced the fan segmentation.

Most of the fans are associated with stream channels that have become steeper as a result of the intermittent uplift. Each time the channel was steepened the succeeding fan deposits formed a new fan segment of steeper slope that was deposited on the upper part of the preexisting fan.

The Little Panoche Creek fan, however, has a history that is associated with progressively gentler stream-channel gradients, because the rate of downcutting by the stream has exceeded the average rate of uplift of the reach immediately upstream from the apex. The intermittent character of the uplift resulted in the cutting of a series of paired terraces which preserve a record of the deformation of the mountain front and fanhead areas. With each uplift, the end of the deepened stream channel moved farther down the fan. After each episode of trenching, the lower part of the stream channel and its adjacent area of fan deposition ultimately attained a more gentle gradient than previously.

Progressive trenching and extension of the downslope end of stream channels would occur also in tectonically stable areas. In such cases the overall fan profile—including upper reaches long since abandoned as areas of deposition—might be expected to show a smooth curvature, as the result of a gradual and continuous flattening of gradients and downslope migration of the locus of deposition. Under these circumstances all but the uppermost edge of any given constant-slope fan segment would be covered and obliterated by subsequent downslope deposition at progressively flatter gradients. In the case of the Little Panoche Creek fan, however, intermittent uplift and accompanying channel trenching repeatedly caused rapid downstream displacement of the locus of deposition. In this manner the intervening part of the preexisting fan slope was preserved, together with a set of paired terraces which terminates at the upslope end of the fan segment that was receiving deposits when the terrace cutting started.

Fan segmentation is useful for deciphering part of the tectonic history of some mountain ranges, and in certain cases, segmentation may be an indicator of climatic change, because the fan profile and the relative age of the fan segments reflect part of the erosional and tectonic history of the drainage basin.

The stream channels of the alluvial fans may be braided, straight, or meandering. Some of the channels are not perpendicular to the contours of the fan. Natural levees are a typical feature along intermittent and ephemeral stream channels, where streams have flowed over their banks occasionally to deposit sediment as the flows spread out and decreased in velocity.

Reports of early settlers, old maps, and field evidence indicate that two periods of fanhead trenching, apparently unrelated to tectonic activity, have occurred since 1854, when many fans were receiving deposits near their apexes.

The trenches generally have a maximum depth of 20–40 feet, and commonly terminate at the downslope ends of fan segments. The downslope part of many of the trenches tends to be eroded down to the same slope as the adjacent lower fan segment.

The fanhead trenching occurred principally during two periods of exceptionally high annual rainfall; one from about 1875 to 1895 and the other from about 1935 to 1945. These periods of high annual rainfall were also periods of high frequency of large daily rainfalls and about average frequency of the small daily rainfalls. Most of the small daily rainfalls would be absorbed by the soil to support vegetation that would tend to check erosion, but the larger rains would furnish the large runoff required to erode the stream channels.

Relict fanhead trenches, nearly obliterated by filling and bank slumping, may be seen on several fans, indicating that relatively short-term cycles of trenching and backfilling of the main stream channel may be a typical morphogenetic response to short-term climatic oscillations.

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