Prehistoric Near-Surface Subsidence Cracks in Western Fresno County, California

GEOLOGICAL SURVEY PROFESSIONAL PAPER 437-C

Prepared in cooperation with the California Department of Water Resources

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By WILLIAM B. BULL

STUDIES OF LAND SUBSIDENCE

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A study of filled tension cracks in alluvial-fan deposits

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GLOSSARY

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

Anastomosing cracks.—A crack pattern characterized by repeated branching and rejoining around blocks of deposits.

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

Bajada.—"Series of confluent alluvial fans along the base of a mountain range * * * parallel to the mountain front. The convexities of the component fans impart to the bajada an undulating surface." (Blackwelder, 1931a, p. 136.)

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.

Channel ridge.—A depositional ridge formed by distributary streams on an alluvial fan.

Compaction.—A decrease in the volume of deposits caused by an increase in load or a decrease in the strength of the deposit. The engineering term "consolidation" has the same meaning.

Critical depth.—The depth at which overburden load is sufficient to cause net compaction of clay-rich deposits being wetted for the first time since burial.

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

En echelon cracks.—A crack pattern characterized by a series of cracks that are parallel, but are successfully offset along a common strike.

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, or upper and middle, parts of the fan.

Fan segment.—A part of an alluvial fan that is bounded by changes in slope.

Field capacity.—The amount of water held in a soil by capillary action after gravitational water has percolated downward and drained away; expressed as the ratio of the weight of water retained to the weight of dry soil. (Stokes and Varnes, 1955, p. 53.)

Historic near-surface subsidence.—Subsidence due to wetting caused by man's activities, such as irrigation.

Hygroscopic water.—"The water in the soil that is in equilibrium with atmospheric water vapor." (Meinzer, 1923, p. 24.)

Intercepting crack.—A crack that joins, but does not pass through another crack.

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.

Near-surface subsidence.—The vertical downward movement of the land surface that occurs whenever deposits compact as water percolates through them.

Prehistoric near-surface subsidence.—Subsidence due to wetting caused by streamflow prior to activity by man.

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.

Seepage bulb.—The bulb-shaped volume of deposits that has been wetted by downward and outward seepage from a surface source of infiltration.

Wilting coefficient.—"The ratio of (1) the weight of water in the soil at the moment when * * * the leaves of the plants growing in the soil first undergo a permanent reduction in their water content as the result of a deficiency in the supply of soil water to (2) the weight of the soil when dry." (Meinzer, 1923, p. 24.)

PREHISTORIC NEAR-SURFACE SUBSIDENCE CRACKS IN WESTERN FRESNO COUNTY, CALIFORNIA

By William B. Bull

ABSTRACT

The thousands of clay-filled tension cracks found in the alluvial fans of the San Joaquin Valley, Calif., during the excavation of the California Aqueduct raised the possibility of postconstruction tensional rupture of the canal. In western Fresno County, the cracks were the result of subsidence caused by compaction due to wetting.

Near-surface subsidence cracks form as vertical support of the deposits above a seepage bulb is reduced. Tension cracks open as blocks of deposits rotate toward the area of maximum subsidence. Block rotation occurs as cracks farther away from the wetted area open, and is accompanied by compressional forces that tend to close the cracks near the wetted area. The cracks widen upward, have parallel sides, or widen downward, depending on the stage of block rotation. Vertical displacement of bedding on opposite sides of cracks is common during the early stages, but is rare after uniform wetting of the susceptible deposits has occurred. The cracks found in the canal and streambanks are vertical and discontinuous; have a rough, hackly fracture along their sides; have a highly variable density of spacing; occur in parallel sets; and have anastomosing, intersecting, and en echelon patterns.

The cracks were studied in two types of alluvial fans—small fans derived from the foothill belt of the Diablo Range and large fans derived from the main Diablo Range. Compaction due to wetting as a result of irrigation has caused settlement of more than 100 square miles of the small fans.

Many filled near-surface subsidence cracks occur in the small fans. The cracks generally have a mean spacing of less than 1 per 100 feet of canal length, are 1–3 inches wide, and are filled with clayey materials containing 10–30 percent sand.

Many, but not all, of the cracks in the small fans are historic. Evidence for historic cracking includes modern plant fragments in the crack fillings; cracks that parallel former ditch alinements, that extend to the top of the bedded fan deposits, that extend through buried stream channels; the lack of cracks in the present streambanks; and partly open cracks.

Compaction due to wetting as a result of irrigation has caused only local settlement on the large fans. Historic subsidence of 2–7 feet has occurred at a few places on the fans of Panoche and Los Gatos Creeks.

Canal construction revealed thousands of near-surface subsidence cracks in the large fans. The cracks generally have a mean spacing of about two to six per 100 feet of canal, are ⅛- to 1-inch wide, and are filled with illuviated clay containing silt finer than 20 microns. Some cracks are filled with well-sorted sand.

Virtually all the cracks in the large fans are the result of prehistoric compaction due to wetting caused by streamflow. Evidence for prehistoric cracking includes cracks that parallel former stream courses, crack fillings truncated by buried stream channels, crack filling in the present streambanks, variable depth of burial of the crack tops, absence of widespread historic near-surface subsidence, and the presence of field capacity moisture conditions in the deposits of unirrigated areas. About 45 percent of the cracks is within 20° of being parallel to the radial lines of the large fans and to the overall direction of prehistoric streamflow on the fans.

About 5–10 feet of near-surface subsidence occurred on the large fans after accumulation of at least 65 feet of deposits during the last 45,000–100,000 years—deposits that remained moisture deficient even during times of Pleistocene glacial and lacustrine expansion.

The wetting of the moisture-deficient deposits occurred during the last 10,000 years. Depths of crack burial indicate that wetting has continued to the present time on the large fans, but ceased on the small fans about 5,000 years ago.

The possibility of future near-surface subsidence on the large fans which would cause serious damage to the San Luis Canal section of the California Aqueduct is slight, because nearly all the cracks in the large fans are prehistoric. Small pockets of moisture-deficient deposits left as a result of erratic prehistoric percolation from the streams probably have been wetted and compacted during 20 years of irrigation.

INTRODUCTION

Cracks in alluvium indicate the presence of stresses that are sufficiently large to rupture cohesive deposits. Study of cracks provides an insight into the post-depositional history of the alluvium. If abundant cracks are found in the vicinity of an engineering structure, such as a canal, their mode and time of formation have a distinct economic bearing on the design and maintenance of the structure.

Thousands of clay-filled cracks were found in the alluvial fans of western Fresno County during the construction by the U.S. Bureau of Reclamation of the San Luis Canal section of the California Aqueduct—the major canal to carry water from northern to southern California. Several Federal and State agencies were interested in learning more about the cracks exposed in the trimmed canal banks. As a result, I studied cracks in 54 of the 74 miles of the canal in the study area, and in 31 miles of arroyos of ephemeral and intermittent streams. The canal excavation provided an excellent means of studying the deposits and cracks along the contours of the fans to depths of as much as 30 feet. The entrenched stream channels provided exposures along radial lines of the fans to depths of as much as 40 feet. Crack fillings also were studied in trenches on various parts of the fans.

The principal purposes of this paper are to summarize the present state of knowledge of cracks in alluvium, to present information about the cracks in the fan deposits of western Fresno County, to evaluate the information in relation to several possible causes of the cracking, to derive conclusions regarding the most likely cause of the cracks, and to assess the time of occurrence of the cracks (historic or prehistoric).

The age and cause of the tension cracks have considerable practical importance. If the cracks are modern, and forming now, future ruptures could seriously affect maintenance of the California Aqueduct in both the western and southern San Joaquin Valley. If the cracks are prehistoric, manmade causes need not be considered, and the cracks will not affect the aqueduct.

The source areas and their respective fans constitute individual erosional-depositional systems, in which the lithology and history of deposition of the fan deposits are determined largely by the characteristics of their individual source areas. The fans that head in the main Diablo Range and those that head in the foothill belt of the Diablo Range are markedly different, but even the deposits of some adjacent fans derived from the foothill belt have noticeable lithologic differences. For the purposes of this paper, the fans are grouped as large fans derived from the main Diablo Range (Panoche, Los Gatos, and Cantua Creeks) and small fans derived from the foothill belt of the Diablo Range (Moreno Gulch, Tumey Gulch, Arroyo Ciervo, and Arroyo Hondo). For convenience, these two categories of fans commonly will be referred to in the text as the "large fans" and as the "small fans."

The width, spacing, and lithology of the crack fillings in the fans of the major streams from the Diablo Range are sufficiently different from the crack fillings found in many of the fans of small streams heading in the foothills to warrant separate discussions of the cracks for the two classes of fans. For each class, this paper describes the width, dip, and nature of the crack fillings; the relation of the cracks to the bedding, land surface, and buried former stream channels; the patterns and orientations of the cracks; and discusses the mode and time of formation of the cracks. These two major sections of the report provide sufficient background to evaluate possible future cracking of the fans.

The investigation was made under the supervision of J. F. Poland, research hydrologist in charge of subsidence investigations for the Geological Survey. The particle-size analyses were made by the U.S. Geological Survey Hydrologic Laboratory.

ACKNOWLEDGMENTS

The financial cooperation of the California Department of Water Resources made this study possible. The interest and assistance of the U.S. Bureau of Reclamation contributed significantly to the results of the study. The author is grateful for the helpful discussions regarding the cracks and valuable criticism of the manuscript provided by Richard Bateman, Jim Berkland, Richard Burket, John Isom, Ira Klein, Nikola Prokopovich, and Robert Trefzger of the U.S. Bureau of Reclamation; to Merrit Bradley (formerly with the Bureau of Reclamation); and to Raymond Richter and Wallace Fuqua of the California Department of Water Resources. The author also thanks his colleagues in the Geological Survey—J. F. Poland and K. M. Scott—for their thoughtful discussions and constructive review of the manuscript.

GEOGRAPHIC SETTING

The area discussed in this paper includes about 1,000 square miles of the west side of the San Joaquin Valley (the southern two thirds of the Central Valley) adjacent to the Diablo Range in central California (fig. 1 and pl. 1). The northern edge of the study area is the northern boundaries of the Moreno Gulch and Panoche Creek fans, and the southern edge is the southern boundary of the Los Gatos Creek fan. The eastern edge of the fans studied is bounded by the flood plains of the San Joaquin River, Fresno Slough, and Kings River.

Between the flood plains and the Diablo Range to the west is a belt of coalescing alluvial fans 12–22 miles wide. The altitude at the base of this bajada ranges from 150 to 200 feet, from which the alluvial fans rise to altitudes of about 500–900 feet at their apexes. The slopes range from about 5 feet per mile near the base of the larger fans to about 150 feet per mile on the upper slopes of some of the small fans. Local relief generally is less than 5 feet except where the stream channels are incised 10–40 feet.

The Diablo Range to the west of the study area consists of several groups of foothills bordering the San Joaquin Valley and the main range, which rises to altitudes of more than 5,000 feet about 10–15 miles from the valley.

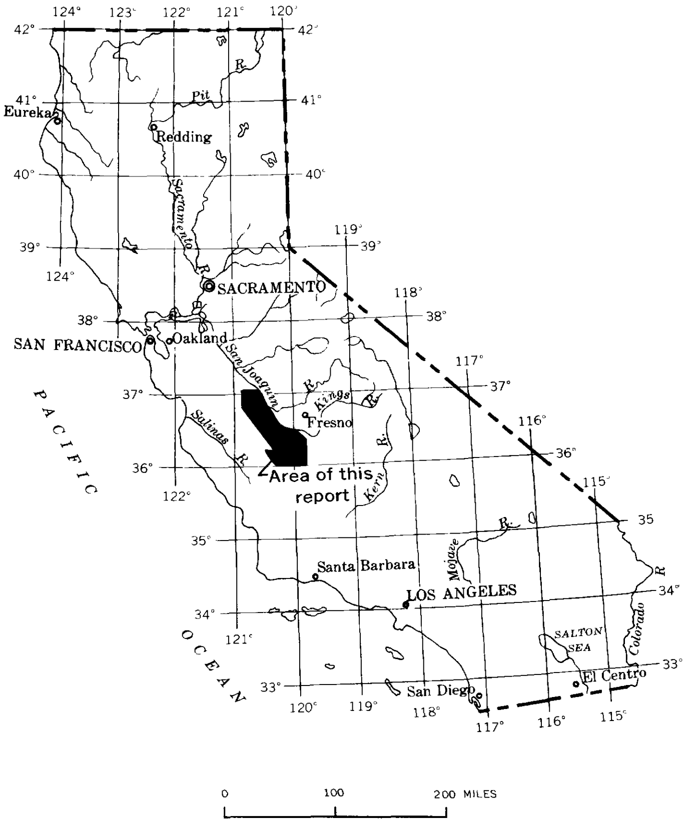

FIGURE 1.—Location of study area.

Panoche and Los Gatos Creeks head in the main Diablo Range and have drainage basins of more than 250 sq mi—basins that are five to 10 times as large as those of the other streams. The study of clay-filled cracks was mainly on these two fans and the Tumey Gulch fan, which was derived from the foothill belt. Basic data on the drainage basins and alluvial fans discussed in this paper are given in table 1. Although the Cantua Creek fan has an area of only 76 sq mi, the cracks in the fan are discussed in the same section as those of the Panoche and Los Gatos Creeks fans, because the cracks, fan deposits, and drainage-basin lithology are similar and because Cantua Creek also heads in the main Diablo Range.

The drainage basins of streams that head in the foothills are less than 30 sq mi. The small fans are derived chiefly from the clay-rich rocks of the foothill belt and have fan areas of less than 55 sq mi.

The streams are classed as intermittent or ephemeral. As the streams do not receive enough water from underground sources such as springs and bank storage to sustain continuous flow to the fan apexes, there are no perennial streams. Panoche, Los Gatos, and Cantua Creeks are intermittent streams that receive enough ground water to flow along their entire lengths for several weeks at a time after some winters of above-normal rainfall. The channels of the other streams are always above the water table; therefore, they are ephemeral and flow only in direct response to rainfall.

Nearly all the precipitation in the area occurs as rainfall. The mean annual rainfall is about 15–20 inches for the main Diablo Range, which intercepts much of the moisture brought into the area by storms and creates a rain shadow across the west side of the San Joaquin Valley. The mean annual rainfall in much of the foothill belt and in the valley is about 6–8 inches. Most of the rainfall occurs from December through March.

Temperatures in the area characteristically are hot in the summer and mild in the winter. The daily temperature range often is 30°–40° F, particularly during the summer. During the period 1913–58 at Coalinga the mean maximum temperature for January was 58°, and for July was 102°.

The type and amount of vegetation is controlled by the amount of rainfall and the type of soil. The lower slopes of the main Diablo Range are covered by brush, but oaks, pines, and cedars grow at higher altitudes. Soils of the foothill belt support a different type of vegetation. Shadscale is a common bush, and the grasses are short types such as downy chess and redstem filaree. The vegetative density of the foothill belt is low. For example, the vegetative density of air-dry grasses and bushes in the Arroyo Ciervo drainage basin ranges from less than 100 to 600 pounds per acre and averages roughly 350 pounds per acre (Bull, 1964a, p. 14, pl. 4). The native vegetation of the fans is similar to that of the foothill belt, including the cottonwood trees that grow along the watercourses of the intermittent streams.

GEOLOGIC SETTING

The alluvial-fan deposits are derived from a variety of rock types. The Diablo Range is mainly a broad anticline that has smaller folds trending obliquely to the course of the main range. The core of the main range consists of deformed and slightly metamorphosed shale and graywacke of the Franciscan Formation of Jurassic to Late Cretaceous age, and of ultramafic intrusive rocks. The Franciscan rocks are overlain unconformably by predominantly Cretaceous marine rocks, which dip toward the San Joaquin Valley and form the east flank of the range. The Cretaceous marine rocks consist mainly of mudstone in the northern part of the area, sandstone in the southern part of the area, and are as much as 20,000 feet thick. The foothill belt is underlain by the Cretaceous marine rocks, easily eroded Tertiary marine rocks, and by younger unconsolidated deposits.

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

Stream	Drainage basin total relief (ft)	Approximate percentage of mudstone and shale in drainage basin	Approximate mean drainage-basin slope	Drainage-basin area (sq mi)	Alluvial-fan area (sq mi)	Overall alluvial-fan slope
Large fans of streams that head in the main Diablo Range						
Panoche Creek	4, 550	32	0. 27	296. 0	260. 0	0. 0035
Los Gatos, Wartham, Jacalitos, and Zapato Chino Creeks	4, 470	23	. 29	380. 0	450. 0	. 0027
Cantua Creek	4, 610	32	. 35	49. 4	75. 6	. 0047
Small fans of streams that head in the foothill belt						
Moreno Gulch	1, 830	67	0. 45	11. 7	20. 6	0. 017
Tumey Gulch	2, 590	67	. 30	29. 1	49. 6	. 012
Arroyo Ciervo	2, 740	68	. 34	8. 0	10. 3	. 018
Arroyo Hondo	2, 550	52	. 29	25. 7	54. 6	. 0094
Martinez Creek	3, 230	34	. 26	8. 9	7. 1	. 013

The approximate percentage of mudstone and shale in the source area for each of the fans studied is listed in table 1. About two-thirds of the drainage basins of fans heading in the foothill belt are underlain by clay-rich rocks such as mudstone and shale. About one-third of the drainage basins heading in the main Diablo Range are underlain by soft clay-rich rocks; the remainder of the source material consists of sandstone, serpentine, and rocks of the Franciscan Formation.

Other reports discuss the geology of the area in detail. The geology and geomorphology of most of the drainage basins of the fans studied in this report, and of other fans, are discussed by Bull (1964a). The surface geology of the continental rocks exposed in the Diablo Range adjacent to the San Joaquin Valley, and the subsurface geology of the study area are described by Miller, Green, and Davis (1971).

The alluvial-fan deposits consist of mudflow deposits and water-laid sediments. The modern deposits are described in detail by Bull (1964a). Mudflow and water-laid deposits are shown in figures 7 and 26.

Water-laid sediments are deposited by a Newtonian fluid, but mudflows are the result of plastic flowage. On the basis of the resulting deposits, it is difficult to determine the concentration at which sediment entrainment becomes irreversible, and at which sediment concentration a threshold shear resistance must be overcome before flow occurs. If the two above factors can be considered criteria for separating mudflows and water flows, the intermediate deposits in the table represent deposits resulting from flows that are close to the transition between Newtonian and plastic flow. The general properties of the deposits, as sampled at the land surface, are as follows:

Characteristics of alluvial-fan deposits in western Fresno County

Type of deposit	Depositional characteristics	Mean parameters from particle-size analyses [1]
Water-laid sediment	Crossbedded, laminated, or massive. No discernible margins; usually clean sand or silt.	Clay content, 6 percent; *So*, 1.8; QD_ϕ, 0.8; σ_ϕ, 1.4.
Intermediate deposits	Clay films around sand grains and lining voids; graded bedding and horizontal preferred orientation of particles. No sharply defined margins.	Clay content, 17 percent; *So*, 4.0; QD_ϕ, 2.0; σ_ϕ, 3.9.
Mudflow deposits	Abrupt, well-defined margins, lobate tongues; clay may partly fill intergranular voids. May have vertical preferred orientation of particles. May not have graded bedding.	Clay content, 31 percent; *So*, 9.7; QD_ϕ, 3.1; σ_ϕ, 4.7.

[1] Sorting: *So*, Trask sorting coefficient; QD_ϕ, phi quartile deviation; σ_ϕ, phi standard deviation (a graphical approximation of the standard deviation).

The deposits of the Panoche, Los Gatos, and Cantua Creeks consist almost entirely of water-laid sediments, but some beds of intermediate-type deposits can be found on each of the fans and a few mudflow deposits occur at the apexes of the Cantua and Panoche Creek fans.

Mudflow and intermediate-type deposits are common on the fans whose streams head in the foothill belt. The Arroyo Ciervo fan consists of more than two-thirds mudflow and intermediate-type deposits. Similar deposits compose more than half of the Moreno and Tumey Gulch fans, but about one-third of these fans consist of water-laid sediments. The Arroyo Hondo fan consists mainly of water-laid sediments, with mudflow and intermediate-type deposits accounting for only one-third, or less, of the fan.

Voids that can be compacted later in the history of the fan are common in the alluvial-fan deposits. They include large intergranular openings between grains held in place by a dry clay bond; bubble cavities formed by air entrapped at the time of deposition; interlaminar openings in thinly laminated sediments; buried, but unfilled, polygonal cracks; and voids left by entrapped vegetation. For further description of these features, see Bull (1964a, p. 31–33).

The predominant clay mineral in the fan deposits is montmorillonite. The results of clay-mineral analyses by R. H. Meade of the Geological Survey of samples collected in the upper 70 feet of the fan deposits have been reported by Bull (1964a, tables 12 and 13). Six fans within the study area were sampled, including the fans of Moreno Gulch, Panoche Creek, Arroyo Ciervo, and Cantua Creek. For the fans of Panoche and Cantua Creeks, the clay is seven parts in 10 montmorillonite. For the other fans, the clay is eight parts in 10 montmorillonite.

Meade (1967, p. 18–22) also studied the clay minerals from cores obtained from depths of as much as 2,000 feet. The mean clay-mineral composition of the sediments of Pliocene to Holocene age approximates the following percentages: montmorillonite, 70; chlorite, 10; illite, 10; kaolinite-type mineral, 5; and mixed-layer montmorillonite-illite and low grade illite-montmorillonite, 5.

Meade's work shows a striking consistency in the dominance of montmorillonite as the principal clay mineral in the study area. The clay of a given sample consists largely of montmorillonite whether the sample is collected from modern sediments at various localities within the area, or whether it is collected from depths of as much as 2,000 feet. Calcium is the dominant exchangeable cation (Meade, 1967, p. 23–25). With increasing depth, the amount of adsorbed magnesium decreases and the amount of adsorbed sodium increases but does not exceed 35 percent.

It is assumed that the clay mineral in the cracks is predominantly calcium montmorillonite. The large amounts of material less than 1 micron in size (fig. 34 and table 3) and the presence of calcium sulfate crystals in the crack fillings support this assumption.

TYPES OF LAND SUBSIDENCE

Four types of land subsidence occur in the study area, three of them being caused by man: tectonic subsidence, subsidence associated with withdrawal of petroleum, subsidence due to artesian-head decline, and subsidence resulting from compaction due to wetting of certain alluvial-fan deposits. Discussion of land subsidence is introduced here because differential settlement is capable of producing forces to crack cohesive alluvium. Cracks in alluvium that are known to have been caused by subsidence and the possibilities of the various types of subsidence causing the clay-filled cracks described in this paper are discussed in later sections.

Tectonic subsidence of much of the San Joaquin Valley probably is continuing at the present time, but at a rate too slow to be measured by most surveying methods. The amounts of subsidence have been large, though, as is indicated by Pleistocene lake clays in the Tulare Lake Basin that are depressed more than 500 feet below present sea level (Davis and Green, 1962).

Subsidence associated with the withdrawal of oil and gas occurs only near the eastern and southwestern edges of the study area. Although leveling control is limited in these areas, control at several points suggests that the amounts of subsidence due to this cause have been less than half a foot in the 1943–66 period.

The most widespread and intense type of subsidence is caused by pumping of ground water for irrigation. The resulting changes in ground-water levels have increased the applied stresses tending to compact the upper 1,000–3,000 feet of sediments. The change in effective stress has accelerated the normal diagenetic compaction rate of the saturated sediments and has caused the land surface to sink as rapidly as 1.8 feet per year. As of 1969, 2,000 sq mi in western Fresno and adjacent counties had subsided more than 1 foot, and the maximum subsidence attributed solely to artesian-head decline was about 28 feet. The entire study area of this report is subject to subsidence due to artesian-head decline. The decline in artesian head exceeds

400 feet in parts of the area, and pumping levels of 700–1,000 feet below the land surface were common as of 1967. Land subsidence caused largely by artesian-head decline between 1920 and 1966 is shown in figure 45. This type of subsidence is discussed in detail in three reports being prepared on subsidence due to artesian-head decline in the Los Banos-Kettleman City area.

Near-surface subsidence results from the compaction of moisture-deficient alluvial-fan deposits by an overburden load as the clay bond supporting the deposits is weakened by water percolating below the root zone of plants for the first time since burial. Moisture-deficient deposits accumulate because the plants are able to transpire the small amounts of water that enter the soil zone. During the 3- to 5-months winter rainy season, flows of short duration may spread out on the fans. During the 7- to 9-month period of little or no rain that follows, evapotranspiration removes most of the moisture from the freshly deposited material. The pattern varies considerably from year to year—from no flows in dry years to repeated flooding of the fans in wet years. Bushes in the areas of present-day deposition may continue to grow vigorously during a dry year that follows a wet year, which indicates that several years may be necessary for the plants to reduce the moisture content of the soil to the wilting coefficient. The presence of widespread near-surface subsidence during the past few decades on some of the small fans indicates that similar lack of deep wetting of the fan deposits was characteristic of most of the time that the upper 100–300 feet of fan deposits was accumulating.

More than 100 sq mi of alluvial-fan deposits in western Fresno County have been affected by near-surface subsidence caused by man during the past few decades (pl. 1 and fig. 45). Subsidence of 3–5 feet is common, and 10–15 feet of subsidence has occurred within small areas. Open cracks form between areas undergoing different amounts of settlement, and are a characteristic feature of compaction due to wetting.

Near-surface subsidence hollows in an area of intense subsidence on the Tumey Gulch fan are shown in figure 2. The hollows are as much as 6 feet deep despite repeated land-leveling operations by the farmer. The hollows indicated by the letter "A" were caused by water leaking from a sprinkler pipeline. A ground view of the hollow around which the road detours is shown by Bull (1964a, fig. 25*C*). The other subsidence hollows are the result of differential settlement within the fields, which had been irrigated for at least 7 years at the time this photograph was taken.

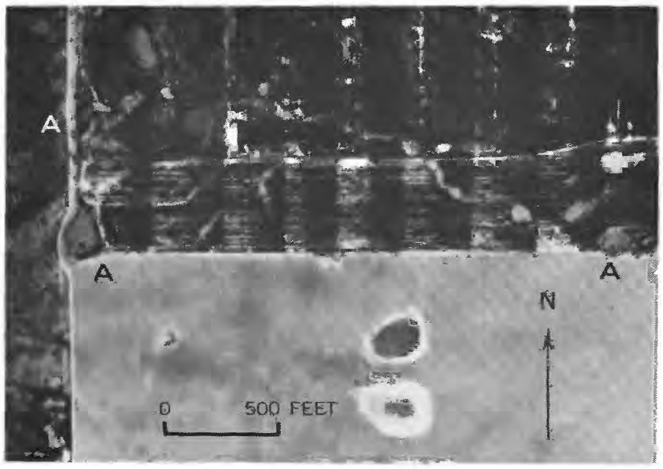


Figure 2.—Aerial photograph of near-surface subsidence hollows on the Tumey Gulch fan. Photograph taken May 25, 1962, by Howard Chapman and Francis Riley, U.S. Geological Survey.

Overburden load and clay content affect the amount of compaction due to wetting. The amount of compaction increases with an increase in overburden load. An irrigation test plot on the Arroyo Ciervo fan operated by the Inter-Agency Committee on Land Subsidence in the San Joaquin Valley provided information regarding the effect of overburden load. The surface of the test plot rose slightly after water was first applied because the clay in the surficial deposits swelled. As the water percolated to greater depths, net reduction of the volume of the deposits occurred. The amount of volume reduction increased with depth and subsurface bench marks beneath the test plot afforded a means of measuring the amount of compaction due to wetting that occurred within each depth interval. The percentage of compaction after 42 months of operation is shown in figure 3. Each point in figure 3 represents

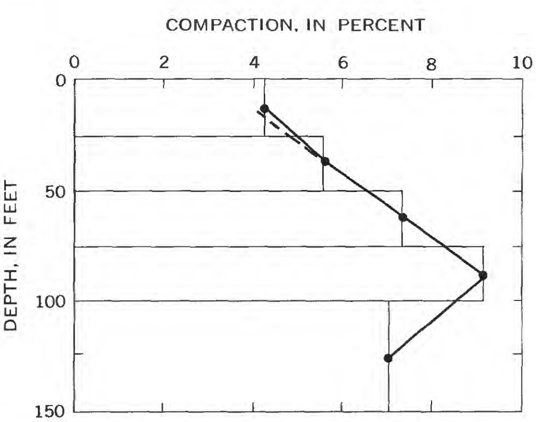


Figure 3.—Effect of overburden load on compaction due to wetting, Inter-Agency Committee test plot B, after 42 months of operation. Arroyo Ciervo fan.

the percentage of compaction within a 25-foot-depth interval except the point at 125 feet, which represents the percentage of compaction between 100 and 150 feet. To a depth of 100 feet there is a nearly straight-line increase in the percentage of compaction; the percentage more than doubled between the points of 12.5 and 87.5 feet. In the 100- to 150-foot depth interval, the percentage of compaction decreases because of higher natural moisture content below a depth of 125 feet. The higher moisture content resulted in less change in the strength of the materials as the water percolated through the deposits, and therefore a lower percentage of compaction due to wetting.

The effect of clay content on compaction due to wetting is shown in figure 4. The consolidation tests were made on samples collected from surface deposits, and therefore, all overburden loads were simulated. A special consolidation test was used (Bull, 1964b). Because all the samples were tested under the same moisture condition and simulated overburden load, the

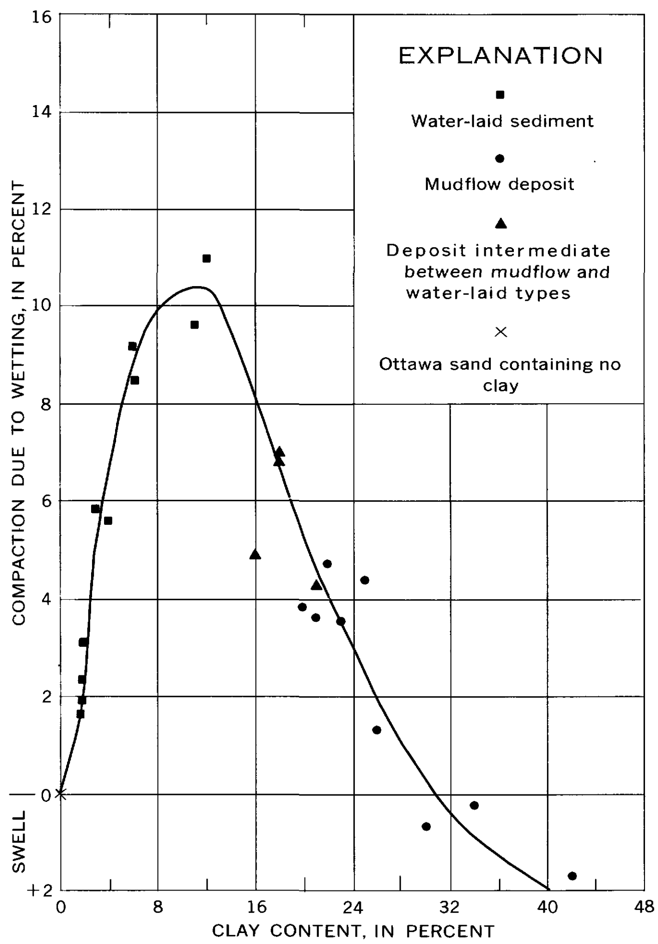


FIGURE 4.—Effect of clay content on compaction due to wetting under a simulated 50-foot overburden load.

amount of clay was the chief variable affecting the amount of consolidation as the water was allowed to percolate through the samples. Samples containing less than 2 percent clay consolidated only slightly when wetted. The other extreme is shown by samples of mudflow deposits containing more than 30 percent clay. The clay-rich samples not only had enough strength to resist collapse when wetted, but also showed a net swell under the simulated load. The maximum compaction due to wetting for the samples tested was at a clay content of about 12 percent (materials that had been deposited as water-laid sediments). If less than 12 percent clay was present, the simulated dry overburden load that was applied before water percolated through the sample accomplished much of the compaction because there was not enough clay to preserve the larger voids. As the amount of clay increases above 12 percent, the resistance to compaction when wetted increases. In addition, montmorillonite swells. Both factors reduce the compaction progressively; and, for the samples tested, the net compaction decreased to zero at about 30 percent clay.

Subsidence causes problems. Subsidence due to artesian-head decline increases the design, construction, and maintenance costs of engineering projects such as canals and drainage systems, and makes the established altitudes of bench marks unreliable within a short time after surveys are made. Rupture of the ground surface is common in areas of near-surface subsidence, and has damaged ditches, canals, roads, pipelines, electric-transmission towers, and buildings, and has made the irrigation of crops difficult. In about 10 percent of the subsiding area, the compaction of moisture-deficient deposits is superimposed on the compaction of saturated deposits due to artesian-head decline.

The problems posed by the different types of subsidence were sufficiently severe that in 1954 the Inter-Agency Committee on Land Subsidence in the San Joaquin Valley was formed. The Geological Survey, Bureau of Reclamation, the California Department of Water Resources, and six other agencies are part of this committee. The purpose of the committee was to plan and coordinate a program that would provide information on the extent, magnitude, rate, and causes of the various types of land subsidence in the San Joaquin Valley (Inter-Agency Committee, 1958, p. 21). Other objectives were to estimate rates and amounts of subsidence that would occur under assumed conditions, and to suggest ways of decreasing or alleviating damage caused by subsidence. The most significant near-surface subsidence project undertaken by the Inter-Agency Committee was the establishment and flooding of three 1/4-acre test plots and the laboratory testing of cores taken from the test plots.

Further testing by the California Department of Water Resources and the Bureau of Reclamation determined the most efficient means of precompacting deposits probably susceptible to near-surface subsidence. As a result, all areas along the canal alinement believed to be susceptible to near-surface subsidence were wetted thoroughly by ponding before construction of the California Aqueduct. Along the San Luis Canal section of the California Aqueduct, two reaches were ponded; the reach between the north edge of the Moreno Gulch fan and the west edge of the Panoche Creek fan, and the reach between the south edge of the Panoche Creek fan and the north edge of the Cantua Creek fan.

THE SAN LUIS CANAL SECTION OF THE CALIFORNIA AQUEDUCT

The California Aqueduct is the major canal under construction for transporting water from areas of abundant water in northern California to areas needing water in central and southern California. Within the study area, the canal is a joint-use facility that is being built by the Bureau of Reclamation, and is called the San Luis Canal section of the California Aqueduct. In this paper, it will be referred to mainly as the canal, or the San Luis Canal. In the northern part of the study area, the canal has a bottom width of 85 feet, and the width at the top of the lining is as much as 217 feet. The depth from the canal floor to the top of the lining is as much as 35 feet, and the design capacity of the canal is 13,000 cfs (cubic feet per second). Water will be withdrawn for irrigation at many points along the canal, and at the southern edge of the study area its capacity is 8,100 cfs.

Most of the locations given in this paper will be in the form of references to locations at various points along the San Luis Canal. The numbers shown on plate 1 are station numbers along the canal and refer to total distance in feet, from the start of the canal at the San Luis Reservoir. For example, station 2587+67 would be 2,587 hundred feet plus 67 feet (258,767 feet) from the start of the canal. Where appropriate, I have added the letters "L," "R," and "B" to the canal station numbers in the text and illustrations to indicate whether the location refers to the left or right bank, or to the bottom of the canal. The usage of left and right refers to the position of the canal banks when one is facing downstream.

Trimming and paving of the San Luis Canal are shown in figure 5. The general shape of the canal prism was excavated in advance of the trimming and paving operations. The trimmer, shown on the right side of figure 5*A*, removed the final 1½ feet of material from the canal prism and dumped it on the top of the canal bank. The teeth of the trimmer are shown in figure 5*B*. The result is a cleanly trimmed slope that has 1 foot of vertical distance for every 2 feet of horizontal distance. The slope generally provides excellent exposures of the alluvial-fan deposits and the compacted fill overlying the original land surface. Most of the horizontal marks shown in the photographs of the canal banks are not bedding features, but are trim marks left by the scraping blade of the trimmer, or scrape marks caused by damaged trimmer teeth. Between the time the slope was trimmed and paved, water trucks kept the slope wet (fig. 5*C*), and after repeated soakings, the fan deposits and the cracks were barely discernible. The area in the right foreground of figure 5*A* has been wetted about 1 hour after trimming.

The paving operation consists of four independent units that provide a continuous pour of concrete, insert plastic strips along expansion joints, smooth surficial blemishes, and spray the concrete with white plastic for proper curing (fig. 5*C*). As shown in figures 5*A* and 5*C*, the truck and trailer units drive onto the paver, and discharge their loads of concrete as they are carried along by the paver. The result is a continuous pour of unreinforced concrete that is 4 inches thick. These huge machines are capable of trimming and paving about two-thirds of a mile of canal bank each day.

The Bureau of Reclamation geologists, where possible, mapped the engineering properties of the fan deposits, and took notes regarding the density of spacing and strike of the clay-filled cracks. The cracks were mapped by Merrit Bradley (formerly with the Bureau of Reclamation) along most of the canal between stations 1500 and 2050. Most of the author's mapping of the Los Gatos Creek and Tumey Gulch fans has been included in this paper as maps of selected areas less than 1 mile long.

Clay-filled cracks were not expected in the banks of the San Luis Canal, and none were noted north of the study area. During the trimming of the right bank, abundant cracks were noted when the trimmer moved from the Moreno Gulch fan southward across the north edge of the Panoche Creek fan (Merrit Bradley, oral commun., May 1966). After both canal banks in the northern half of the Panoche Creek fan were paved, the trimmer returned to the Moreno Gulch fan, where a few clay-filled cracks were noted in the left bank of the canal. Later, clay-filled cracks were found

A

B

C

FIGURE 5.—Trimming and paving the San Luis Canal. *A*, Trimmer and paver on the Arroyo Ciervo fan, station 2800. *B*, The teeth of the trimming machine. Three-foot mattock handle for scale. *C*, The paving equipment.

in the canal banks in nearly all the fans in the study area and in the fan deposits exposed in the banks of the stream channels of Panoche and Los Gatos Creeks.

The discovery of the clay-filled cracks in the banks of the canal aroused considerable interest among the geologists and engineers of the Bureau of Reclamation, the Geological Survey, and the California Department of Water Resources, and resulted in this study of the description, causes, and time of occurrence of the cracks. Other reports concerning the cracks include those by Bull (1966), Bradley and Bateman (1966), Prokopovich and Bateman (1967), and Bull (1967).

TYPES OF CRACKS IN ALLUVIUM

Several types of cracks occur in cohesive alluvium. Each crack process described here will be considered later in the paper as a possible cause of the clay-filled cracks in western Fresno County.

Cracking of saturated alluvium and jetting of sediment-laden water have been described as occurring during earthquakes in many localities, but are not discussed here because this paper is concerned only with cracks in unsaturated alluvium.

TECTONIC, DESICCATION, AND SLUMP CRACKS

TECTONIC CRACKS

Folding that has occurred in unconsolidated alluvium generally is not intense, and cracks in folded alluvium have not been described.

Faulting commonly ruptures alluvium. Movement along strike-slip faults can cause large horizontal, and minor vertical, displacement of the bedding. Small faults and joints that occur at angles to the strike-slip fault are common adjacent to the fault.

High-angle normal and reverse faults are the most common type of fault cutting alluvium. In much of the Western United States, normal faults form the boundary between bedrock source areas and alluvium-filled valleys. In addition to the main faults bounding the mountain ranges, sets of related but smaller faults occur in the alluvium of the adjacent intermontane basins. Unfortunately, these secondary faults are not exposed in areas undergoing deposition.

Erosion has exposed these secondary types of fault patterns in a few areas, one of which is the alluvial sequence on the south side of the Catalina Mountains in southern Arizona. Detailed studies by Pashley (1966) have revealed a complex history of recurring periods of movement along the fault bounding the mountain range and along the faults in the alluvium, alluvial-fan deposition, and erosion of the valley fill. Both normal and reverse movements have occurred along the east-west fault bounding the south side of the Catalina Mountains. Associated with the bounding fault are major faults cutting alluvial-fan deposits adjacent to the range. These faults trend either northeast or northwest, and the northwest-trending faults are offset by the northeast-trending faults.

The blocks of alluvial-fan deposits within the northeast- and northwest-trending faults are broken by numerous minor normal faults with displacements that range from a few inches to a few feet. The cracks are narrow and contain calcareous material. A normal fault in alluvial-fan deposits with a displacement of several feet is shown in figure 6.

DESICCATION CRACKS

Shrinkage cracks resulting from the drying of clayey deposits are common, and usually form a polygonal pattern in which the cracks narrow downward from the surface. The spacing of the cracks increases with increasing thickness of deposits, and the width of the cracks increases with increasing clay content. Both intercepting and intersecting cracks are common. Desiccation cracks resulting from post-depositional drying of alluvial-fan deposits may penetrate several layers of deposits. If several episodes of deposition occur before desiccation, the deposits will dry as a unit, and the polygonal cracks pass through the bedding planes. If interbedded sand and clay are deposited, the cracks rarely continue through the sand beds. In figure 7*A*, the water-laid sand in back of the shovel was deposited before desiccation of the mudflow deposit in the foreground, and the desiccation cracks in the mudflow deposit do not extend through the sand bed. When the deposits dried after the rainy season, the sand dried first, but cracks did not develop because of the low clay content (10 percent). The mudflow deposit continued to dry and a pattern of polygonal shrinkage cracks formed as the clay (34 percent) dried. The result was the development of buried, but open, polygonal cracks in the mudflow. The sand did not fall into the open cracks because it had attained sufficient dry strength to bridge the gaps between the polygonal blocks.

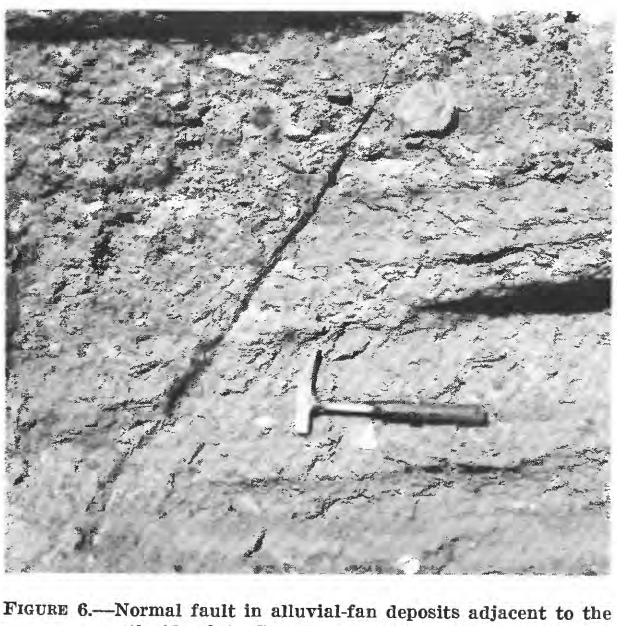


FIGURE 6.—Normal fault in alluvial-fan deposits adjacent to the south side of the Catalina Mountains, Ariz.

Water-laid material that is deposited after desiccation cracks form, fills the cracks with sediment. The polygonal cracks in the mudflow deposit shown in figure 7*B* are filled with water-laid sand from the overlying bed.

Desiccation cracks also can occur in clayey fan deposits as a result of seasonal wetting and drying, but these cracks form only where all the surficial beds are clay rich and the resulting cracks do not extend below the zone affected by seasonal drying.

Polygonal cracking of thick playa deposits in the Basin and Range province has resulted in polygons more than 200 feet across (Marchand, 1960; Neal and others, 1968). The cause of the fissures, as much as several inches wide, between the polygons is attributed to seasonal and long-term desiccation.

SLUMP CRACKS

Mass movement of alluvium generally occurs adjacent to stream channels. If part of the deposits are saturated, landsliding will occur which will be accompanied by the formation of tension and shear cracks in the alluvium near the head of the unstable mass.

A more common type of slump crack occurs in the alluvium of streambanks in semiarid regions. The banks of many arroyos slump into the stream channel as a result of being undermined by the stream. Cracks that parallel the stream channel open on the surface of a fan 5–50 feet from the edge of nearly vertical or undermined streambanks, and may form anastomosing,

A

B

FIGURE 7.—Desiccation cracks in mudflow deposits. *A*, Mudflow deposit on the Arroyo Hondo fan; the polygonally cracked mudflow in the foreground is overlain by water-laid sands in the background. *B*, Sand-filled polygonal cracks in a mudflow in the Tumey Gulch fan. Looking up the trimmed slope of the San Luis Canal at station 2576 + 96R. Three-foot mattock handle for scale.

intercepting, or en echelon patterns. The cracks are nearly vertical, or slope toward the stream channel at angles of 80°–90°. The cracks continue to widen at the surface, and after a period of months or years during which the top of the block of alluvium rotates toward the stream channel, the alluvium at the base of the block fails and the block slumps into the stream channel. The processes of formation and failure appear to be similar to those described by Schumm and Chorley (1964) for sandstone cliffs, except that the sequence of events is completed in much less time. Cracks associated with slump rotation blocks always narrow downward, and may be filled with loose debris that has fallen from the crack walls. Water-deposited crack fillings are rare.

A slump and slump crack in the stream channel of Arroyo Hondo are shown in figure 8*A*. This crack formed shortly after undercutting by the stream during an unusually wet winter, and part of the slump rotation block had collapsed into the stream channel within 4 months after the crack first opened. The remaining part of the slump rotation block, the crack, and fresh exposures of thin-bedded water-laid sediments of the fan are shown in the photograph.

Failure of slump rotation blocks commonly takes several years, and for one block adjacent to Arroyo Ciervo that was 10–25 feet wide and 200 feet long, 6 years passed before the block slumped into the stream channel. This crack had the appearance of being open for several years when it was first observed.

The surficial expression of cracks bordering a slump rotation block in the banks of Tumey Gulch is shown in figure 8*B*. The cracks narrow rapidly with increasing depth below land surface. Part of the crack width at the surface is the result of erosion and slumpage of material into the cracks. The channel at this location is incised 40 feet into the alluvial fan.

CRACKS IN AREAS OF COMPACTION DUE TO ARTESIAN-HEAD DECLINE

Fissuring of the land surface has been reported in many alluvium-filled basins in Arizona (Leonard, 1929; Robinson and Peterson, 1962; Peterson, 1964; Minikka, 1964; Kam, 1965; and Schumann and Poland, 1969) and in one basin in Nevada (Malmberg, 1964; Domenico and others, 1964).

A characteristic feature of the cracks is their great length. Most of the cracks are more than 1 mile long, and single cracks may be more than 5 miles long. Peterson (1964) in his study of the abundant earth fissures in the Picacho area, Pinal County, Ariz., concluded "that the breaks do not occur suddenly; instead, they develop over a period of months, perhaps years, as narrow openings an inch or less in width." Vertical displacement on opposite sides of the cracks may or may not be evident. Some cracks have en echelon patterns.

A

B

FIGURE 8.—Slump cracks adjacent to stream channels incised in alluvial-fan deposits, western Fresno County, Calif. *A*, Arroyo Hondo; shovel for scale above X. *B*, Tumey Gulch; shovel for scale.

After a crack has opened, water from heavy rainfall or from irrigation may enter it. This water causes the sides to slough and produces an opening at the surface that is large compared to the crack width at depth. The cracks are much more noticeable after erosion by water; in many places cracks have not been reported until surface enlargement by water has occurred. Where newly formed cracks cross ephemeral stream channels, headward erosion proceeds up the stream channel; at other places, new gullies form upstream from the cracks (Kam, 1965). Some workers have attributed the fissures to piping (Fletcher and others, 1954).

Aerial views of water-eroded cracks cutting the alluvium about 40 miles south of Phoenix, Ariz., are shown in figure 9. Gullies extending upslope from the crack are visible at A. In figure 9*B*, the large size of the xerophytic shrubs along the crack alinement indicates that the crack has been intercepting surface runoff for at least several years.

The surficial parts of the cracks commonly are filled with debris, which has slumped into them and with water-laid sands and gravels. Water-laid clay has not been reported in the cracks.

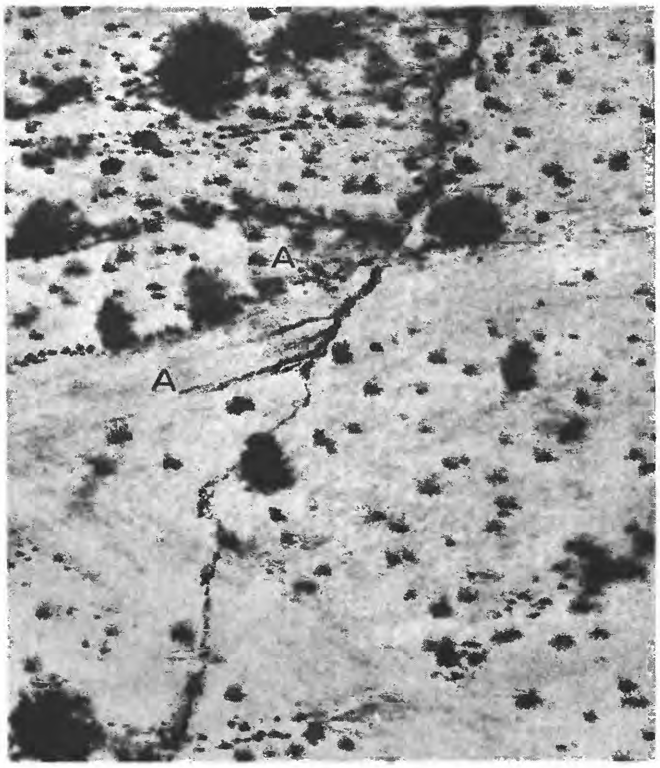
Many of the cracks in Arizona and Nevada have formed after large declines in ground-water levels have occurred in the vicinity as a result of agricultural or municipal demand for water. The withdrawal of ground water from aquifer systems has resulted in accelerated compaction of the sediments, which has caused the land surface to subside several feet.

Peterson (1964) has made a gravity survey of the Picacho area. He found that most of the cracks occur in the vicinity of steep gravity anomaly gradients and that the cracks parallel the gravity highs. Peterson interprets the gravity-anomaly configuration west of Picacho Peak as representing a buried pediment, which is terminated 2 miles west of the peak by a boundary fault separating the mountain mass and the downfaulted alluvium-filled basin (also see Schumann and Poland, 1969, fig. 5).

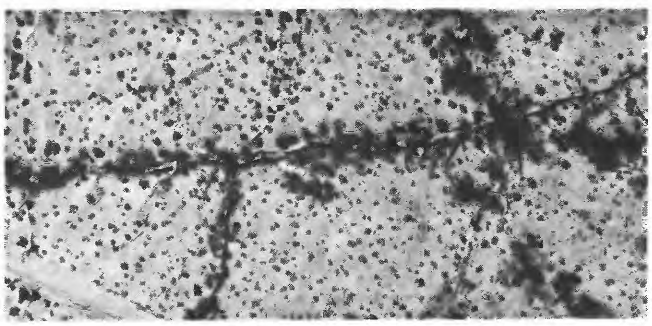
Although the cause of all the fissures that have opened in alluvial basins in Arizona and Nevada since the development of ground water has not been determined, it seems probable that some of the fissures, such as those shown in figure 9, are the result of differential compaction due to water-level decline in unconsolidated sediments that have pronounced lateral changes in thickness and lithology. This was the tentative conclusion reached by Peterson (1964) for fissures in the Picacho area.

CRACKS RESULTING FROM COMPACTION DUE TO WETTING

A diagnostic characteristic of near-surface subsidence is the pattern of discontinuous cracks that occur between wetted subsiding areas and the area that has remained stable. The cracks were initially described by Bull (1964a, p. 43–44). They are most common in areas of intense differential compaction due to wetting, such as at locations where a source of abundant water, such



A



B

FIGURE 9.—Cracks widened by erosion in alluvium about 40 miles south of Phoenix, Ariz. Dirt roads for scale. *A*, Gullies extending upslope from crack. *B*, Increase in vegetative density adjacent to crack. Photographs taken September 7, 1962, by Howard Chapman.

as a ditch or a sump, is adjacent to land that has never been irrigated before.

A variety of crack patterns is common. The cracks are anastomosing, intercepting, intersecting, or en echelon and commonly occur in parallel sets. Crack patterns near the southwest corner of Inter-Agency Committee test plot D on the Moreno Gulch fan are shown in figure 10. The cracks tend to parallel each other and the general boundary of the ponded area. Intercepting cracks are shown at *a*, overlapping cracks at *b*, and en echelon cracks at *c*.

Vertical displacement of the surface on opposite sides of the crack is common, but cracks without vertical displacement on opposite sides are common also. Crack widths vary from hairline fractures to fissures 1 foot wide.

Cracks that are not subject to streamflow or irrigation water may be open, filled with debris that has slumped or blown into the cracks, or closed and contain no filling. Cracks in irrigated areas are buried by tilling operations soon after they form, and have not been excavated to determine the type of crack filling, if any.

PROCESS OF CRACKING

The formation of near-surface subsidence cracks is related to the decrease in the volume of the deposits as the water front moves downward and outward in the fine-grained moisture-deficient deposits. An explanation of the process of cracking must conform to the following facts:

1. The cracks are open fissures that are nearly vertical and may extend to depths of at least 20–30 feet.
2. Vertical displacement of the surface on opposite sides of a crack may not be evident, or may be as much as 3 feet.

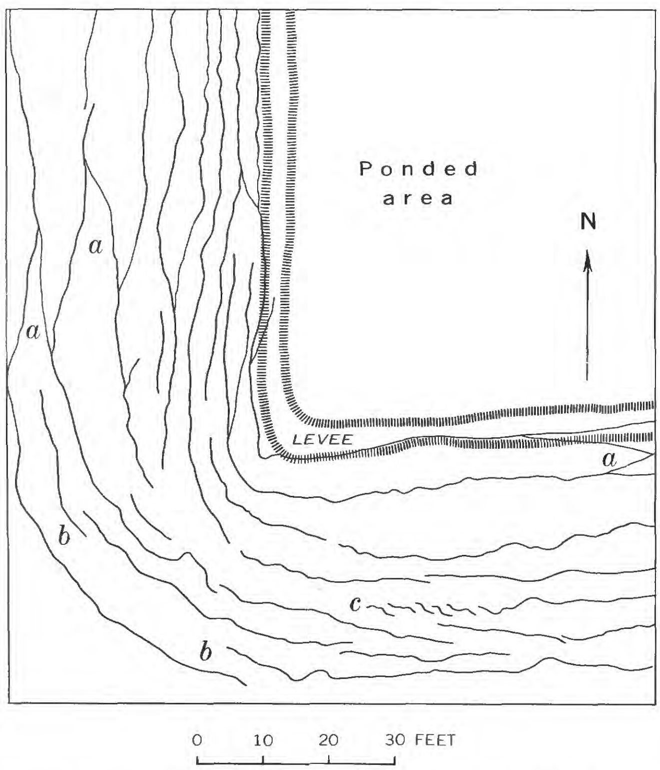


FIGURE 10.—Patterns of near-surface subsidence cracks that formed during first 42 days of flooding of Inter-Agency Committee test plot D, Moreno Gulch fan.

3. The sides of the cracks may narrow downward, narrow upward, or be parallel.
4. The surface of the blocks between the cracks usually slopes toward the wetted area at less than 10°.
5. As a new crack farther from the wetted area opens, the cracks nearer the wetted area close.

The view of the concentric cracks around a test plot shown in figure 11 illustrates several of the features noted above. The man is standing on the edge of an area that had been ponded. The surfaces of the blocks between the cracks slope toward the wetted area. The cracks farther away from the ponded area have vertical displacements of more than 1 foot. The cracks near the wetted area have little or no vertical displacement; they had large vertical displacements at an earlier stage in the plot wetting, but have partly closed and have had their vertical displacements reduced greatly.

The overall slope of the blocks toward the ponded area and the remaining vertical displacements on opposite sides of cracks are both largely the result of decreasing amounts of compaction away from the ponded area. The differential subsidence is determined largely by the shape of the seepage bulb, the top of which slopes downward from the wetted area. The shape of the seepage bulb progressively reduces the thickness of deposits wetted by lateral and capillary flow with increasing distance from the ponded area. The thickness of the wetted deposits decreases to zero at the outer edge of the seepage bulb. Thus the differential subsidence is simply a function of decreasing thickness of compactible deposits that have been wetted.

The general shape of the seepage bulb below Inter-Agency test plot B on the Arroyo Ciervo fan is shown in figure 12. The solid line is based on drilling 7 months after the plot was flooded (G. L. Long, Calif.

FIGURE 11.—Concentric near-surface subsidence cracks along one side of a test plot on the Arroyo Ciervo fan. Mendota test site of the California Department of Water Resources.

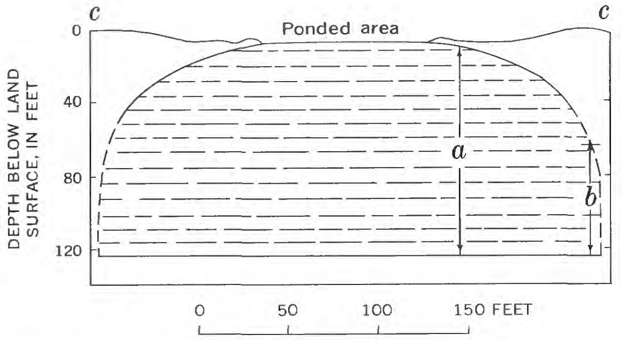


FIGURE 12.—Approximate shape of the seepage bulb below Inter-Agency Committee test plot B, on the Arroyo Ciervo fan, after 7 months of ponding. See text for discussion of symbols.

Dept. Water Resources, written commun., September 1957). The dashed line is largely hypothetical, but the depth of the bottom of the seepage bulb is based on information from a set of subsurface bench marks in the center of the ponded area and from drilling information. After 7 months of ponding, 7½ feet of subsidence had occurred, the wetted front had penetrated to about 126 feet below the presubsidence land surface, and the seepage bulb had a width of more than 250 feet. The seepage bulb width was more than 2½ times the ponded area width.

The lateral movement of water away from the ponded area was largely a function of variations in the permeability of the deposits and the tendency of beds of low permeability, if present, to impede vertical seepage and promote lateral flow. The fact that the seepage bulb under plot B extended at least 80 feet away from the edge of the ponded area suggests a large amount of vertical inhomogeneity between adjacent beds at this site.

Figure 12 illustrates lateral change in thickness of the seepage bulb. The thickness of the wetted deposits decreases rapidly near the outer edges of the seepage bulb—the thickness at *a* is twice the thickness at *b*. The outer limit of cracking is shown by the letter *c*. The configuration of the land surface is hypothetical.

In plan view, the seepage bulb has a circular shape, even though the ponded area was a 100-foot square. The wetted front initially was square, but it gradually assumed a circular shape. The change in the shape of the seepage bulb is reflected by the subsidence cracks at the surface. In figure 10, the first cracks curved sharply around the corner of the test plot, but later cracks were progressively more circular.

A process for the formation of near-surface subsidence cracks is shown diagrammatically in figure 13. The process is different from cracking caused by hill

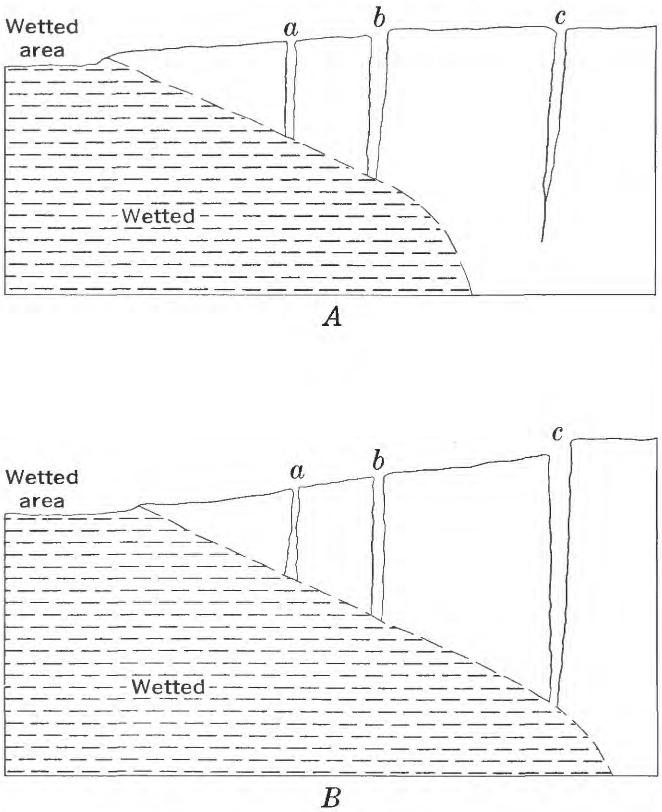


FIGURE 13.—Diagrammatic sections showing the process of near-surface subsidence cracking: *a*, *b*, and *c* are progressively younger cracks. *A*, Before the wetted front has moved as far as crack *c*. *B*, After the wetted front has moved past crack *c*.

slope failure because vertical instead of lateral support is being removed. Also, tensional, instead of shear stresses are the cause of the cracking; but as will be discussed later, compressional stresses are characteristic of the later stages of settlement. In figure 13*A*, crack *a* already has opened and partly closed, and little vertical displacement is present on opposite sides of the crack. Crack *b* is still in the process of opening, and the block between cracks *a* and *b* has been downdropped relative to the block between cracks *b* and *c*. Crack *c* has started to open. The sides of crack *a* are parallel, and cracks *b* and *c* narrow downward. The wetted front has moved past the lower part of crack *b* and has been accompanied by a reduction in volume of the wetted materials in the underlying deposits. The left side of the block between cracks *b* and *c* is not fully supported by the underlying deposits, and the block is rotating toward the wetted area as crack *c* opens.

In figure 13*B*, gravity induced rotation of the two blocks has resulted in further closing of crack *a*, has partly closed and reduced the vertical displacement at crack *b*, and has resulted in further opening of crack *c*. Crack *a* narrows upward, crack *b* has parallel sides, and crack *c* narrows downward. The blocks slope toward the wetted area, and the maximum vertical displacement on opposite sides of the cracks is at crack *c*. If vertical displacement still is present at cracks *a* and *b*, it indicates that a block nearer the wetted area has subsided more than the block farther from the wetted area. Variations in the amount of offset would be a function of the shape of the seepage bulb. Continued outward movement of the wetted front will tend to cause a clockwise rotation of the outermost block, thereby reducing the amount of vertical offset between blocks.

The cracks are shown as not extending into the wetted deposits. The extent of near-surface subsidence cracks in wet deposits is unknown, and the assumption that the wet deposits have insufficient strength to allow cracks to remain open may be untrue.

A variation of the above type of cracking was noted around small test plots in which the ponded area was contained within a section of culvert pipe with a diameter of 8 feet. In these small plots, the wetted area was virtually a point source of wetting, and a tight circular pattern of cracks developed around the plots. The blocks had little tilt toward the ponded area, but had large amounts of vertical offset. The dominance of vertical offset instead of block rotation is attributed to a geometry where the blocks between the cracks resisted tilting toward the plot because of their arcuate shape. Tensional fracturing, not shear, is still the basic cause of rupture, however.

The cracks may be classed as primary or secondary. The primary cracks are the first to open, and roughly parallel the boundary of the wetted area. They occur in parallel sets, or if the cracking from two nearby areas of settlement overlaps, intersecting patterns of primary cracks form.

Several types of secondary cracks may form after the primary cracks are established. The intercepting cracks shown at location *a* in figure 10 are the result of the wide blocks between primary cracks not having sufficient strength to withstand secondary rupture. In each place, a diagonal intercepting crack formed within 5 days after the outermost crack had started to open, but before it had opened to its greatest extent. The overlapping crack patterns and the en echelon crack patterns shown at *b* and *c* in figure 10 may reflect torsional forces produced near the corner of the plot. Torsional forces may be the result of tensional rotation of blocks of dry cohesive material above the seepage bulb from two sides of the plot. Intercepting and en echelon cracks may be primary as well as secondary.

At a still later stage in the sequence of cracking, other types of gravity-induced secondary tensional and shear failures cause the bedded fan deposits to fail and slump into the existing open primary and secondary cracks. Small grabens form, slumpage makes some cracks appear 5 feet wide, and shear collapse of the blocks of deposits produces anastomosing crack patterns.

Tensional forces cause near-surface subsidence cracks to open, and compressional forces tend to close the cracks as the blocks rotate toward the wetted area. Evidence of the compression is shown by cracks that originally narrowed downward, but which later in the history of settlement have parallel sides, or narrow upward. An example of compression resulting from near-surface subsidence is shown in figure 14. The concrete lining is part of a prototype canal that was constructed over the sites of three previous subsidence test plots. As much as 12 feet of subsidence had occurred in the prior plots, but the areas between the plots had not been wetted completely. As a result, part of the concrete was placed on top of blocks of fan deposits that had been subjected to tension, but not to compression. Filling of the prototype canal renewed the wetting, and completed the rotation of the blocks of deposits between the subsidence cracks. The concrete buckled upward as much as 3 feet under the compressive forces. The subsidence cracks under the concrete trend from the upper left to the lower right part of the photograph, but the direction of movement of the concrete slabs was controlled in part by the orientation of the expansion joints.

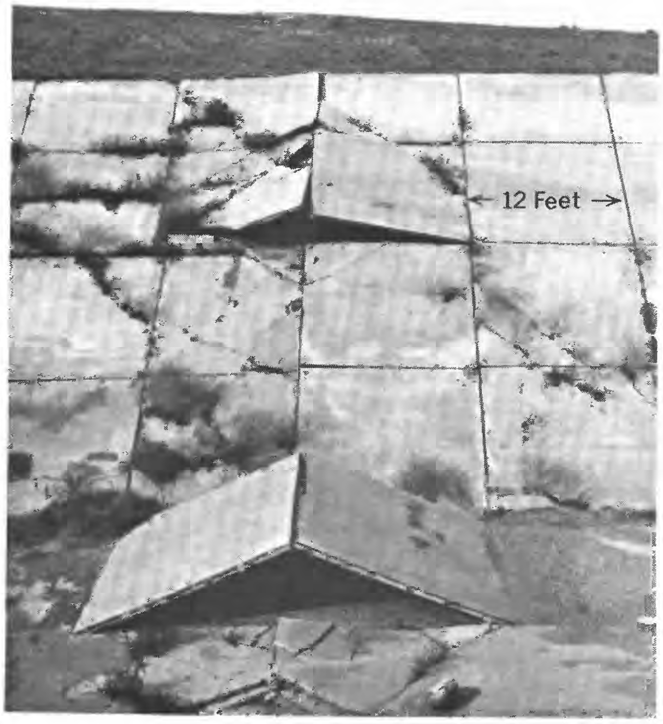


FIGURE 14.—Compressional buckling of 12-foot square concrete slabs caused by near-surface subsidence. Mendota test site of the California Department of Water Resources.

CRACKS IN THE ALLUVIAL FANS OF PANOCHE, LOS GATOS, AND CANTUA CREEKS

Thousands of cracks occur in the large fans of streams heading in the main Diablo Range. The general features, orientations and patterns, and crack fillings are described, and the possible modes and times of formation will be discussed in this section.

Many of the photographs in this and other sections of this paper have been selected to show a variety of features; thus, there will be considerable cross reference to photographs in other sections. The most common scale in the photographs is a mattock. The mattock has a 3-inch cutting edge and a 3-foot handle.

The photographs of cracks in the trimmed banks of the San Luis Canal provide neither a horizontal nor vertical view of the subject matter. As a result, the stratification and crossbedding of water-laid sands appear distorted, and buried stream channels may appear to have overhanging banks, because of the domination of the horizontal component in views of the trimmed slope. Photographs of cracks in the bottom of the canal provide a representative horizontal view.

The cracks were studied on 2-to-1 canal banks—a $26\frac{1}{2}°$ slope, and true horizontal distances and displacements differ from the distances measured on the slopes. For a crack normal to the canal centerline, the horizontal component of a distance between two points is 0.89 the slope distance, and the vertical component is 0.445 the slope distance. As the angle departs from normal to the canal centerline, the horizontal component of the distance increases, and the vertical component decreases. Thus, for a slope distance parallel to the canal centerline there is no vertical component, and the horizontal component is equal to the observed distance. The orientation of the photographs with respect to the canal centerline is indicated by the large marks left by the trimmer, which are parallel to the canal centerline. (For examples, see figures 17*A*, 23, and 47*H*.) Photographs of small areas also may show small marks left by the trimmer blade, which are normal to the canal centerline. (For examples, see figures 22 and 24*A*.) Both types of trimmer marks are shown in figures 21 and 59*B*.

GENERAL FEATURES

The cracks (excluding desiccation and slump rotation block cracks) in the fans of Panoche, Los Gatos, and Cantua Creeks are filled with clay, silt, or sand; no unfilled cracks and only one partly filled crack were observed.

The width of the cracks ranges from less than 1/32 of an inch to 4 inches, but most are 1/8- to 1-inch wide. Crack widths on the trimmed slopes commonly remain constant for distances of 50 feet or more which indicates that the sides of the cracks remain virtually parallel both horizontally and vertically. Some cracks that roughly parallel the canal had constant widths for more than 200 feet.

Although most cracks exposed in vertical cuts have parallel sides, many cracks can be found that narrow upward or downward near their tops. An example of a crack that narrows upward from 1 inch to 1/4 of an inch in a vertical distance of 7 feet is shown in figure 15. The top of the crack is truncated 2.8 feet below land surface, and the crack has a constant width of 1 inch below a depth of 11 feet to a depth of 18 feet where the crack is concealed by debris that has slumped into the channel. This crack was the most extreme example of a crack narrowing upward. The change in crack widths shown in figure 30 (discussed later) suggests the presence of cracks that narrow both upward and downward. However, an equal number of cracks narrow downward as narrow upward in figure 30, which indicates that the change in crack width on the trimmed banks may be in part the result of gradual changes in crack width in a horizontal direction.

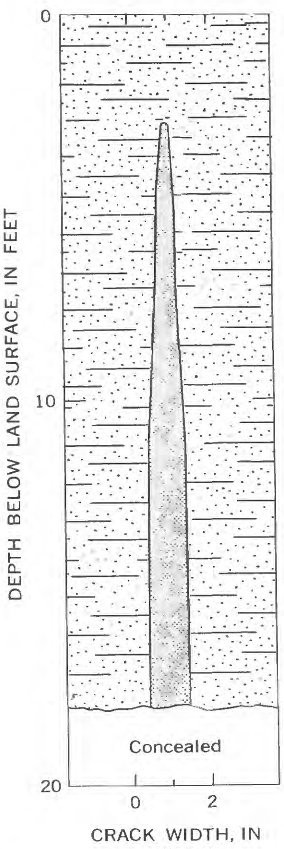


FIGURE 15.—Change in width of crack exposed in a vertical bank of Los Gatos Creek. Location of crack is shown by the letter *H* in figure 52.

A clay-filled crack that narrows downward from one-fourth to one-eighth of an inch in 2½ feet is shown in figure 16. The top of the crack is truncated about 4–5 feet below the surface of the Panoche Creek fan.

The contacts between the crack fillings and the adjacent sediments suggest that the sides of the cracks had a rough hackly fracture before they were filled. This can be seen readily in excavated pits and by the sharp angles and changes in direction of the crack filling exposed in the trimmed banks. Figure 17*A* shows typical clay-filled cracks with angular margins that indicate a hackly fracture before filling. Figure 17*B* shows the undulating nature of the sides of a crack exposed in a pit in the canal bottom. The particle-size distribution of a sample from the crack filling is shown in table 3 and figure 34 (sample 19). Evidence of shearing along the sides of the crack fillings or in the adjacent fan deposits was not observed.

Almost all the cracks are within 5°–8° of being vertical, and the minimum overall dip measured was

FIGURE 16.—Clay-filled crack that narrows downward in the bank of Panoche Creek. Location is about 7,000 feet southwest of San Luis Canal station 2060.

A

B

Figure 17.—Trimmed sections showing irregular sides of clay-filled cracks in the Los Gatos Creek fan. *A*, San Luis Canal station 4783L. Minor offset bedding at bottom of photograph. *B*, San Luis Canal station 4811 + 68B. Piece of measuring tape is 7 inches long.

78°. Changes in overall dip with depth were not apparent. Vertical crack fillings are shown in figure 18. Desiccation cracks in the crack fillings form only after exposure to air, and are not found in fresh excavations (figs. 17*B*, 32*A*). In figure 18*A*, desiccation cracks do not occur at distances of more than 1½ feet in from the edge of the untrimmed canal bank. The particle-size distribution of a sample from the crack filling is shown in table 3 and figure 34 (sample 18). The armored mud balls occur in the clean water-laid sand, and one of the mud balls is cut in half by the clay-filled crack. Part of a 12-foot exposure of vertical crack filling is shown in figure 18*B*. The crack filling is almost parallel to the streambank, and continues into the bank to the left of the mattock.

Evidence for the vertical nature of the cracks on a larger scale is shown in figure 19. The inferred position of concealed parts of the cracks is shown by dashed lines. For almost 500 feet along the canal, not only the general bearing, but also the number of cracks match from one side of the canal to the other, despite the fact that the canal banks slope in opposite directions at 26½°. The example shown in figure 19 is better than most parts of the canal, because many of the cracks are discontinuous. The general lack of change in strike where the cracks cross from the sides to the bottom of the canal shows that they are predominantly vertical (pl. 2*A* and figs. 29*A* and 50). Most of the cracks shown in figure 19 could be traced only a few feet into the disturbed material covering the canal bottom, but in some areas cracks could be mapped in the bottom as well as in the canal banks. The material above the top of the bedded fan deposits in figure 19 consists of artificial fill.

Undisturbed crack tops are not common, but those found all have similar characteristics. Near its top, the crack width increases to 2–18 inches within a vertical distance of 1–3 feet. The clay filling appears to bifurcate upward and form the outer edges of a funnel-shaped cross section. The inside of the crack top is filled with water-laid sand and silt, or debris that has slumped into the crack top. A funnel top is shown in figure 38, and the material within the crack is described in the section about crack fillings.

A

B

FIGURE 18.—Sides of vertical clay-filled cracks, Los Gatos Creek fan. *A*, San Luis Canal station 4712 + 21R. Scale is 4 inches long. *B*, Bank of Los Gatos Creek. Mattock handle is 3 feet long. Location of crack is shown by the letter *H* in figure 52.

Most of the upper parts of the cracks end within the bedded fan deposits and appear to have been cleanly truncated during the process of erosion, transportation, and deposition of the water-laid sediments. Truncated clay-filled cracks are shown in figure 20. In figure 20*A*, the truncation is 9 feet below the fan surface, and in figure 20*B*, the truncation is 1–2 feet below the top of the bedded fan deposits. Some cracks disappear at the base of the tilled zone, about 2 feet below the fan surface, and it is not possible to determine the nature of the original tops of these cracks.

RELATION OF CRACKS TO BEDDING

Bedding on the opposite sides of the cracks does not show any signs of bending or deflection along the crack, and offset, which is not common, rarely exceeds a few inches as exposed on the 2-to-1 slopes. Lack of offset bedding is shown in figure 26. Minor offset bedding may be present at the bottom of the photograph in figure 17*A*.

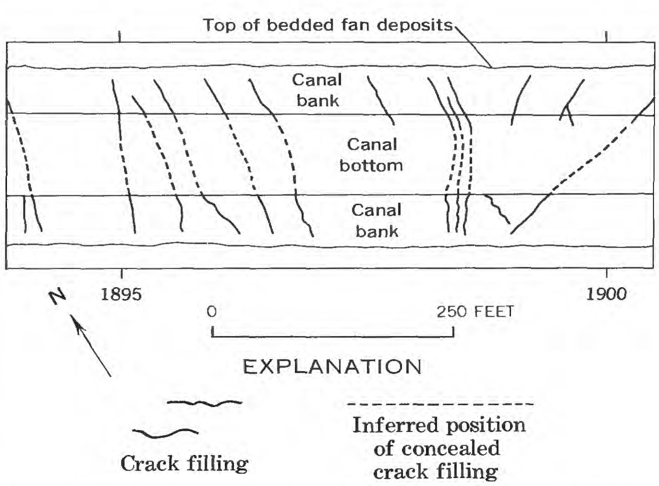
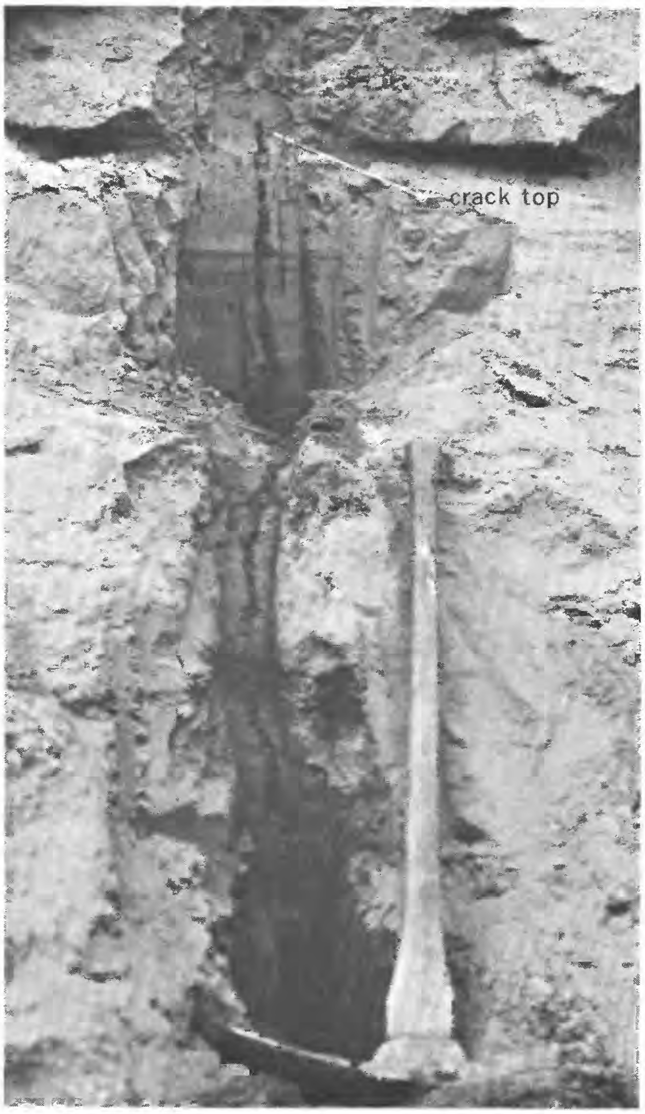


FIGURE 19.—Near-vertical clay-filled cracks in the Panoche Creek fan at canal station numbers 1895 and 1900. From U.S. Bureau of Reclamation map by M. K. Bradley.



A

B

FIGURE 20.—Truncated tops of clay-filled cracks. *A*, Crack in trench on Panoche Creek fan about 1,000 feet southwest of canal station 2060. Mattock handle is 3 feet long. *B*, Crack in the Los Gatos Creek fan at canal station 4796 + 33R. White scale is 4 inches long.

Beds that are offset 2½ inches as exposed on the trimmed slope are shown in figure 21. Excavation of the offset revealed a true offset of only 1 inch. At distances of more than 20 feet up and down the slope, offset was not apparent. The 4-inch scale is on a scrape mark left by the trimmer. A filled rodent burrow cuts the crack immediately below the scrape mark. Sand occurs in the middle of the clay-filled crack at the top of the photograph.

Offset of intersecting crack fillings (fig. 32*B*) is rare, as is offset of crack fillings by unfilled cracks. An example of the latter is shown in figure 22.

Changes in the thickness of beds on the opposite sides of a crack as exposed in the trimmed canal banks suggest different amounts of rotation of the blocks. In figure 23, the thickness of the sequence of well-defined thin beds crossing the middle of the mattock handle changes abruptly at a crack filling. The apparent thickness of the sequence of thin beds to the left of the crack is 3 inches, and to the right of the crack, 5–6 inches. The block to the right of the crack has rotated vertically counterclockwise relative to the block to the left of the crack. The counterclockwise rotation has caused the angle of intersection of the bedding and the trimmed slope to be smaller, and thereby increases the apparent thickness of the sequence of beds.

RELATION OF CRACKS TO BURIED STREAM CHANNELS

Buried stream channels of ancestral streams are common in the fans studied. Compound cut-and-fill structures several hundred feet wide were noted in a few places, and indicate repeated channel entrenchment and backfilling. The depth of the channels in the Panoche Creek fan is about 20 feet, which is the same as the depth of the present-day channel incised into the fan where the stream crosses the canal alinement. The channels of Los Gatos and Cantua Creeks are incised into the upper parts of their fans, but do not extend as far downfan as the canal alinement. Backfilled ancestral channels exceeding 20 feet in depth were exposed in both fans by the canal construction.

The sediments filling the ancestral channels generally consist of coarse crossbedded sands and sandy gravels. The coarseness of the channel fills contrasts sharply with the fineness of the enclosing and overlying sediments which were deposited as thin sheets by

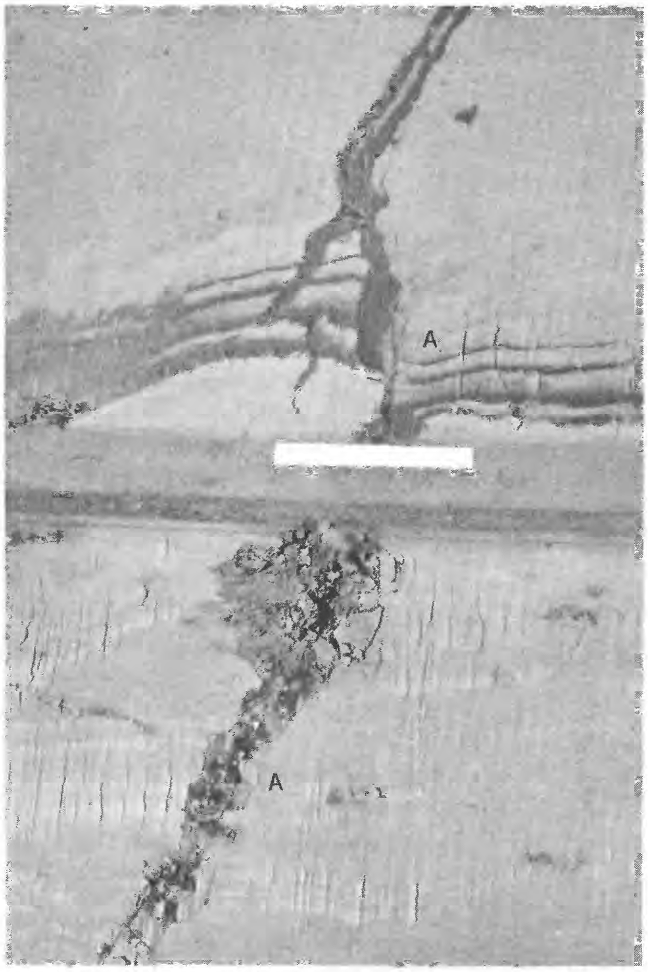


FIGURE 21.—Offset bedding (A) on the opposite sides of a crack filling in the Los Gatos Creek fan. San Luis Canal Station 4802 + 97R. Scale is 4 inches long.

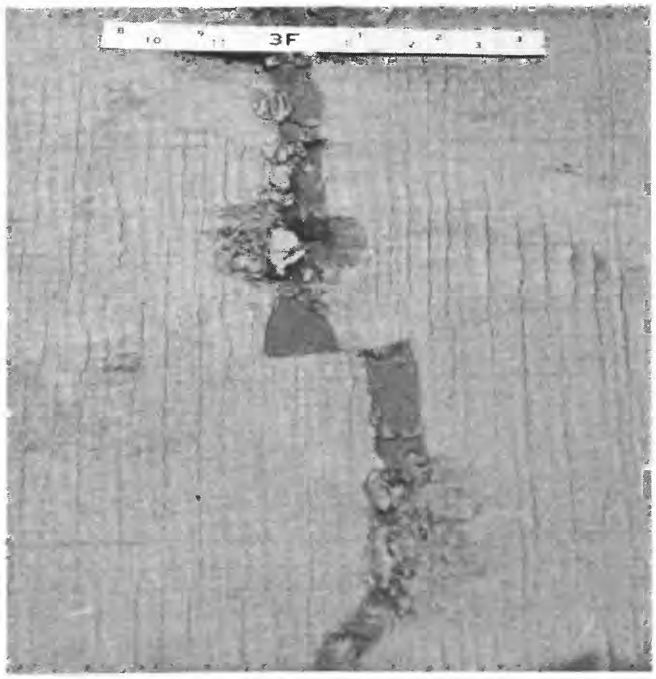


FIGURE 22.—Crack filling offset by unfilled but closed crack, Los Gatos Creek fan. San Luis Canal station 4810 + 72L. The piece of measuring tape is 7 inches long.

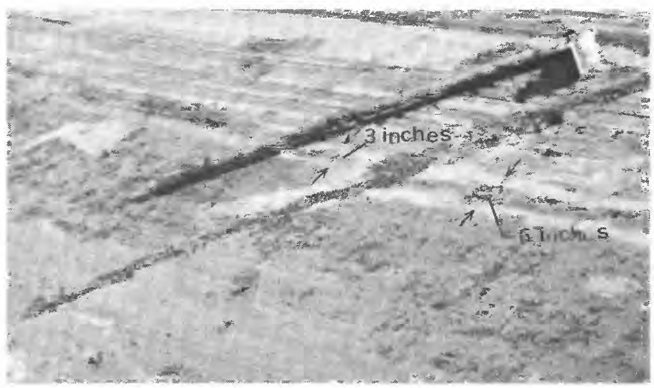


FIGURE 23.—Block rotation shown by change in bed thickness on opposite sides of a crack filling in the Panoche Creek fan. San Luis Canal station 1927 + 30L.

braided streams. The fine-grained deposits compose the bulk of the fan deposits.

In general, crack fillings were not observed in the coarse-grained material filling channels or in the finer grained thin-bedded fan deposits above the cut-and-fill structures.

Existing cracks were truncated during the course of channel entrenchment. Crack fillings that are truncated by cut-and-fill structures are shown in figure 24. In figure 24*A*, a 1-inch clay-filled crack in massive clayey sand is truncated by a buried stream channel 25 feet below the present land surface. Gravelly sand in the bottom of the channel is overlain by crossbedded sand. This channel was 490 feet wide as exposed in the canal bank. In figure 24*B*, a 1½-inch crack filling consisting of clay with some sand in the middle of the filling, protrudes as a truncated stub 4–5 inches into the bottom of a former stream channel about 18 feet below the present land surface. Massive clayey sand underlies the channel, which is filled with clean crossbedded sands containing less than 5 percent clay. The widening of the crack filling near the base of the channel suggests that this part of the crack may be part of a funnel top that has been largely removed by erosion.

No cracks were observed passing from the underlying sediments into the channel fills on the Panoche Creek fan, and only one crack in the canal banks on the Los Gatos Creek fan extended into a cut-and-fill structure. On the Cantua Creek fan, however, several cut-and-fill structures had prominent crack fillings extending into them from the underlying sediments (J. O. Berkland, oral commun., May 27, 1967).

A

B

FIGURE 24.—Clay-filled cracks truncated by cut-and-fill structures. *A*, Panoche Creek fan, San Luis Canal station 2138 + 10R. The paired arrows end at sides of cracks. *B*, Los Gatos Creek fan, San Luis Canal station 4805 + 00L. The paired arrows end at sides of crack and funnel top.

Crack fillings occurring only within the coarse-grained deposits of the cut-and-fill structures were virtually nonexistent. A few channel fills on the Los Gatos Creek fan had 1/8-inch-wide clay-filled cracks extending for about 10–15 feet (as exposed on the trimmed canal banks). These thin cracks pinch out both upslope and downslope.

Alluvial fill within the present-day stream channels is common, and occurs as fill terraces set inside the entrenched stream channels. The water-laid deposits in the fill terraces are similar to the fan deposits with which they are in contact, but changes in the overall color of the beds or the thickness of the bedding of the adjacent sequences are common on the opposite sides of the unconformities.

Crack fillings were not found in the fill terraces on any of the fans. Crack fillings below the terrace fills were truncated at the base of the fill in the few places where the base of the fill could be observed.

Although an intensive search was made, no crack fillings were found in the banks of Cantua Creek. The main reason that crack fillings were not found was that fill terraces occur along most of Cantua Creek. The creek has done extensive lateral cutting—more than one-third of a mile in some reaches—and then has backfilled the broad channel to a large extent with a complex of fill terraces. Other factors that prevent finding crack fillings along Cantua Creek include the depth of incision of the stream, which is less than 15 feet, and the greater extent of plowing and destruction of the banks by man, as compared to the other stream-banks.

PROXIMITY TO THE LAND SURFACE AND AREAL DISTRIBUTION OF CRACKS

Most of the crack fillings extend to within a few feet of the base of the tilled zone. Occasional cracks or sets of cracks are truncated as much as 20 feet below land surface, but these are rare. Along the canal, the bedded fan deposits are overlain by a 1- to 2-foot tilled zone. In most of the stream-channel exposures, the surficial fan deposits have not been distributed by plowing.

None of the cracks studied in or near the banks of stream channels extends to land surface. An example is the group of cracks exposed adjacent to Panoche Creek in a trench used to bypass streamflow during construction of the canal siphon under Panoche Creek (fig. 25). All but one of the cracks have truncated tops that are 8–10 feet below the fan surface. The cracks occur in thin-bedded fan deposits consisting of water-laid sands, clayey silts, and silty clays. Much of the bedding is discontinuous, but a few beds extend for at least 200 feet along the ditch; one such bed is shown near the bottom of the cross section. The cracks exposed by the trench are typical of those found in all three large fans whose streams head in the main Diablo Range. The width of most of the crack fillings is 1/4–3/4 of an inch but parts of some crack fillings are as much as 1½ inches wide. Most of the cracks have parallel sides; three narrow upward slightly in the

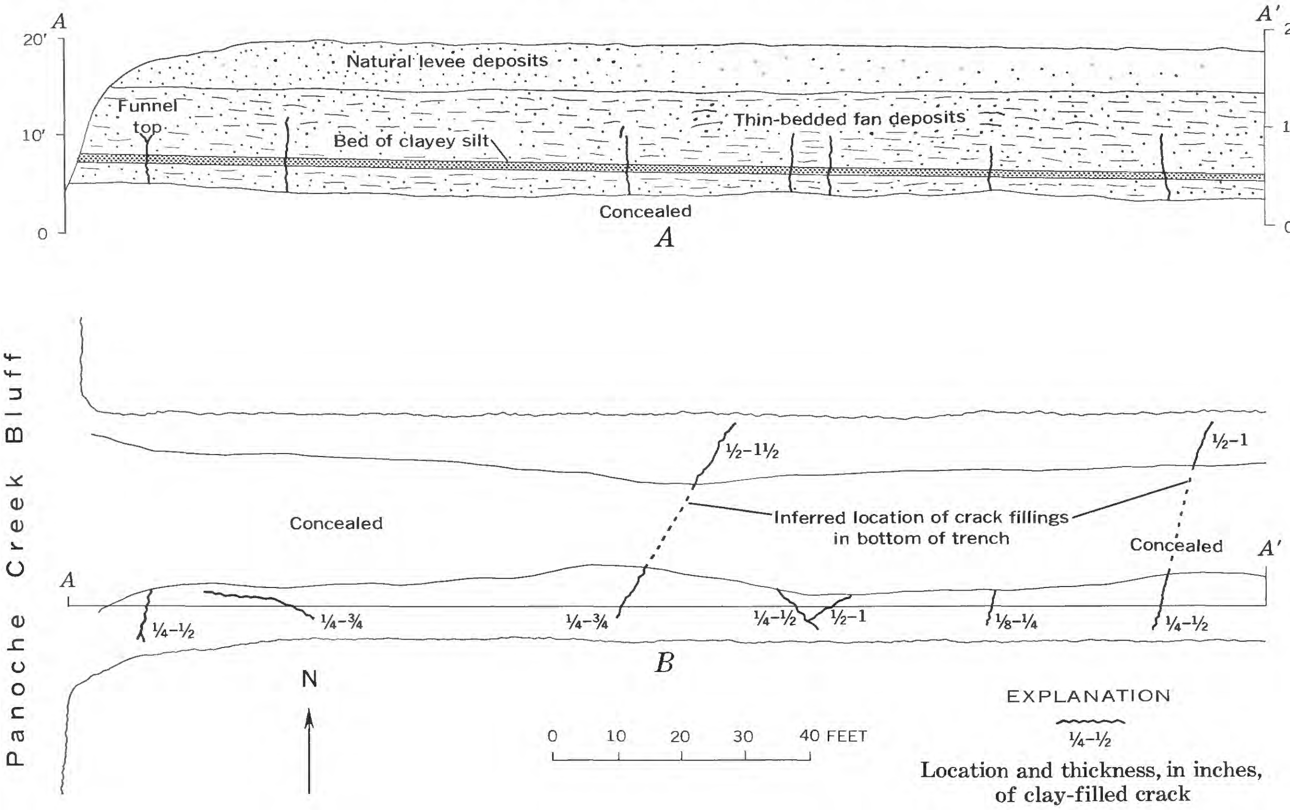


FIGURE 25.—Clay-filled cracks exposed in trench about 1,000 feet southwest of San Luis Canal station 2060. *A*, Cross section of cracks and fan deposits along line *A–A'*. *B*, Map of cracks.

upper 1–2 feet. One crack narrows downward. Two cracks have en echelon offsets of about half a foot. All but one of the cracks have truncated tops; this one crack has an undisturbed funnel top filled with water-laid sand. The cracks are filled with clay, and the particle-size distribution for the filling in the second crack east of Panoche Creek (sample 2) is shown in figure 34 and table 3.

Overlying the thin-bedded deposits is a coarser grained unit, 4–5 feet thick, consisting of massive crossbedded water-laid sands. The sands are typical of the natural levee deposits on the fans of the intermittent streams. The thin-bedded lower unit is typical of the sheetlike deposits that spread out on the fan from the end of the fanhead trench. The natural levee deposits probably were formed when the stream was sufficiently entrenched during the 1875–95 period (Bull, 1964c) to prevent the entire flow from spreading out on the fan, but not trenched so deeply as to completely confine the streamflow to the channel. The natural levees represent times of rapid deposition during infrequent episodes of high discharge of Panoche Creek. The amount of time needed to deposit a given thickness of natural levee deposits probably is small compared to the time required for deposition of an equal thickness of the thin-bedded fan deposits.

A photograph of the easternmost crack filling on the north side of the trench (fig. 25) is shown in figure 26. The truncated top and lack of offset bedding of the bedded fan deposits on opposite sides of the crack are typical of the cracks studied in the trench. A more complete view of this crack is shown in figure 20*A*.

The proximity of the cracks to the land surface was harder to determine in the canal banks than in the stream channels and trenches because the exposures were not as good and because the top of the bedded fan deposits was overlain by a tilled zone that was overlain by artificial fill. In studies such as those shown in figures 30 and 50, the cracks were mapped in detail, and the top of each crack was determined by cutting into the canal bank at the point where it disappeared. It was not practical to do this for most of the cracks in the canal banks, and along most of the canal only the strike, or the thickness and the strike, were noted for the crack fillings.

In general, most of the cracks exposed in the canal banks ended within a few feet of the top of the bedded fan deposits, although many cracks were found that extended to the base of the tilled zone.

One consistent feature was the uniformity of the position of adjacent crack tops. For distances of several hundred to several thousand feet, virtually all the crack

FIGURE 26.—Clay-filled crack in thin-bedded fan deposits exposed in trench about 1,000 feet southwest of San Luis Canal station 2060. Rock hammer for scale.

tops occur at a similar common level below the base of the tilled zone. An example outside of the canal was given in figure 25, and an example in the canal is given in figure 27.

Most of the cracks in figure 27 end 10–15 feet below the original land surface, although one crack extends to the base of the tilled zone. Most of the crack fillings are truncated, although the tops of many were hard to discern where they ended in clayey sediments of about the same color as the crack filling. For 1,300 feet along the fan contour, the cracks terminate at roughly the same depth below the original land surface. For the 500 feet to the northwest of the section shown in figure 27, the crack fillings extend to within 4–9 feet of the original land surface. For 1,000 feet to the southeast of the section shown in figure 27, the crack fillings extend to the base of the tilled zone in many places. In most parts of the canal, the cracks do not terminate as far below the land surface as those shown in figure 27.

The variable depth of burial of the cracks is consistent with a model of fan deposition in which rapid aggradation occurs along a local radial belt of deposition until the stream channel shifts to an adjacent, or another, part of the fan.

The distribution of the cracks on the various parts of the fans is not well known, particularly downslope from the canal where the cracks were observed only in two trenches. Study of the streambanks of Panoche and Los Gatos fans indicates that the cracks are common in the fans upslope from the canal, except that cracks were not found near the fan apexes. The lack of cracks at the fan apexes is in part due to the greater abundance of fill terrace material near the apexes than downfan, but even the exposures of fan deposits at the apexes did not have clay-filled cracks in them. The abundance of the cracks in the canal and streambanks, and in isolated trenches, suggests that the cracks are common and widespread on at least the upslope two-thirds of the fans except for the areas on the fan apexes. Additional information, both upslope and downslope from the canal, will be available when the distribution systems are constructed to deliver water from the canal.

CRACK ORIENTATIONS AND PATTERNS

The orientation of most of the cracks is roughly parallel to radial lines of the fans on which they occur. This orientation is particularly apparent along the canal, which follows the general contours of the fans. The cracks are roughly normal to the canal centerline. Very few cracks on the Panoche Creek fan are parallel to the canal centerline, although one crack roughly parallels the centerline for 270 feet. Cracks that are roughly parallel to the canal centerline are more common on the Los Gatos Creek fan; an example is shown in figure 50.

The deviation of the crack strikes from a bearing normal to the fan contours was determined for 415 cracks at the six sites on the Panoche and Los Gatos Creek fans shown in figures 19 and 27–30 and plate 2*A*, 2*B*. The contours of topographic maps made in the 1920's were used as a reference for the orientations of the cracks exposed in the canal. The maps of the 1920's have a 5-foot contour interval, and represent the land-surface configuration before 10–25 feet of subsidence due to artesian-head decline and before

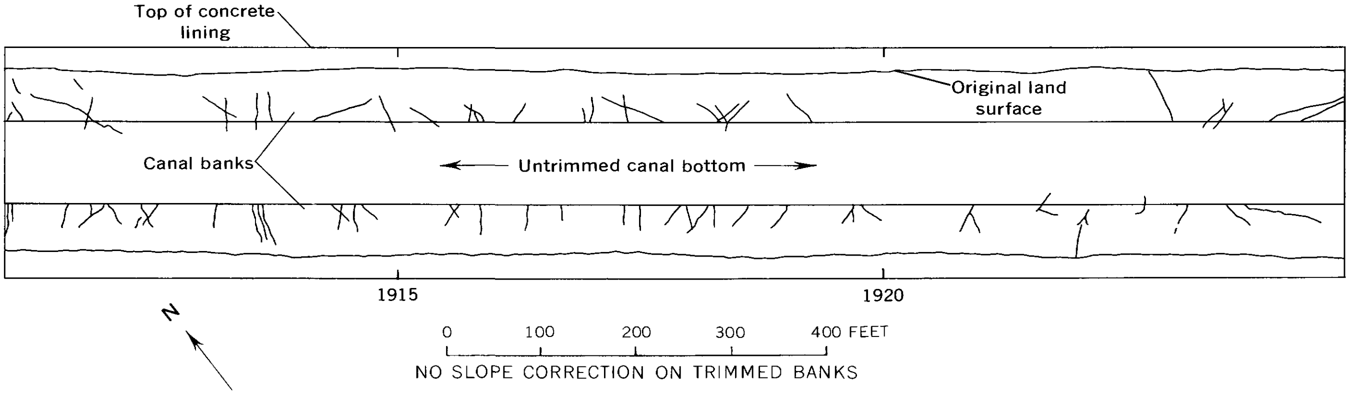


FIGURE 27.—Clay-filled cracks terminating 10–15 feet below the original land surface, Panoche Creek fan, in the San Luis Canal at stations 1915 and 1920.

local changes in topography were made as a result of land-leveling operations during the course of agricultural development. The canal alinement could not be used as a reference for studying crack orientation, because, for the most part, it consists of straight reaches connected with curving reaches. (See pl. 1.) Parts of the canal are at angles of as much as 27° to the 1920's fan contours.

The orientation of cracks at six sites—three on the Panoche and three on the Los Gatos Creek fan—are shown in figure 28 and summarized in table 2. The crack orientation in the northwest side of the Panoche Creek fan is shown in figure 28*A*. Most of the cracks deviate less than 50° from being normal to the fan contours, and the greatest frequency is at deviations of 20° or less. In figure 28*B*, the cracks have a marked tendency to be normal to fan contours, with 56 percent of the cracks deviating 10° or less. Visual inspection of the cracks in the trimmed canal banks of the Panoche Creek fan gives the impression that most of the cracks have the general orientation shown in figure 28*B*, but when the orientations are measured, more scatter is revealed than is apparent in the field. An example of a higher degree of scatter would be figure 28*C*, where a conspicuous central tendency between ±20° is obvious. Secondary modes of orientation are also obvious at deviations of 40°–50°. The orientation of cracks in the canal bottom in the Los Gatos Creek fan is shown in figure 28*D*, where more than half the cracks have deviations of 20° or less. The orientations of cracks in both the canal bottom and banks are shown in figure 28*E*. The number of cracks that deviate more than 20° may be the result of many small secondary cracks being mapped at this site—cracks that were not included in the general mapping that was done at most of the other sites. The orientation of cracks in the canal banks on the east side of the Los Gatos Creek fan is shown in figure 28*F*. Although many cracks have deviations of 20° or less, it is readily apparent that large numbers of cracks do not tend to be normal to the fan contours in this reach.

Significant differences in crack orientation in the Panoche and Los Gatos Creeks fans are revealed in table 2. For the Panoche Creek fan, the percentage of cracks with deviations of 20° or less ranges from 44 to 69, but for the Los Gatos Creek fan the range is 36–59 percent. The percentages of cracks with deviations of 50° or less ranges from 82 to 88 percent for the Panoche Creek fan and from 71 to 78 percent for the Los Gatos Creek fan. For both fans, however, there is a general tendency for the cracks to roughly parallel the radial lines and to be normal to the contours of the fans.

The overall orientation of the cracks in the Panoche and Los Gatos Creek fans is shown in figure 29, which summarizes the orientation of 415 cracks at the six sites on the two fans. This large sample of crack orientations shows a pronounced mode of orientation of cracks deviating 20° or less is the dominant feature of the plot—45 percent of the cracks have deviations of 20° or less. About 80 percent of the cracks have deviations of 50° or less. However, secondary modes of orientation occur between 40° and 60°, with the mode on the left side of the plot being more pronounced.

The density of spacing of the cracks is highly variable and changes abruptly within short distances on all the fans. The spacing of cracks in the Panoche Creek fan shown on plate 2*A* is characteristic of all three of the large fans. The cracks occur in clusters or equally spaced sets of parallel cracks, and the intervening areas contain few or no cracks. Plate 2*A* also shows crack fillings that are truncated by buried stream channels, and illustrates the difference in abundance of cracks between the Panoche Creek and the adjacent small fans derived from the foothill belt of the Diablo Range. In general, the cracks are much more closely spaced on the

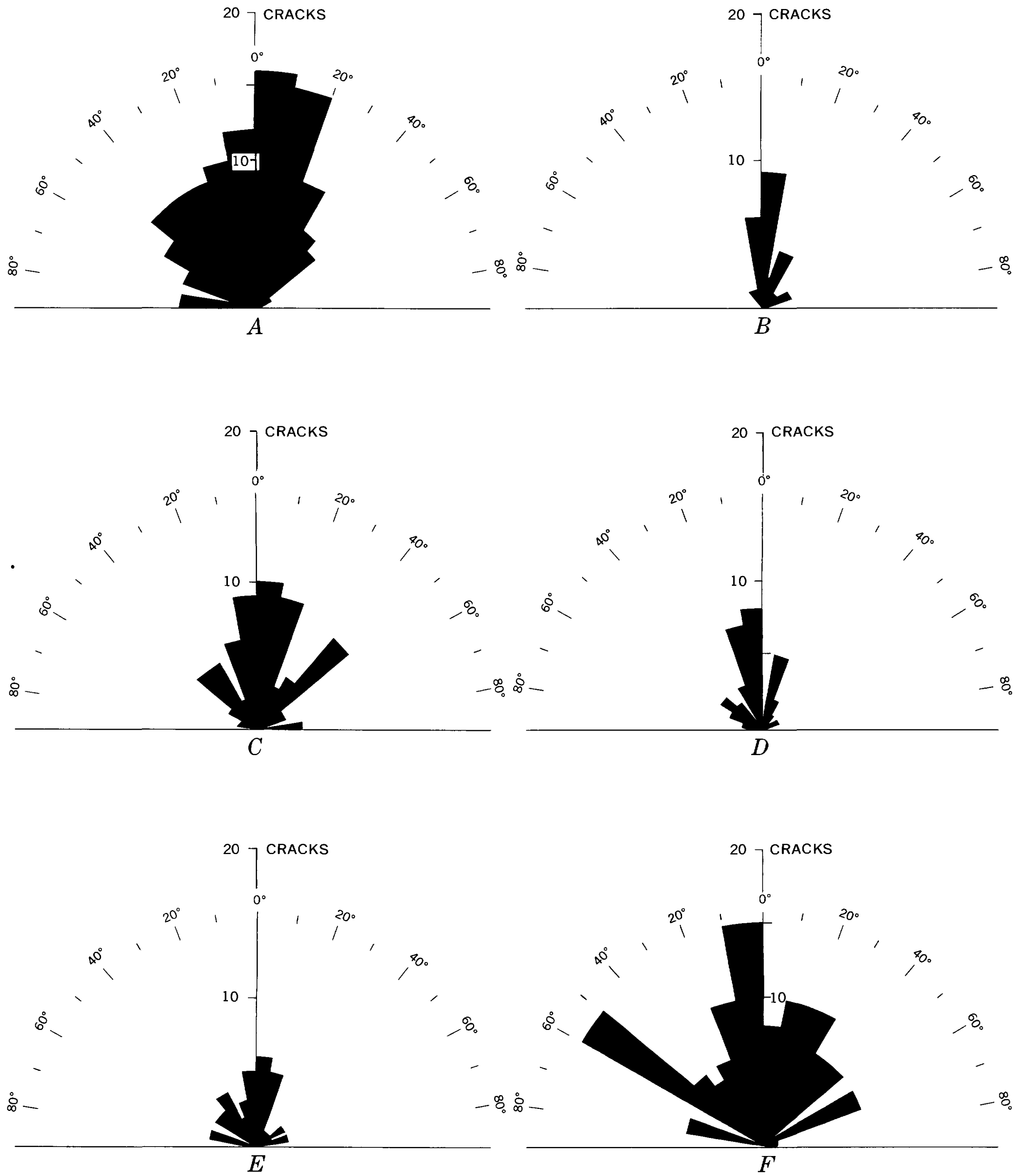


FIGURE 28.—Deviation of crack strikes from bearings normal to the fan contours, Panoche and Los Gatos Creek fans. *A*, Panoche Creek fan, station 1820–1860. *B*, Panoche Creek fan, station 1894–1900. *C*, Panoche Creek fan, station 1911–1924 + 50. *D*, Los Gatos Creek fan, station 4170–4181. *E*, Los Gatos Creek fan, station 4450–4452. *F*, Los Gatos Creek fan, station 4662–4674.

TABLE 2.—*Deviation of crack strikes from bearing normal to the fan contours, Panoche Creek and Los Gatos Creek fans*

Location	Number of cracks measured	Percentage of cracks with deviations of 20° or less	Percentage of cracks with deviations of 50° or less
Panoche Creek fan:			
Station 1820–1860 (*pl. 2A*)	120	44	82
Station 1894–1900 (fig. 19)	26	69	88
Station 1911–1924+50 (fig. 27)	72	47	85
Los Gatos Creek fan:			
Station 4170–4186 (fig. 30*B*)	37	59	76
Station 4550–4552 (fig. 30*A*)	42	38	78
Station 4662–4674 (*pl. 2B*)	118	36	71
Total for Panoche and Los Gatos Creek fans	415	45	80

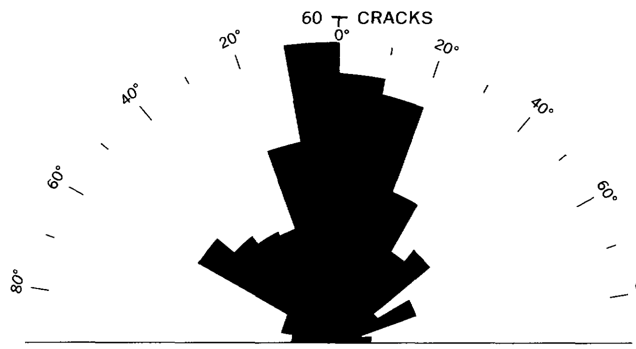


FIGURE 29.—Orientation of 415 cracks in the Panoche and Los Gatos Creek fans, with respect to bearings normal to the 1920 fan contours.

large fans than on the small fans. For most of the Panoche Creek fan, one to seven cracks occur per 100 feet of canal alinement, but locally as many as 10–12 cracks occur within a 100-foot interval.

Crack fillings are more numerous in the Los Gatos Creek fan than on the other fans studied. Four to eight cracks per 100 feet are common, and parts of fans exposed in the canal banks have more than 25 cracks per 100 feet. An example is given in figure 30*A*. All the cracks shown in figure 30*A* are 1/8- to 1-inch wide except one 2-inch crack at station 4551+05. The cracks appear to be more common in the canal bottom than in the bank, because many of the smaller cracks in the bank were concealed because of repeated wetting of the slope. Most of the cracks disappear several feet below the top of the bedded fan deposits. The dominant trend of cracks is roughly normal to the canal centerline, but several cracks reveal the presence of a secondary trend about parallel to the canal centerline.

Closely spaced cracks in the northwest part of the Los Gatos Creek fan are shown in figure 30*B*. The density of spacing in the bottom of the canal ranges from two to 10 cracks per 100 feet. Most of the cracks are normal to the canal centerline, but one crack parallels the canal.

Most of the cracks exposed in the stream-channel banks are roughly parallel to the channel banks, particularly along Panoche Creek (fig. 25), where crack fillings were found only in meandering reaches of the stream or in trenches and roadcuts adjacent to the stream. Along Los Gatos Creek, one crack filling formed part of the streambank for 75 feet, but cracks at large angles to the streambanks are common.

Although many cracks can be traced for distances of more than 200 feet, they appear to be discontinuous features. Exposures along the radial lines of the fans are not sufficiently long to indicate the maximum length of the cracks.

A variety of patterns are formed by the crack fillings. They occur in parallel sets, are anastomosing, intercepting, intersecting, and en echelon. Photographs of each of these types are compared with photographs of known near-surface subsidence crack patterns in the section about possible causes of the cracks.

Parallel sets are one of the most common crack patterns. Examples are shown in figure 19 and on plate 2*A*. The spacing between cracks in a given set varies between 3 and 100 feet, but within a given set most of the cracks are evenly spaced.

Most of the crack patterns studied are illustrated on plate 2*B*. Between stations 4661+90 and 4668+40 each crack was mapped along its entire exposure, and the changes in lithology and width noted. Between stations 4668+40 and 4674+20, the overall strike, thickness, and lithology were noted for each crack. The bottom 8 feet of the slope was concealed by a sand-filled toe drain and disturbed material associated with the construction of the drain. Several sand-filled cracks were observed in this reach of the canal, and the 1-inch sand-filled crack at the base of the map at station 4670+05 has a 3/4-inch clay-filled crack passing through it (J. O. Berkland, written commun., Sept. 6, 1967). Other clay-filled cracks contained sand in their centers; or consisted entirely of sand in the upper parts of the slope.

Between stations 4661+90 and 4668+40, eight cracks narrow upslope, eight cracks narrow downslope, and 35 cracks maintain about a constant width. It could

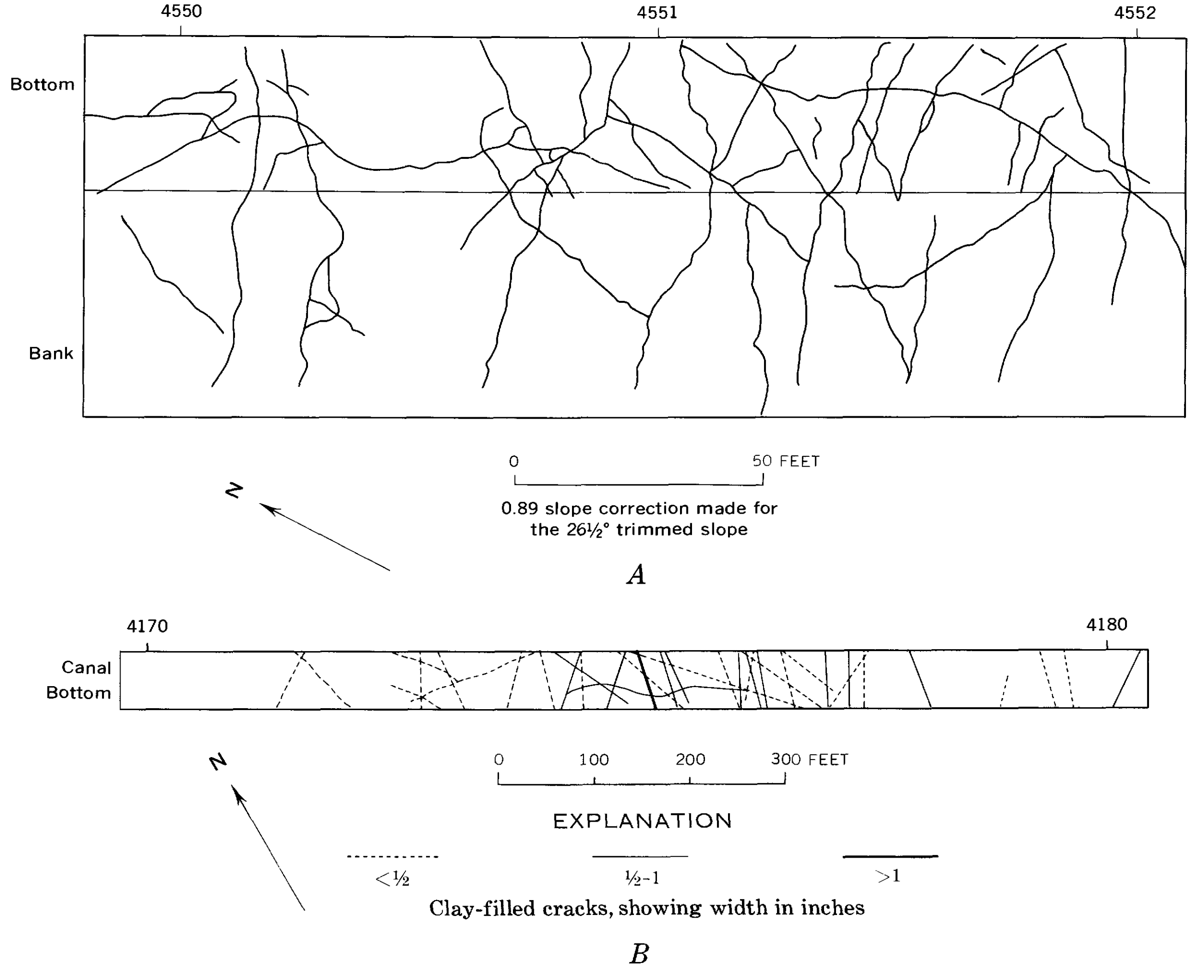


FIGURE 30.—Closely spaced clay-filled cracks in the Los Gatos Creek fan at canal station numbers 4550, 4551, and 4552. *A*, The middle of the fan between San Luis Canal stations 4549 + 80 and 4552 + 10. *B*, The northwest side of the fan between San Luis Canal stations 4170 + 00 and 4180 + 40. From U.S. Bureau of Reclamation map by R. B. Burket.

not be determined if change in width was occurring in a horizontal direction, vertical direction, or both.

Although parallel sets of cracks are not conspicuous on the map, most of the other crack patterns are. Anastomosing, intersecting, intercepting, and en echelon patterns occur at several locations between stations 4661+90 and 4668+40.

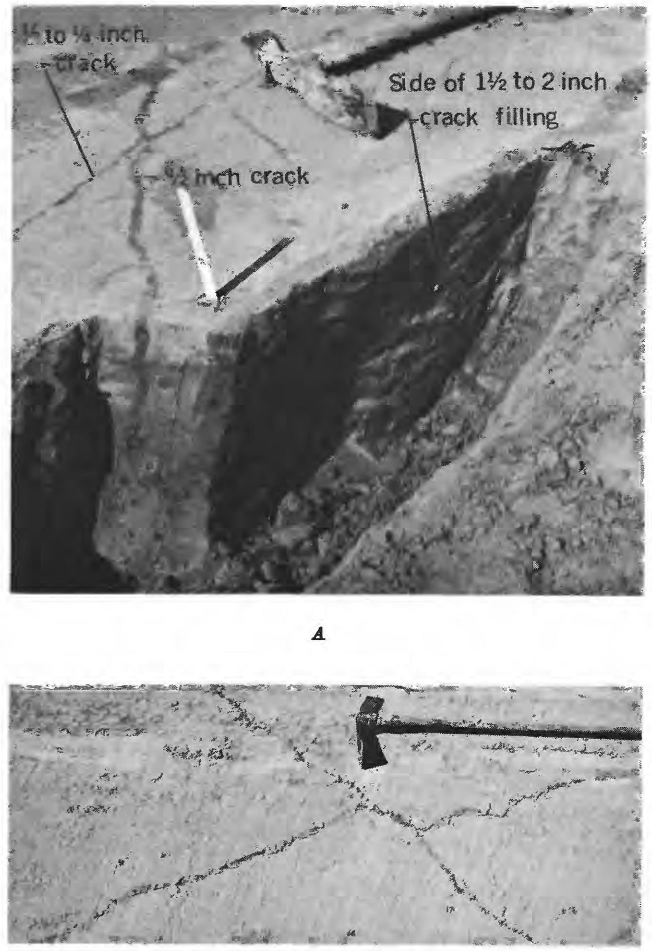
Anastomosing cracks (figs. 17*A* and 30*A*) may divide and join repeatedly for distances of as much as 200 feet. A variety of anastomosing cracks are those that split into many small cracks that die out within a short distance. An example of dividing cracks in the Cantua Creek fan is shown in figure 31. Different parts of the network of cracks shown in figure 31 are filled with clay, silt, and sand, or mixtures of these materials.

Intersecting crack patterns are most common in the Los Gatos Creek fan, but both intersecting and intercepting crack patterns are common on all three fans studied. In figure 32*A*, an excavation in the canal bottom shows the undulating side of a steeply dipping clay-filled crack. A near-vertical cut across the thick crack filling revealed a 1/2-inch crack filling that intercepts but does not pass through the thicker crack. On the trimmed surface of the canal bottom in front of the head of the mattock, a 1/8- to 1/4-inch crack filling intersects the 1/2-inch crack filling with no apparent offset of either crack.

Despite the abundance of intersecting cracks in the Los Gatos Creek fan, offset is rare. Of the hundreds of crack intersections examined, only one showed displacement. The displacement that appeared to be 3 inches on the trimmed canal bank was only 1 inch in a vertical cut made in the bank to examine it. Apparent minor offset such as this may be largely due to the irregular hackly type of rupture pattern in the cohesive deposits.

Offset of intersecting cracks was more common in the canal banks of the Panoche Creek fan, particularly in the northern third of the fan. A crack offset about

FIGURE 31.—Network of clay- and sand-filled cracks that split into many small cracks that die out within a short distance. Cantua Creek fan, San Luis Canal station 3192L.



A

B

FIGURE 32.—Intersecting and intercepting clay-filled cracks. *A*, Intercepting and intersecting cracks in the Los Gatos Creek fan, San Luis Canal station 4785 + 21B. *B*, Offset of intersecting cracks in the Panoche Creek fan, San Luis Canal station 1974 +65L.

6 inches is shown in figure 32*B*. Apparent offsets that were examined generally were less than 3 inches on the trimmed slopes, but displacements of 6, 12, and 21 inches were noted.

The displacement of intersecting cracks does not require a strike-slip horizontal movement. If one or more of the planes is not vertical, gravity movements will include a horizontal component and the intersection of the planes will be offset. The magnitude of offset of nonvertical crack fillings as indicated on the 26½° slope may be much greater than the true displacements if the trimmed slope and the nonvertical crack dip in the same direction, and less than the true displacement if the slope and crack dip in opposite directions.

En echelon crack patterns are common, particularly in the Los Gatos Creek fan. Most of the en echelon offsets were observed as horizontal cracks striking in the same direction, because vertical cuts of sufficient magnitude were not available in the canal. Vertical exposures in streambanks and ditches revealed cracks that were offset en echelon vertically. Two such cracks were found in the sides of the trench shown in figure 25. Vertical en echelon cracks in the bank of Los Gatos Creek are shown in figure 33.

CRACK FILLINGS

Most of the cracks are filled with clay, a few with sand, and a few cracks are found that consist of more than one distinct lithology. Several different structures found in the crack fillings provide clues as to the modes of formation of the cracks and fillings.

CLAY

Most of the cracks are filled with clay. Clay-filled cracks that contain minor amounts of coarse silt and sand commonly have this coarser material concentrated in the medial part of the crack. Cracks filled with silty clay or clayey silt are rare. A few cracks filled with silty material were noted in the fans of Cantua Creek and Los Gatos Creek, but none were observed in the Panoche Creek fan. The crack fillings are

FIGURE 33.—Vertical en echelon clay-filled cracks that end in a funnel top (A) 3–4 feet below land surface. Right bank of Los Gatos Creek, location shown by letter G in figure 52. Tape is extended 1 foot.

not injected laterally between the bedding planes of the fan deposits.

The particle-size distribution of samples from clay-filled cracks is shown in table 3, and the cumulative curves of five of the samples are shown in figure 34. Most of the material in the crack fillings consists of moderately well sorted clay. Four of the five samples shown in figure 34 did not contain any particles larger than 20 microns. Sample 18 had a medial parting filled with sand, similar to that shown in figure 36*B*. About 63 percent of sample 18 consisted of material less than 1 micron in size. The eight samples shown in table 3 as having a lithology of clay have a mean clay (material less than 4 microns in size) content of 82 percent. The size distribution of the material less than 1 micron in size was determined by a centrifuge method.

The particle-size distributions of all the samples shown in table 2 were determined by the Hydrologic Laboratory of the Geological Survey. For several samples, a centrifuge method for determining the size distribution of the material less than 1 micron in size was developed by Edward Sammel and Donald Bingham of the laboratory. After the hydrometer analysis had reached the 4 micron size, two or four 200-ml (milliliter) aliquots were decanted from the samples and centrifuged simultaneously. Successively finer fractions were removed by decantation after specified time intervals of centrifuging (E. A. Sammel, U. S. Geol. Survey, written commun., Oct. 20, 1967). Comparison of the results from each set of subsamples indicated that duplicate results could be made with an error of less than 1 percent. The analyses were based on the settling velocities of spheres (Stokes' law), and no attempt was made to correct for the platy nature of the fine-grained particles being centrifuged. As a result, the results are in error by an unknown amount, and the actual curves in the clay-size range may be lower than those shown in this paper.

Except for samples 18 and 21, the cumulative curves for the eight samples from the large fans having a lithology of clay fall in the narrow band between the curves of samples 1 and 19 in figure 34. Because of the close spacing and overlapping nature of the curves, only three of the six cumulative curves within the band are shown. The similarity of particle-size distribution of crack fillings in widely separated fans suggests a similar process of crack filling in the Panoche Creek and Los Gatos Creek fans, and implies that the process is highly selective in regard to the particle sizes of the materials allowed to fill the cracks.

The crack fillings may be massive or laminated, contain medial partings or lithologies, or be folded. Most of these features are shown best in fillings that have dried. Drying emphasizes the minor differences in color and lithology of adjacent parts of the fillings. Most of the fillings appear to be massive, even in cracks that are less than 10 feet below the land surface. However, many cracks contain materials of different lithology or color in their medial parts. The crack fillings are oxidized materials.

Laminations are common and characteristically occur as matching pairs on both sides of the crack. The number of laminae range from two to as many as eight in the wider cracks. A laminated crack filling is shown in figure 36*A*.

The central parts of many crack fillings, particularly the ones thicker than half an inch, have been deformed

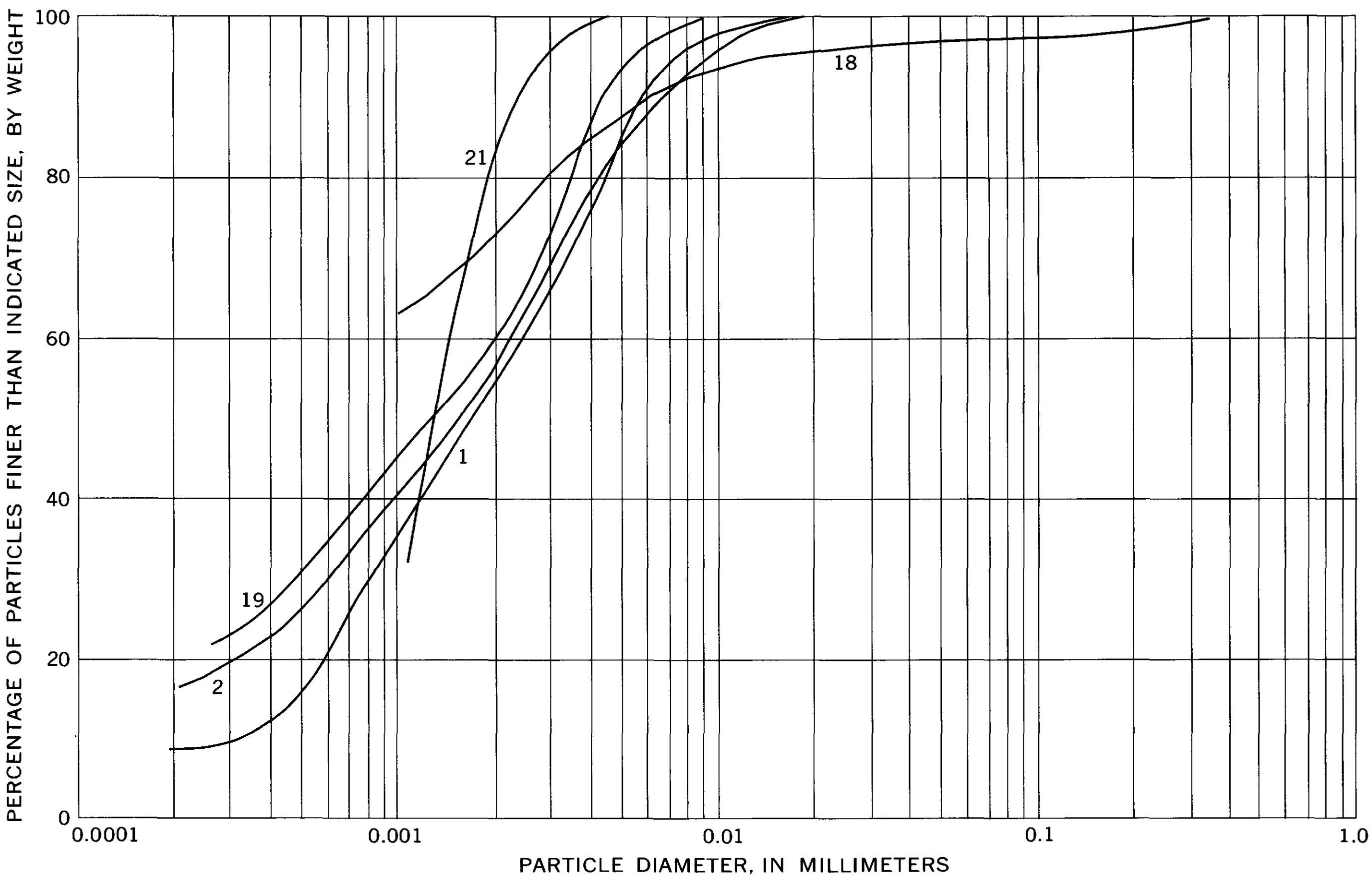


FIGURE 34.—Particle-size distribution of samples from clay-filled cracks in the large fans. Numbers adjacent to curves refer to samples in table 3.

by folding which is seen best in the shrinkage cracks that form after the filling has dried. Compression folds in the center of a faintly laminated crack filling are shown in figure 35. In many crack fillings, only the central part of the crack is folded. In others, the folds occupy almost the entire width of the crack (Bradley and Bateman, 1966, pl. 6, fig. 2). The axes of the folds are parallel to the crack, and thus are oriented vertically in the fans. When a broken surface normal to a fold axis is examined, small arcuate desiccation cracks may be seen. The folds, as seen in figure 35, are the surfaces of discontinuous arcuate cracks extending vertically along the cracks. The particle-size distribution of a sample from the folded crack filling is shown in table 3 (sample 5).

Medial partings, or stringers of sand or silt, are common in the clay-filled cracks, and are seen best in the dry crack fillings exposed in the banks of the stream channels. In figure 36*A*, a conspicuous medial parting has opened as the result of desiccation of a 1-inch crack filled with laminated clay. The smooth surface of the truncated crack is the result of erosion by the previous winter's streamflow along Los Gatos Creek. The cracks that are roughly normal to the medial crack are part of the overall pattern of polygonal desiccation cracks in the crack filling (fig. 18). Most of the material adjacent to the sides of the medial crack did not appear to be different than the rest of the crack filling.

A medial stringer of sand in a massive clay-filled crack is shown in figure 36*B*. The sand was similar to the sand enclosing the ½-inch crack filling. The sand stringer is sufficiently thin and discontinuous that the bond between the clay in both sides of the crack was not broken, and a medial parting was not visible. Sand stringers in the medial parts of clay-filled cracks commonly can be traced for more than 10 feet both vertically and horizontally.

Open, or partly filled, cracks are rare. All the cracks studied in the canal banks were closed completely, and most of the openings in the cracks exposed in the stream-channel banks appeared to be medial partings that can be attributed to desiccation, such as the one shown in figure 36*A*. A crack that is only partly filled is shown in figure 37. The sides of the crack are coated with two matching laminae of clay. The crack width ranges from one-eighth to one-half of an inch, and the opening between the clay coating the sides of the crack is as much as one-third of an inch. At a few points, the crack was completely closed with clay. The

TABLE 3.—*Particle-size distribution of crack fillings and adjacent deposits*

[Location by reference to San Luis Canal station number. Classification from Shepard (1954). *C* is the coarsest percentile, in μ (microns). Size distribution less than 1.0μ determined by centrifuge. Particle-size analyses by Hydrologic Laboratory, U.S. Geological Survey, Denver, Colo.]

Sample	Alluvial fan	Location	Estimated depth below former land surface (ft)	Classification	*C* (μ)	Distribution (percent)					Remarks
						Sand	Silt	Clay <4μ	<1μ	<0.2μ	
Large fans of streams that head in the main Diablo Range											
1	Panoche Creek	9,000 ft southwest of 2060	12	Clay	12	------	22	78	36	9	From Panoche Creek bank.
2	do	1,000 ft southwest of 2060	15	do	14	------	21	79	39	17	Do.
3	do	2121+00B	26	do	20	------	22	78	47	--------	Sample collected by J. O. Berkland.
4	do	2179B	26	Silty clay	28	------	27	73	49	--------	Do.
5	Los Gatos Creek	26,000 ft southwest of 4425	17	Clay	13	------	21	79	41	18	Samples 5–17 from Los Gatos Creek bank.
6	do	28,000 ft southwest of 4425	12	Sand	500	87	4	7	6	--------	Sand-filled crack.
7	do	30,000 ft southwest of 4425	14	do	860	91	4	5	4	--------	Do.
8	do	do	6	do	780	87	8	5	4	--------	Sand bed immediately above top of crack represented by sample 7
9	do	31,000 ft southwest of 4425	8	do	870	92	3	5	4	--------	Sand bed adjacent to sample 15.
10	do	do	4	Silty sand	280	65	22	13	9	--------	Vertical sampling of a single crack filling: depth below crack top 0–0.2 ft.
11	do	do	4	do	260	64	22	14	10	--------	Vertical sampling of a single crack filling: depth below crack top 0.2–0.5 ft.
12	do	do	4	Sand-silt-clay	250	37	37	26	17	--------	Vertical sampling of a single crack filling: depth below crack top 0.5–0.9 ft.
13	do	do	5	Silty clay	110	3	45	52	28	--------	Vertical sampling of a single crack filling: depth below crack top 0.9–1.6 ft.
14	do	do	6	do	95	2	49	49	28	--------	Vertical sampling of a single crack filling: depth below crack top 2.5–3.0 ft.
15	do	do	8	do	58	1	41	58	34	--------	Vertical sampling of a single crack filling: depth below crack top 4.0–5.0 ft.
16	do	do	11	do	45	0	41	59	34	--------	Vertical sampling of a single crack filling: depth below crack top 7.0–8.0 ft.
17	do	do	14	do	60	0	44	56	31	--------	En echelon offset crack, 10.0–11.0 ft below crack top.
18	do	4712+21R	21	Clay	250	3	12	85	63	--------	
19	do	4811+68B	24	do	7	------	13	87	44	22	
20	Los Gatos Creek	4811+68B	24	Silty sand	280	74	16	10	7	--------	Sand adjacent to sample 19.
21	Cantua Creek	11,000 ft northeast of 3480	9	Clay	3.7	1	0	99	28	--------	From trench.
Small fans from the foothill belt of the Diablo Range											
22	Tumey Gulch	2311+26L	22	Silty clay	260	10	20	70	[1] 63	--------	Crack 3–6 in. wide.
23	do	2458+10R	20	Sand-silt-clay	520	31	31	38	[1] 33	--------	Blotchy limonitic stains in crack filling.
24	do	2529+66R	20	do	560	34	22	44	[1] 40	--------	Bottom of exposed crack of sample 25.
25	do	2529+85R	5	Clayey sand	1,000	74	7	19	[1] 14	--------	Top of exposed crack of sample 24.
26	do	2530+70R	21	Sandy clay	320	24	19	57	[1] 50	--------	
27	do	2548+71R	5	Sand-silt-clay	270	23	27	50	[1] 32	--------	Nine feet downslope from where crack leads from buried channel.
28	Arroyo Hondo	2992+00L	24	Silty clay	420	15	18	67	61	--------	Fragments of reeds in crack filling.
29	do	3133+90R	15	Clay	65	1	13	86	78	--------	Interpreted as derived from a Cantua Creek source.

[1] Extrapolated from the 2-micron position on the cumulative curves.

surface of the clay coating the sides of the crack is smooth and undulating. The crack, as exposed in the streambank, pinches out in water-laid sands at both its upper and lower ends.

Although most of the tops of the clay-filled cracks have been truncated, the undisturbed crack tops found have a cross-sectional appearance of a funnel that widens to 2–18 inches in a vertical distance of 1–3 feet. The clay filling bifurcates, and forms the outer edges of the funnel. A funnel top exposed in the bank of Los Gatos Creek is shown in figure 38. A photograph of the crack, which is en echelon, is shown in figure 33. The width of the funnel top is not as wide as most tops, being only 2½ inches at the widest part. The upper 0.2 of a foot is filled with silty sand studded with small fragments of clay, and appears to be material that has slumped into the crack top. The material 0.2–0.5 of a foot below the top consists of silty sand that appears to have been deposited by water. The material 0.5–0.9 of a foot below the top is a water-laid mixture of sand, silt, and clay. The clay on either side of the funnel top contains considerable silt.

The particle-size distribution was determined for eight samples, three of which were taken from different depths in the funnel top, and five were taken from lower parts of the crack to a depth of 11 feet. Sand from the adjacent fan deposits that was adhering to the sides of the crack filling was removed by brushing and scraping. No attempt was made to analyze the different laminations or medial lithologies within the crack because splitting the sample would result in insufficient material for particle-size analyses. The particle-size distribution of four of the samples is shown in figure 39. The set of curves shows an overall

FIGURE 35.—Folds in a clay-filled crack that are parallel to the crack sides. Sample from left bank of Los Gatos Creek; location shown by the letter *H* in figure 52.

decrease in sand and an increase in clay with depth. The change in lithology with depth is not uniform, but instead is abrupt at the bottom of the funnel top, as can be noted by comparison of the distribution of sand, silt, and clay in samples 10 through 17 in table 3. In figure 39, the curves for samples 10 and 12 are from the funnel top, and the curves for samples 14 and 16 are from the crack.

The samples tested from the Los Gatos Creek crack (fig. 33) were not homogeneous, particularly those from the upper 6 feet. The type of material in the sample from a depth of 4.0–5.0 feet below the top is shown in figure 40. The material near the sides of the crack consists of clay with minor amounts of silt, but the medial part of the crack contains sand and silt, and has a lithology that ranges from silty clay to clayey sand. Pieces of the crack filling have been stacked to show the variations in thickness and lithology of the medial part. The sand on the sides of the crack filling is from the adjacent beds of crossbedded water-laid sand that enclose most of the crack. The particle-size distribution of a thick adjacent sand bed is shown in table 3 (sample 9).

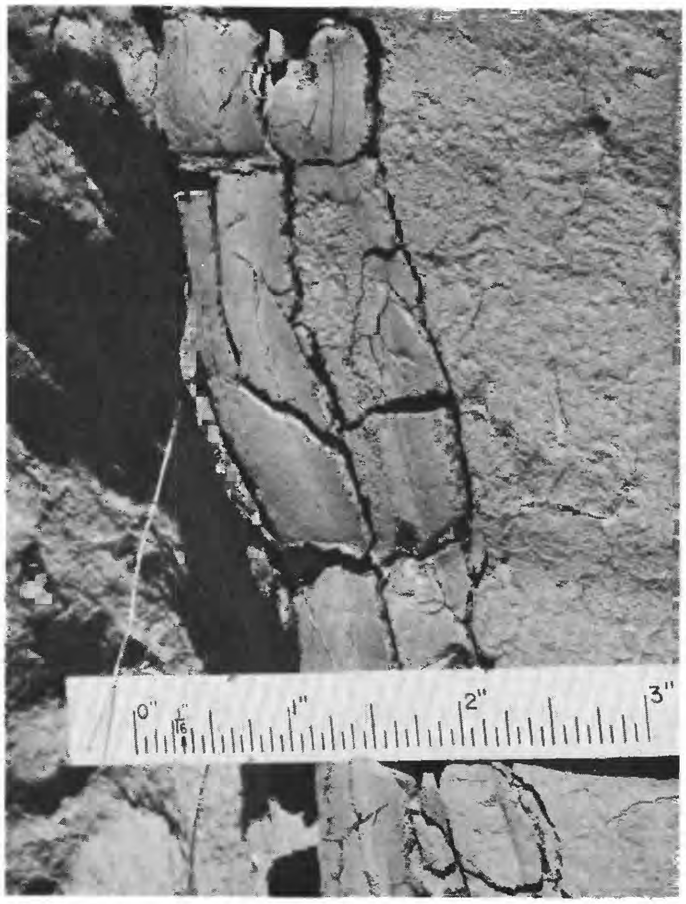
The change in the coarsest percentile and the amount of material less than 1 micron in size is shown in figure 41. The plots consist of two parts—the data from samples collected in the funnel top and the data from samples collected from the underlying crack. The totally different plots suggest dissimilar modes of deposition of material in the funnel top and in the crack. Within the funnel top there is a rapid increase in the amount of clay finer than 1 micron and a moderate decrease in the size of the coarsest percentile. Within the crack there is a slight increase with depth in the amount of clay finer than 1 micron and a decrease in the coarsest percentile from 110 to 45 microns in 7 feet. The sample from a depth of 10.0–11.0 feet (table 3) was in an en echelon offset of the crack, and contained slightly more sand in the medial part of the crack than the material sampled at a depth of 7–8 feet below the crack top.

PROCESSES OF CRACK FILLING

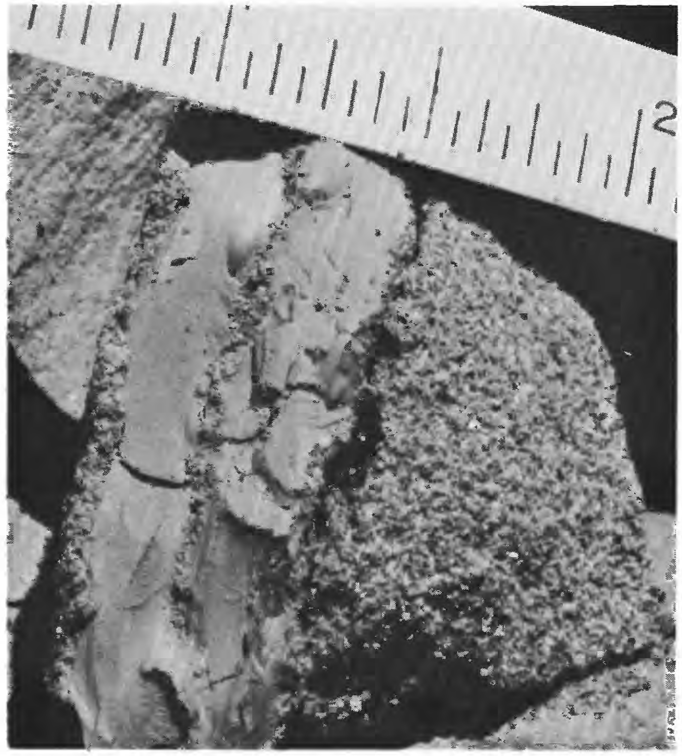
The decrease in particle size with depth, presence of matching laminae on both sides of the cracks, medial partings, and medial parts of material coarser than clay all suggest that the process of filling is one where an open crack is filled from the sides toward the center by material transported into the crack by water.

More than one process probably is responsible for emplacement of the clay in the cracks, but the source of the clay appears to have been from above the point of deposition and the general mode of emplacement appears to have been by water. The main reason for the hypothesis that the cracks were filled from above is the extremely fine grained nature of the crack fillings. The fine clay that fills most of the cracks has no counterpart in any of the bedded deposits in the western San Joaquin Valley. Even the Pleistocene lake clays contain large amounts of silt and the most clay-rich sample from the modern fan deposits that were sampled by Bull (1964a, p. 66) contained 76 percent clay, 21 percent silt, and 3 percent sand. The lack of bedded clays of sufficient fineness means that there is no source of clay that could be injected upward in a manner similar to the emplacement of some clastic dikes. Even if there were a source at depth, the resulting injection fillings would not have matching laminae, or contain centered medial parts consisting of materials such as clayey silt and clayey sand.

The laminated nature of the crack fillings strongly suggests that the clay has been deposited through the action of water moving down the cracks. Two sources of water are possible. Irrigation water may remove clay from the fan deposits and concentrate it in the cracks, but there is little evidence to support this hypothesis. Also, the cracks studied along the banks of the stream channels are in areas that have never been irrigated.



A



B

FIGURE 36.—Medial partings and lithologies in clay-filled cracks in the banks of Los Gatos Creek. Location shown by the letter *H* in figure 52. *A*, Medial parting in 1-inch laminated clay-filled crack. *B*, Sand in medial part of a ½-inch clay-filled crack.

Most of the fan surface has been subjected to repeated flows of abundant water as a result of streamflow over short periods of time at irregular intervals during the deposition of the fan. Thus, stream-transported clay is a likely source of the clay in the cracks. The streams carry dispersed montmorillonite, but the clay commonly tends to flocculate after the water has been allowed to stand for several hours. Meade (1967, p. 74) has shown that the suspended clay in Panoche and Cantua Creeks and the clay in the bed material from the channel of Los Gatos Creek consists of about seven parts in 10 of montmorillonite. Vegetation, sandy alluvium, and the material in the funnel tops of the cracks would filter the sand and silt from flows spreading out on the fan. Different periods of flow would supply slightly different materials that would cause the matched color banding commonly seen in the laminated crack fillings.

Some of the cracks that are not filled with clay have thin films of clay lining their sides (fig. 44*A*.) The clay in the thin coating may be derived from the adjacent beds of clayey sand, or may be brought into the crack by water percolating through the sand adjacent to the crack. Changes in the clay content of the enclosing deposits are not apparent adjacent to the crack, and the velocity of flow may not have been sufficient to transport colloidal clay for more than a few feet laterally in an unsaturated or partly saturated sand bed.

Although the filtering of sediment-bearing water may be a likely hypothesis for the filling of cracks with pure fine-grained clay, it does not explain the nature of the funnel top, nor the presence of sand and silt in the medial parts of the cracks. The presence of silty clay forming the outer edges of funnel tops (fig. 38) indicates that the silty clay was deposited before the sand and silt was deposited in the funnel.

A process that would account for the clay linings so commonly associated with the crack tops would be that part of the lining is deposited by sediment-bearing water that trickles down the sides of open cracks or percolates through the deposits adjacent to the crack. The source of the sediment-bearing water could be streamflow, or local runoff from the fan surface during periods of heavy rain.

Either process of crack deposition requires that the crack be open during the time that it is being filled.

FIGURE 37.—Partly filled crack in the right bank of Los Gatos Creek. Location is shown by the letter *G* in figure 52.

Cracks in clay-rich deposits can remain open for decades. For example, a few of the cracks caused by near-surface subsidence near a ditch constructed by the Panoche Development Co. in the mid-1880's remained partly open until the land was tilled in 1960. The likelihood of cracks remaining open for long periods of time in clean water-laid sands seems considerably less, but many clay-filled cracks are found in water-laid fan deposits containing less than 5 percent clay.

It is hard to dispute the evidence that cracks in clean water-laid sands remain open while they are being filled. The upper parts of some cracks are filled with sand that commonly occurs as a wedge in the middle of a clay filling. Some cracks are filled entirely with clean sand. Pieces of carbonized wood as much as 1 inch long were found in a filled crack cutting the sandy deposits of the Cantua Creek fan (J. O. Berkland, oral commun., May 27, 1967). The deepest piece of carbonized wood was found 18 feet below the former land surface which indicates that the crack above the wood was sufficiently open to permit the fragment to be carried to this depth. Open cracks associated with slump rotation blocks are found in the water-laid sands in the vertical banks of Panoche and Los Gatos Creeks. These open cracks show little evidence of collapse, despite the fact that they are exposed to the elements.

A combination of filtering and trickling may account for all the features noted in the cracks. The following sequence is set forth as a possible mode of emplacement of the sediment in the cracks. A crack is formed and stays open long enough to have its surficial form altered by the action of wind, water, and rodents; some of the material may slough into the crack. The resulting funnel top is lined with clayey silt deposited by water trickling down the side of the funnel. The trickle of sediment-bearing water may not flow below the bottom of the funnel top because of the debris that has slumped into the crack. Then the funnel top is filled either with water-laid sediment, or by additional slump debris, or by both. Intermittent streamflow furnishes suspended clay that is carried down the crack after the silt-size and coarser material has been filtered out by the material above the narrow part of the crack. Repeated periods of flow, filtration, and depo-

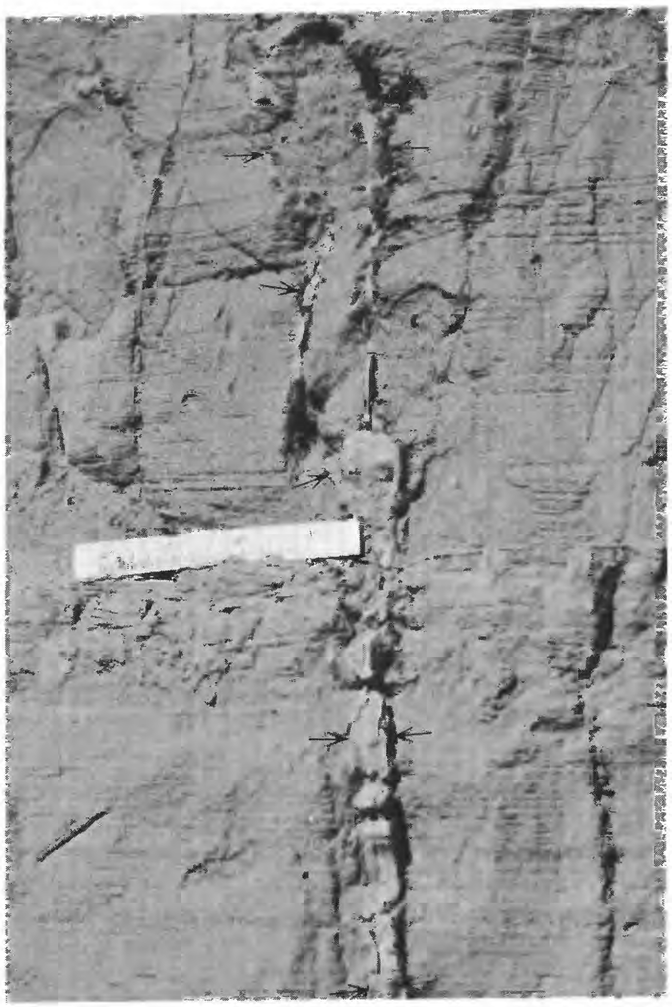


FIGURE 38.—Funnel top of clay-filled crack in the right bank of Los Gatos Creek. White scale is 4 inches long. Paired arrows end at sides of crack and funnel top. Location of crack is shown by the letter *G* in figure 52.

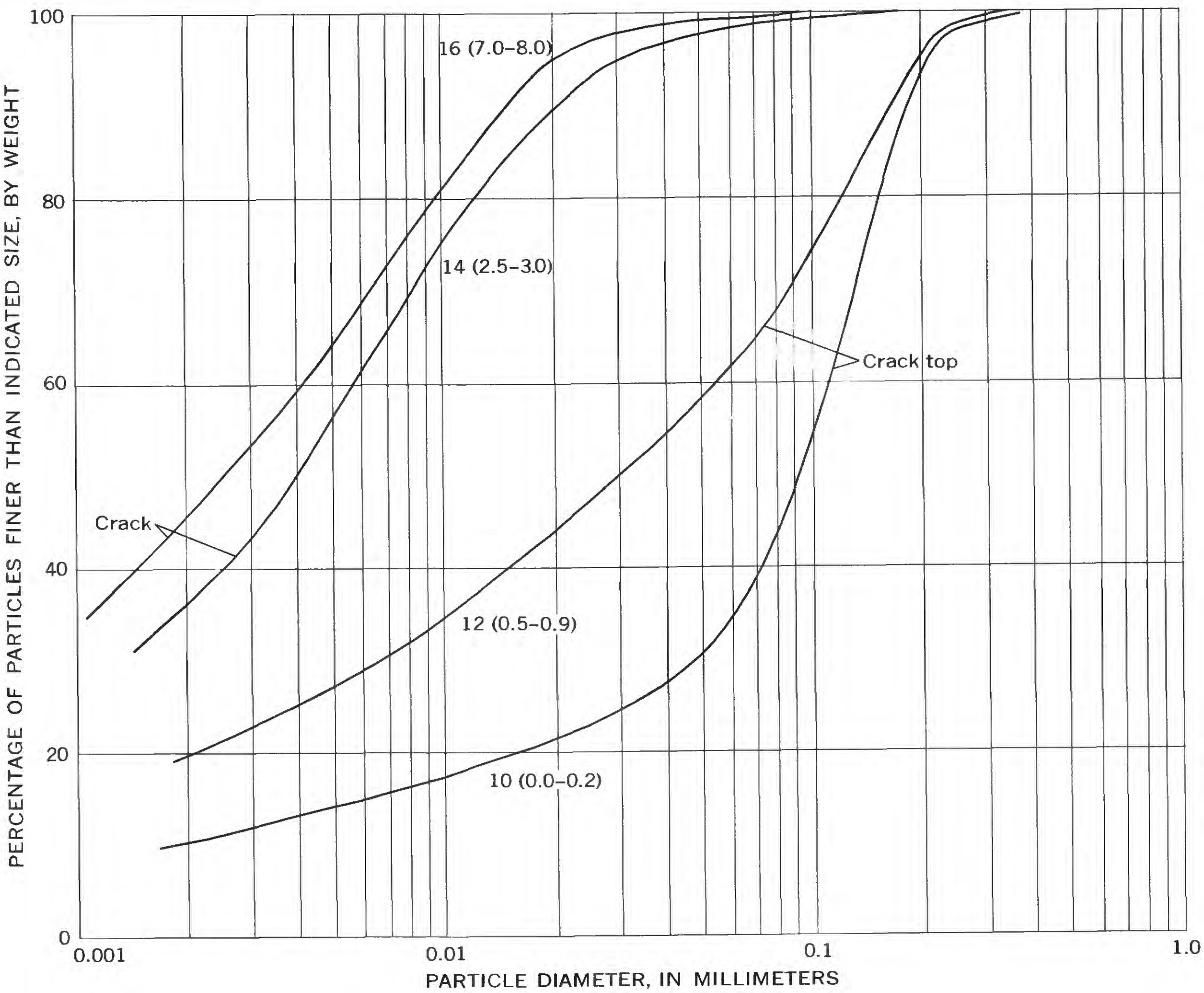


Figure 39.—Cumulative curves showing change in particle-size distribution with depth for a crack exposed in the bank of Los Gatos Creek. Numbers adjacent to curves refer to samples in table 3. Depth below crack top, in feet, is shown in parenthesis.

sition (eluviation and illuviation) result in laminated fillings in the cracks. If, during the process, the filter top is imperfect or is breached at some point along its horizontal extent, discharge of water down the crack may carry sediment of silt and sand size that rapidly fills the medial part of the crack. If the funnel top is not breached, or if the crack top ends several feet below the land surface, sand and silt may never have an opportunity to enter the crack and the entire crack filling will consist of illuviated clay and minor amounts of fine silt. The presence of a minor amount of sand that is similar to the sand in the adjacent beds, such as is shown in figure 36*B*, suggests that percolating water may discharge laterally from a sand bed directly into a partly filled crack and carry locally derived sand into the unfilled medial part.

SAND

Some cracks are filled entirely with sand. Sand-filled cracks are rare in the Panoche Creek fan and uncommon in the Cantua Creek fan, but are fairly common in the Los Gatos Creek fan. In most respects, the sand-filled cracks are similar to the clay-filled cracks; they are discontinuous near-vertical fissures that roughly parallel the radial lines of the fans, offset bedding is rare on opposite sides of the cracks, and the crack fillings do not extend into cut-and-fill structures.

Some differences between the clay- and sand-filled cracks are apparent, however. The width of the sand-filled cracks is not as variable as that of the clay-filled cracks, generally being about 1 inch, but ranging between ¾ and 1½ inches. A few of the sand fillings have good horizontal bedding. The sand-filled cracks in one canal bank were never found in the opposite bank. Funnel tops were never found at the top of sand-filled cracks. Instead, the characteristic top was simply an abrupt ending in an overlying sand bed of similar lithology. Some of the differences between the clay- and the sand-filled cracks may simply re-

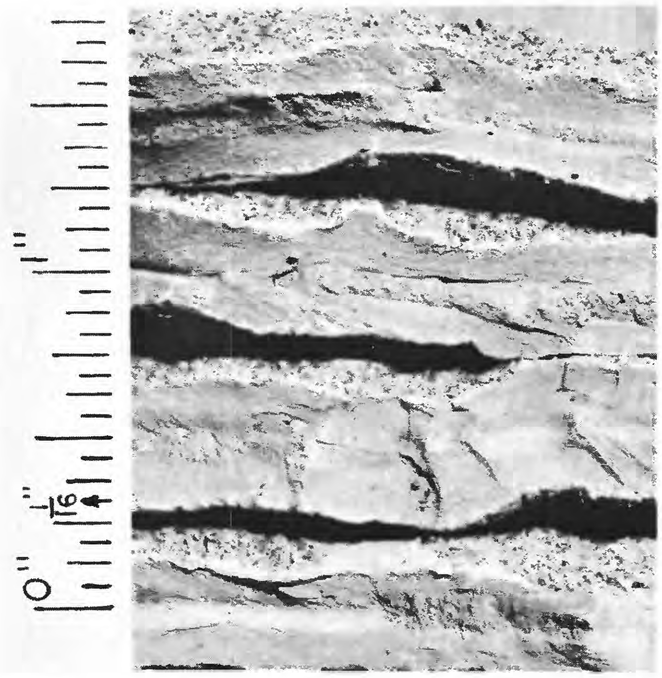


FIGURE 40.—Four pieces of a crack filling that show the variation of lithology in the medial part of the crack filling. The sample (15 in table 3) was collected 4.0–5.0 feet below the crack top. Location shown by the letter *G* in figure 52.

flect the number of cracks of each type studied. Thousands of clay-filled cracks but only about 50 sand-filled cracks were observed.

The particle-size distribution of samples from two sand-filled cracks in the banks of Los Gatos Creek are shown in figure 42 (samples 6 and 7). The sand is well sorted and contains only 10 percent silt and clay. The dashed curves in figure 42 are for samples of overlying or nearby sand beds. The bedded sands in the arroyo banks have virtually the same particle-size distribution as the sand within the cracks. Sample 9 was collected a few hundred feet upstream from the crack from which sample 7 was collected. Sample 8 was collected from the laminated sands adjacent to the crack top shown in figure 43. Sample 7 was collected 8 feet below the crack top.

A photograph and sketch of a crack top of a sand-filled crack are shown in figure 43. The crack width does not increase greatly as it approaches the overlying sand bed. The crack filling is massive, and the sand immediately above the crack is massive also. The laminations in the sand of the overlying bed do not extend into the sand immediately above the crack. These relations suggest that sand was forced out of the crack top into the bed of laminated sand. The top of the crack is about 6 feet below the fan surface, and the crack extends vertically downward 9 feet to concealment by the present-day stream-channel deposits. The overlying sand bed is only a few inches thick as shown in figure 43, but, within a lateral distance of 200 feet, the same sand bed thickens to more than 3 feet.

PROCESS OF CRACK FILLING

The field evidence suggests that the sand-filled cracks are filled more rapidly than the clay-filled cracks. The presence of bedded sand within some cracks and the similarity of the sand filling the crack and that in the bed that is always found overlying the crack top provide good evidence that the sand was carried down the cracks by water. The lack of a funnel top for the sand-filled cracks indicates that the crack was open only briefly before it was filled.

The following sequence is suggested as a mode of emplacement of the sand in the cracks. A crack opens within a short period of time in a streambed or on that part of the fan downslope from the end of a stream channel. If the crack opens during a period of streamflow, sand and water quickly flow down the crack with little erosion of the crack sides. If the streamflow

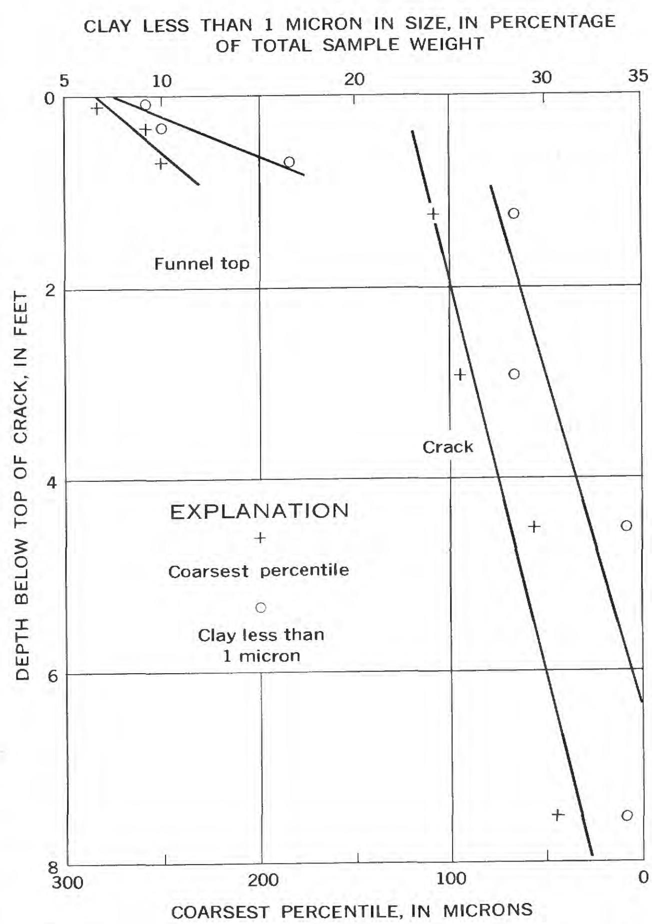


FIGURE 41.—Change with depth in the coarsest percentile and the amount of material less than 1 micron, for a crack exposed in the bank of Los Gatos Creek.

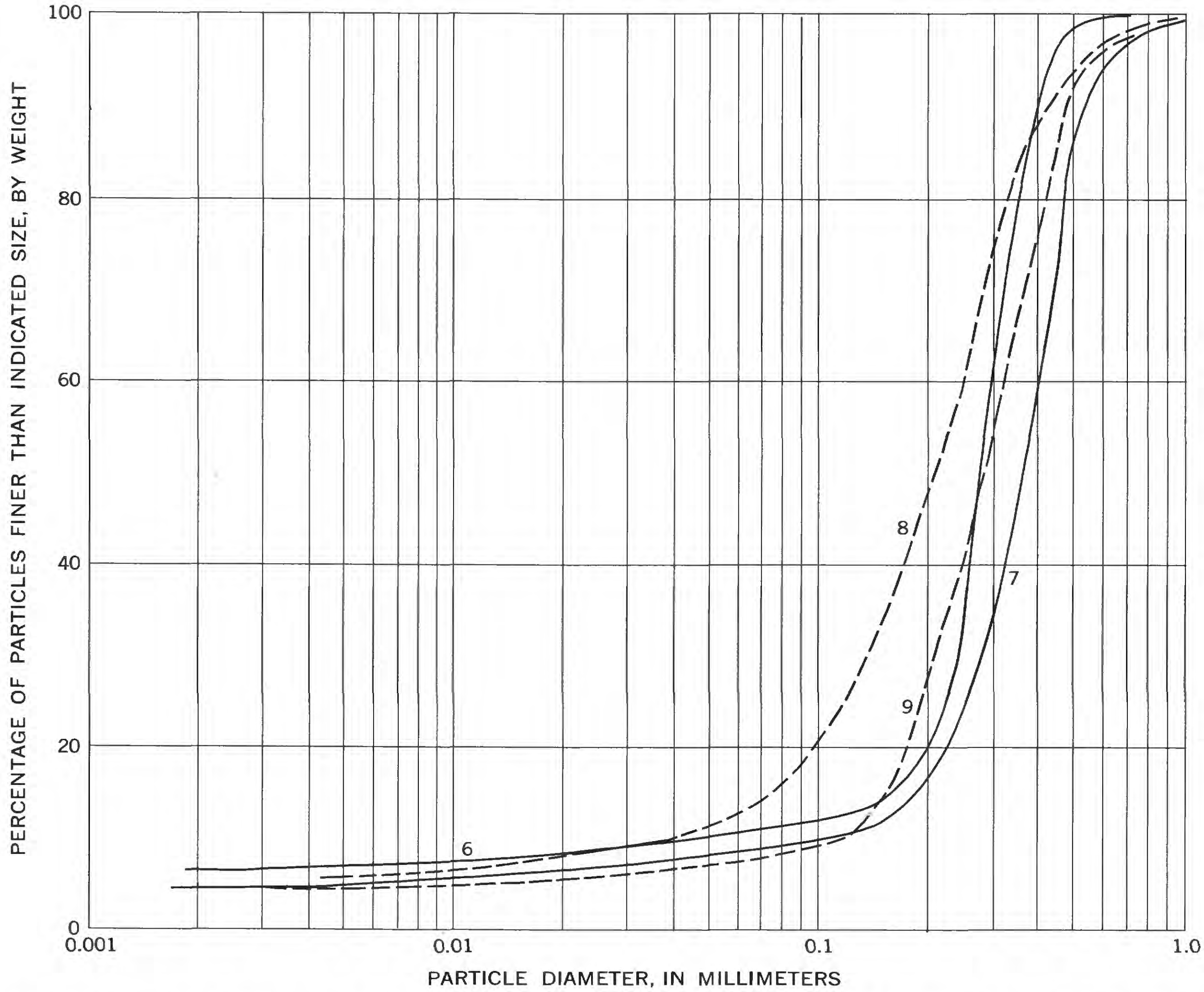


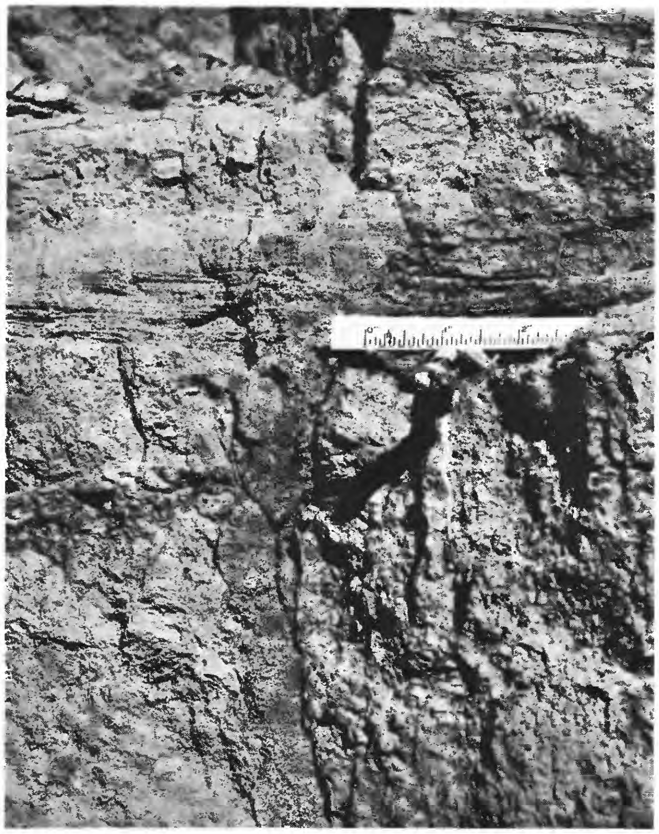
FIGURE 42.—Particle-size distribution of samples from sand-filled cracks in the Los Gatos Creek fan. Dashed curves are for samples from overlying or nearby sand beds. Numbers adjacent to curves refer to samples in table 3.

varies or is interrupted during the filling of the crack, bedding within the crack will reflect these changes in the source of the incoming sediment. Any tendency of the crack to close after it is filled with saturated sand will result in part of the sand being forced out of the top of the crack by upward seepage forces. The disruption of the laminae in the sand bed overlying the crack shown in figure 43*A*, is interpreted to be an example of expulsion of sand from the crack as it was closed by compressive forces. Above the half-inch mark of the scale in figure 43*A*, the laminae appear to have been dragged upward by the ejection of sand from the crack.

MULTILITHOLOGIC CRACK FILLINGS

Some crack fillings appear to be the result of more than one period of opening and filling of the crack, or appear to be modified by erosion of the sides of the crack and deposition of new material adjacent to the preexisting crack filling. Clay-filled cracks that have medial parts filled with sandy or silty material are not included in this category, because their history of opening and filling appear to be simpler than the cracks discussed in this section. A good example of a multilithologic crack filling in the bottom of the canal is shown in figure 44*A*. The following sequence occurs in the crack in front of the scale from the foreground toward the scale: brown clay, gray sand, brown clay, yellow silt, and brown clay. The crack is in massive fine sand. The sequence indicates that two periods of crack opening and filling occurred at this site.

The multilithologic crack in the Cantua Creek fan (fig. 44*B*) is a different type than that shown in figure 44*A*. Two clay-filled cracks intercept below the hand level in the cut made in the canal bank. Clayey sand containing organic particles was deposited adja-



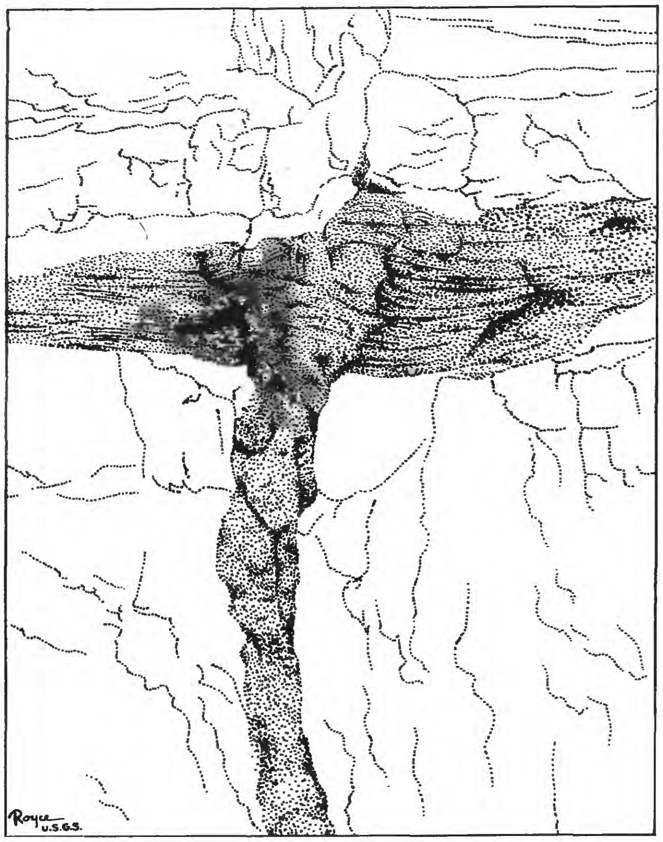


FIGURE 43.—Top of a sand-filled crack exposed in the right bank of Los Gatos Creek. Location is shown by the letter *G* in figure 52. Left, Photograph of top of sand-filled crack. Right, Sketch of top of sand-filled crack drawn by M. E. Royce from photographs.

cent to and after the clay-filled cracks. The secondary filling occurs only near the juncture of the two clay-filled cracks. Crack junctures may be zones of weakness that permit minor erosion of the enclosing deposits by percolating water, and backfilling of the openings by material washed down the zones of weakness.

SUMMARY OF THE DIFFERENCES OF CRACKS IN THE PANOCHE, LOS GATOS, AND CANTUA CREEK FANS

The cracks in the fans of Panoche, Los Gatos, and Cantua Creeks were discussed together because of the similarity of the width, patterns, proximity to land surface, and lithology of the cracks in the three fans. Minor differences between the crack fillings on the three fans are as follows:

1. Cracks are more numerous in the fans of Los Gatos and Cantua Creeks than in the Panoche Creek fan.
2. Minor offset bedding on opposite sides of the cracks is not common in any of the fans, but occurs more often in the Los Gatos Creek fan than in the other two fans.
3. Crack fillings generally are truncated by cut-and-fill structures, but in the Cantua Creek fan, some buried stream channels had crack fillings extending through them.
4. Although most of the cracks are roughly parallel to the radial lines of the fans, the cracks in the Los Gatos Creek fan strike in other directions more than the cracks in the other fans.
5. Intersecting cracks are most common in the Los Gatos Creek fan, and offset of intersecting cracks is most common in the Panoche Creek fan.
6. En echelon crack patterns are most common in the Los Gatos Creek fan.
7. Sand or clayey sand occurring in the medial part of clay-filled cracks are more common in the Cantua and Los Gatos Creek fans than in the Panoche Creek fan.
8. Sand-filled cracks are most common in the Los Gatos Creek fan.

POSSIBLE CAUSES OF THE CRACKS

The fissures examined in this study are tension cracks. Evidence for tensional origin of the cracks includes lack of offset bedding on opposite sides of most cracks, the rough hackly fracture along the sides of the cracks, and the fact that the cracks were open sufficiently long to be filled with laminated clay and bedded sand.

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A

B

FIGURE 44.—Multilithologic crack fillings. *A*, Los Gatos Creek fan, San Luis Canal station 4810 + 23B. Piece of measuring tape is 7 inches long. *B*, Cantua Creek fan, San Luis Canal station 3192L. Hand level for scale.

The following hypotheses were considered as possible causes of the tensional stresses: tectonic movement, desiccation of the fan deposits, stream-channel entrenchment, subsidence resulting from artesian-head decline, and near-surface subsidence. The following discussion concerns primarily the types of settlement that might be responsible for the cracks. It is assumed that the tension cracks paralleled the zones of maximum settlement, and occurred chiefly between the area that settled most and the area that remained stable, or settled to a lesser degree.

TECTONIC

Tectonic stresses have been suggested as a possible cause of the clay-filled tension cracks. Tectonic stresses associated with shear or fault zones may produce cracks in unconsolidated materials. Sharp folding of anticlinal structures may develop tension cracks in rock, but cracks in overlying unconsolidated deposits are rare or unknown.

Features of the clay-filled cracks that are similar to cracks in faulted alluvium include the near-vertical aspect of the cracks, and the presence of intercepting, intersecting, and en echelon fracture patterns. However, the cracks are not ascribed to this cause because of the lack of systematic patterns related to structural features.

Folding of the alluvium has occurred in the study area in the geologic past, as is indicated by the gently folded lake clays interbedded with the deeper fan deposits (Miller and others, 1971). One of the larger anticlinal folds in the Pleistocene Corcoran Clay Member of the Tulare Formation occurs about 600 feet under the surface of the Cantua Creek fan. The anticline has about 75 feet of closure in a distance of 2–3 miles normal to the fold axis. Folding of the alluvium near the surface would be equally or more gentle. It is difficult to explain the extensive cracking of unconsolidated sediments as being caused by such broad tectonic movements. Local variation in the density of spacing of the cracks and intersecting sets of cracks are even more difficult to ascribe to gentle folding. Also, abundant cracks occur where folding of the Corcoran is not apparent.

DESICCATION

Many small desiccation cracks were observed in the clay-rich beds exposed in the canal and streambanks (fig. 7*B*). The cracks generally were less than a foot long, were filled with sandy material, and rarely extended into the beds above and below the bed in which the principal cracking occurred. Desiccation cracks were not observed in the clean water-laid sands that are common in the fans. Desiccation cracks characteristically have intercepting and intersecting crack patterns, but aside from this there is no evidence to attribute the clay-filled cracks to this cause.

STREAM-CHANNEL ENTRENCHMENT

The banks of the streams within the study area are susceptible to extensive deep cracking that is associated with rotation of large blocks of alluvium into the stream channels. Both tension and shear cracks are common within 50 feet of the sides of the present-day stream channels entrenched as much as 40 feet into the alluvial fans. The cracks are destroyed by slumpage of the blocks into the stream channel. The present trenching is primarily the result of changes in the daily and seasonal amounts of rainfall since 1850, and repeated trenching and backfilling of the fans has occurred in the geologic past. The present trenching of the streams appears to be as deep as the former entrenched stream channels exposed in the canal and streambanks.

The occurrence of anastomosing, intercepting, and en echelon cracks that form during the process of slumping of alluvium into the present-day channels is the best evidence to support this mode of cracking as the cause of the clay-filled cracks. The principal evidence against the channel-entrenchment hypothesis is that the clay-filled cracks are not more abundant near the banks of the buried stream channels exposed in the canal banks than elsewhere, and that clay-filled cracks were numerous in reaches of the canal ½–1 mile from the nearest buried stream channel.

SUBSIDENCE DUE TO ARTESIAN-HEAD DECLINE

More than 20 feet of subsidence due to artesian-head decline has occurred since 1920 along parts of the canal alinement, and subsidence has exceeded 8 feet in much of the study area. The land subsidence that has occurred between 1920 and 1966 is shown in figure 45. Parts of the area were continuing to subside at a rate of more than 1 foot per year during canal construction.

The presence of extensive fissuring and cracking in other areas of intensive subsidence due to artesian-head decline suggests the possibility of similar cracks occurring in the study area. Prokopovich and Bateman (1967) discuss subsidence resulting from artesian-head decline as the cause of the tensional forces responsible for the clay-filled cracks.

A careful search was made in two areas by the author for cracks that could be attributed to subsidence due to artesian-head decline. The two areas are shown by the letters *A* and *B* in figure 45. Location A is along the road southwest of the town of Five Points, and location B is northeast of Monocline Ridge. These areas were selected as being the most likely locations to find cracks associated with subsidence due to artesian-head decline because of the large difference in the total amounts of subsidence that have occurred within short distances.

At location *A*, the difference in the 1920–66 subsidence along a 1-mile stretch of road was 8 feet, and the difference in the amounts of subsidence in the 1955–66 period for two bench marks spaced 1 mile apart was 5 feet. New asphalt paving has been placed on top of pavement that had been used for many years, but the older pavement was exposed near the side of the road. The search for possible subsidence cracks was concentrated in the old pavement and in the shoulder adjacent to the pavement. Every foot of a 1½-mile stretch of road was examined. Where cracks were found in the old pavement, fresh exposures of the adjacent shoulder were made to see if the cracks extended into the shoulder.

The search at location A revealed nothing that could be attributed to subsidence resulting from artesian-head decline. Cracks in the old pavement did not continue into the shoulder of the road and were assumed to be contraction and expansion cracks. Exposures of the shoulder revealed an orthogonal network of desiccation cracks that were parallel and normal to the edge of the pavement, but none of these cracks continued into the older pavement.

The other location at which a search was made for cracks resulting from subsidence due to artesian-head decline (location *B* in fig. 45), was on the surface of a fan that had never been tilled or irrigated. The search area is south of a near-surface subsidence area. An area 1 mile long was searched and no cracks of any type were observed.

After searching these two areas, it was concluded that long narrow fissures such as those that occur in the areas of large ground-water withdrawal in Arizona and Nevada (fig. 9) are not occurring in the study area despite the large amounts of subsidence in recent years. It also seems unlikely that small cracks have occurred in the alluvium as a result of subsidence due to artesian-head decline. The complete absence of open cracks in the trimmed banks of the San Luis Canal indicates that artesian-head decline is not causing the deposits to crack now, even in areas where the head decline has caused rapid subsidence since canal excavation.

The maximum rates of subsidence due to artesian-head decline occurred before excavation of the canal, when the land surface was sinking as rapidly as 1.8 feet per year. Subsidence rates in most of the area increased from about 1920 to about 1955 and have decreased moderately since then.

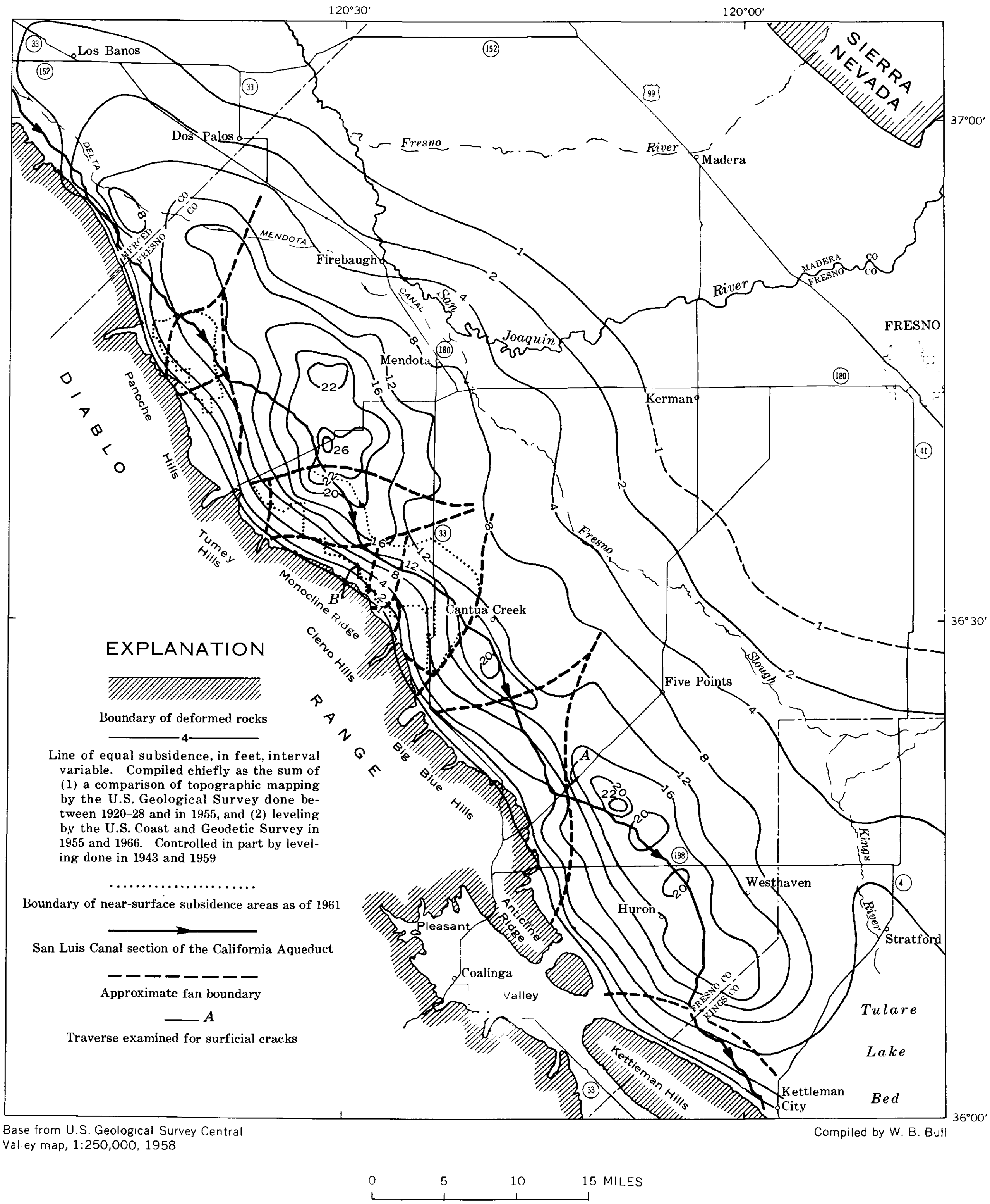


FIGURE 45.—Land subsidence, 1920 to 1966, Los Banos-Kettleman City area.

If tension cracks did result from subsidence at earlier times, one would expect them to parallel the lines of equal subsidence. As was described earlier, the cracks are roughly normal to the canal alinement. Figure 45 shows only three areas where the lines of equal subsidence are normal to the canal alinement—the north side of the Panoche Creek fan and the north and south boundaries of the Los Gatos Creek fan.

The patterns and density of spacing of the cracks are difficult to explain by the artesian-head decline hypothesis. Aquifer-system compaction to depths of as much as 3,000 feet hardly seems possible as the cause of abrupt changes in the density of spacing of the clay-filled cracks within 100-foot distances (pl. 2*A*). Also, intersecting crack patterns indicate the presence of more than one local center of settlement producing the tensional forces to crack the alluvium.

The abundance of the cracks changes abruptly at the fan boundaries (pl. 2*A*), but the lines of equal subsidence shown in figure 45 show little relation to the fan boundaries. The main reason for the lack of a relationship between the fan boundaries and the lines of equal subsidence is because three-fourths of the compaction due to artesian-head decline is occurring below the Corcoran Clay Member of the Tulare Formation (the principal confining clay). The Corcoran occurs as much as 900 feet below the land surface in parts of the area. The change in abundance of cracks in adjacent fans would more logically be ascribed to changes in the compaction characteristics of the deposits enclosing the cracks rather than compaction of materials below depths of 400–900 feet.

In conclusion, the artesian-head decline hypothesis appears untenable as the cause of the clay-filled cracks on the basis of the evidence presently available. Deep tension cracks are not opening in, or adjacent to, the areas of greatest differential subsidence resulting from artesian-head decline, either in the canal banks or in other parts of the area. The abrupt change in density of crack spacing at fan boundaries, highly variable density of spacing of cracks, and the presence of intersecting cracks all are features that are incompatible with regional stresses such as those produced by artesian-head decline. The lines of equal subsidence do not parallel the general trend of the cracks in much of the area, and show no apparent relation to the fan boundaries that separate cracks of greatly different spacing density and width.

The lack of cracks due to artesian-head decline probably is because differential compaction within short distances is not as pronounced as in the intermontane basins of Arizona and Nevada. Although the lithology and mode of deposition of individual beds may vary greatly, the gross lithology of a given 200-foot thickness of fan deposits within the study area is remarkedly uniform. Differences in compressibility between the saturated deposits of adjacent fans exist, but they are not large enough to cause greatly differing amounts of compaction due to artesian-head decline. The deposits beneath the fan deposits consist of interbedded deposits of Coast Range and Sierra Nevada origin. Lateral contrasts in compressibility are not great between these deposits, and the intertonguing nature of the deposits reduces any contrast that may be present.

Another important factor responsible for the lack of sharp differential compaction within short distances in the study area is the lack of abrupt changes in the configuration of the underlying consolidated sediments, such as would be caused by buried boundary faults between consolidated rocks and unconsolidated alluvium. Such boundaries may be an important factor contributing to the cracking that is associated with areas of intense subsidence due to water-level decline in Arizona and Nevada.

NEAR-SURFACE SUBSIDENCE

Compaction due to wetting is the only hypothesis that explains the cause of the filled cracks and fits the facts available from western Fresno County at the present time.

In an earlier paper of this series (Bull, 1964a), compaction due to wetting by irrigation water was described in detail for the near-surface subsidence areas shown in figure 45, but the Panoche Creek fan was not considered as an area currently affected by widespread near-surface subsidence. Although a few reports of local residents to the California Department of Water Resources indicated that some very small areas of settlement had occurred after irrigation, it was generally considered that the fan would not be susceptible to widespread near-surface subsidence. The irrigated fields did not show the pronounced hummocky relief and subsidence hollows (fig. 2) that were typical of the areas of known near-surface subsidence. Just as strong was the evidence from core holes that showed that the deposits, even in areas that had not been irrigated, were roughly at field capacity instead of being moisture deficient. The possibility of damage to the canal from near-surface subsidence was considered to be low, and the canal alinement on the Panoche, Los Gatos, and the Cantua Creek fans was not ponded before construction of the canal. The Los Gatos Creek fan was not included in the study reported by Bull in 1964.

In earlier studies of compaction due to wetting (Inter-Agency Committee, 1958; Lofgren, 1960; Bull, 1964a), the amounts of compaction and subsidence were studied in detail, but the cracks associated with near-surface subsidence were studied only as exposed on the land surface, or in shallow excavations. Most test plots were not in areas subject to streamflow, and the cracks in irrigated areas were not excavated to determine whether or not the cracks contained fillings and what the nature of the fillings, if present, might be.

Many aspects of the cracks exposed in the canal and streambanks are the same as those of known near-surface subsidence cracks caused by man. In the following paragraphs, cracks due to modern near-surface subsidence are compared with the clay-filled cracks described earlier in this paper, in order to show that they are the same type of crack. Both the cracks in the canal and in areas of known near-surface subsidence are mainly vertical. The evidence supporting the vertical nature of the known near-surface subsidence cracks is not as good as that for the cracks exposed in the canal and streambanks, but open cracks to depths of 10 feet commonly were observed, and occasionally the vertical nature of the fissures could be determined to depths of as much as 25 feet.

The sides of the cracks exposed in the canal and stream channels, like near-surface subsidence cracks, are undulating and exhibit a hackly type of fracture.

The width characteristics of the cracks are the same also. The cracks in the canal and streambanks are parallel, narrow upward, or narrow downward, as do near-surface subsidence cracks between blocks in the various stages of rotation described on pages 14, 15. Evidence for differential block rotation was indicated in a few places in the canal banks by differing thicknesses of beds on opposite sides of the cracks, as exposed on the $26\frac{1}{2}°$ slope.

Offset bedding on opposite sides of the cracks in the canal and streambanks was not common—the typical crack did not have visible offset bedding. At first consideration, this fact seems to clash with the presence of large amounts of offset bedding associated with near-surface subsidence cracks around some irrigation test plots. The test plots were established in areas that had never been irrigated and where the thickness of moisture-deficient deposits was 100–300 feet.

The pattern of cracking and the amount of vertical displacement on opposite sides of the cracks adjacent to the test plots were determined to a large extent by the shape of the bulb of wetted deposits that was formed by the downward and lateral movement of water from the ponded area. The thickness of the bulb of wetted deposits decreases away from the wetted area, and is the main reason for the differential subsidence that occurs with increasing distance away from the ponded area. Thus, most test plots characteristically have decreasing amounts of subsidence away from the ponded area, have offset bedding on opposite sides of the cracks, and have block surfaces that slope toward the ponded area.

The part of the seepage bulb that is associated with the least differential settlement is adjacent to the ponded area (fig. 12). Little or no offset bedding is observed in this zone after the wetted front has moved more than 50–100 feet from the edge of the ponded area, even in test plots that have subsided many feet (fig. 11).

The cracks adjacent to test plots in areas of less intense subsidence have little offset of the land surface on the opposite sides of the cracks, or vertical offset may be lacking. For example, at Inter-Agency Committee test plot D on the Moreno Gulch fan, the maximum vertical displacement on opposite sides of a crack after 42 days of ponding, and 1.7 feet of subsidence, was only three-eighths of an inch for a crack 30 feet from the ponded area. Cracking had extended more than 50 feet from the plot and the maximum crack width was 1.2 feet. Eleven months after water was introduced into the plot, maximum offset was only 5 inches for a crack about 40 feet from the ponded area. Cracks adjacent to the ponded area at test plot D are shown in figure 46. The photograph of the cracks in figure 46*A* shows narrow parallel cracks with no visible offset within a few feet of the test plot, and was taken only 5 days after water was introduced into the test plot. The photograph in figure 46*B* shows a large arcuate crack 60 feet from the southwest corner of the test plot about 6 months after the plot was flooded. The stakes mark the position of earlier cracks that have partly closed and have been partly concealed. Vertical offset is minor or lacking on all the cracks.

Although excellent conditions for causing large amounts of offset prevail around some test plots, the offset probably is temporary. If the wetting around a test plot were completed from the land surface to the water table offset bedding would not be present. The only way for offset bedding to occur would be for marked differences in the compressibility of the deposits to occur within short horizontal distances.

Little is known about offset bedding associated with near-surface subsidence cracks in areas where conditions differ from those around test plots. The effects of multiple seepage bulbs and of complete wetting of the moisture-deficient deposits from the land surface to the

A

B

FIGURE 46.—Near-surface subsidence cracks around Inter-Agency Committee test plot D. *A*, Five days after flooding of the plot began. Photograph by Wallace Fuqua of the California Department of Water Resources. *B*, Six months after flooding of the plot began. Photograph by B. D. Glaha of the U.S. Bureau of Reclamation.

water table have not been studied in detail. The width, patterns, and amounts of vertical offset between adjacent blocks that result from compaction due to wetting are not known for moisture-deficient deposits whose thickness are less than at test plots. It is assumed that thin moisture-deficient deposits (thicknesses of 50 ft or less) will cause compaction-due-to-wetting features similar to those associated with the test-plot areas.

Information about near-surface subsidence also is available from irrigated fields. Within a given square mile—a common size for the fields in the study area—local areas settle at a more rapid rate and appear as subsidence hollows. The hollows may represent areas of more permeable surficial material than adjacent areas that permit more rapid infiltration of water to depths where the overburden load is sufficient to cause appreciable compaction due to wetting. Once formed, the hollows persist for years. While the water continues to gather and to percolate downward, the area subsides; also the material used in attempts to fill the hollow compacts slightly when irrigation is resumed. Thus, the hollows tend to remain potential low areas in which more water can collect and percolate down per unit area than in adjacent parts of the field.

The characteristic subsidence cracks observed in and adjacent to fields are less than 2–3 inches wide and show little or no vertical offset. In these respects, the cracks in fields are similar to those around test plots that are associated with blocks that have largely completed their rotation. Subsidence cracks are not readily observed around subsidence hollows because of the frequency of cultivation; cracks bordering irrigated fields are covered quickly by disking because of the farmer's fear that water will enter them and cause more extensive cracking.

In summary, one general conclusion of this paper is that vertical offset of the land surface or bedding is not characteristic of near-surface subsidence where complete wetting from the land surface to the water table has occurred. The presence of offset indicates that wetting is incomplete, because different thicknesses of deposits susceptible to compaction due to wetting have been wetted. If the primary subsidence cracks were the result of shear, offset would be common. However, the primary cracks are the result of tensional stresses tending to cause open cracks and of collapse as a result of removal of vertical support by compaction of the underlying deposits. When compaction is complete, vertical offset should be rare.

Tension and then compression occur during the formation of near-surface subsidence cracks, as cracks form between blocks of deposits and then are largely closed as a block rotates downward toward the area that is undergoing maximum compaction due to wetting. The crack fillings in the canal and streambanks also reveal a history of tension that is followed by compression. The fact that the cracks were open long enough to fill with laminated clay and were wide enough to be filled with bedded water-laid sand suggests that tension continued after the cracks first appeared as incipient fractures in the deposits.

Compression of the cracks is shown by the nature of the fillings. The small folds observed in the center of clay-filled cracks (fig. 35) show that compression occurs after cracks have been filled. In most places, the folding is restricted to the central part of the crack filling, which appears to be the youngest (and probably the softest at the time of folding) part of the crack filling. The sand-filled cracks show the effects of compression in a different manner. Saturated sand is deposited in the crack soon after it opens, and later compression is demonstrated in a few places by the upward extrusion of sand (fig. 43).

Both the abundance of and the abrupt changes in the abundance of cracks in the canal and streambanks are readily explained by the near-surface subsidence hypothesis. The change in the abundance of cracks where the canal crosses fan boundaries simply indicates changes in the compaction characteristics of the deposits, differences in the history of wetting of the adjacent fans.

The change in the density of cracks within a single fan is illustrated by short reaches of abundant cracks with intervening reaches of no cracks, or widely spaced cracks. Changes in the occurrence and spacing of sets of parallel cracks are shown on plate 2*A*. In accord with the near-surface subsidence hypothesis, areas of few cracks indicate uniform wetting and compaction, and areas of abundant cracks indicate temporary nonuniform wetting and temporary differential settlement.

The patterns of cracks in the canal and streambanks are the same as the patterns of known near-surface subsidence cracks. The crack patterns discussed below may occur as the result of several causes of tensional rupture. However, the dimensions and frequency of occurrence of the patterns of the clay-filled cracks and near-surface subsidence cracks are markedly similar. The similarity of patterns is readily apparent in figure 47, despite the fact that patterns in figures 47*B*, *D*, and *H* are on 2-to-1 slopes. The Mendota test site is on the Arroyo Ciervo fan, and as much as 14 feet of subsidence has been measured in some of the test plots. The thickness of deposits susceptible to compaction due to wetting exceeds 300 feet. The typical near-surface subsidence cracks that have formed during the operation of the site afford an excellent opportunity for comparison of crack patterns.

The anastomosing cracks in figure 47*A* resulted from the partial disintegration of a block of fan deposits between two primary cracks. The clay-filled cracks in figure 47*B* have a similar anastomosing appearance. In figure 47*C*, crack width is a function of both variation in the amount of separation in a primary crack and secondary slumpage in the throat of a crack bifurcation. Figure 47*D* shows a crack in the Panoche Creek fan that is almost identical to the one in the Arroyo Ciervo fan in figure 47*C*, even to the bifurcation of the primary crack that occurs at one end of the secondary slump. The en echelon cracks at the Mendota test site shown in figure 47*E* cause the fracture zone to be offset about 3 feet in 10 along the strike of the cracks. The en echelon clay-filled cracks in the Los Gatos Creek fan shown in figure 47*F* cause an offset of the fracture zone of about 1 foot in 6. Cracks that intercept and end abruptly at another crack are common both in areas of known near-surface subsidence and in the canal and streambanks. Intersecting crack patterns in areas of near-surface subsidence have been observed only where cracking from two adjacent ditches or test plots overlap. An intercepting crack that ends abruptly at a primary crack is shown in figure 47*G*. Intercepting and intersecting cracks in the canal are shown in figure 47*H*. The horizontal scrape marks on the canal bank were made by the trimmer. Near-surface subsidence is the only hypothesis that readily explains the presence of intersecting patterns of clay-filled cracks that cut through tens of feet of fan deposits. All that is needed to produce intersecting cracks is the existence of two or more nearby centers of differential subsidence.

After careful examination of many possible hypotheses and serious consideration of the more likely ones, the conclusion is that the abundant clay-filled cracks in the fans of Panoche, Los Gatos, and Cantua Creeks are the result of near-surface subsidence. The vertical nature of the cracks, the tendency of the cracks to narrow downward, narrow upward, or have parallel sides, the rough hackly break along the sides, the lack of offset bedding, the compressional movements that occur after the tensional movements, the change in the abundance of cracks on adjacent fans, the abrupt variation in abundance of cracks, and the presence of parallel sets and anastomosing, en echelon, intercepting, and intersecting crack patterns are all characteristic of the near-surface subsidence process. In short, there are no features of the clay- and sand-filled cracks that cannot be explained by the near-surface subsidence hypothesis.

POSSIBLE CAUSES OF WETTING

The possible sources of water to wet the moisture-deficient deposits and cause the near-surface subsidence are water-table rise, irrigation of crops, and streamflow that percolates below the root zone. The water table has risen as much as 100 feet between 1952 and 1965 in parts of the study area, as a result of pumping of deep confined water for irrigation. In areas where ground water in the upper 100–400 feet of the deposits is not affected by pumping, the water that percolates below the root zone raises the water table.

It is unlikely that water-table rise has caused the cracking that is so common in western Fresno County. The main objections to a rising water-table hypothesis are: (1) water-table rise would cause uniform wetting and would provide little opportunity for differential settlement and cracking of the fan deposits, (2) the cracks occur in areas where the water table has been lowered as much as 400 feet as well as in areas of water-table rise, (3) compaction recorders show that the 4–26 feet of land subsidence is due almost entirely to compaction of deposits below the water table in most of the area, and (4) if the deposits were susceptible to compaction due to wetting from below, they certainly should have been compacted from above as a result of irrigation, and the resultant hummocky topography would be readily apparent.

Irrigation of crops has been the main cause of compaction due to wetting in the areas of known near-surface subsidence. The effects of percolating irrigation water have been described in detail by Bull (1964a). The application of irrigation water should readily cause compaction due to wetting of clay-rich moisture-deficient deposits on the large fans outside of the areas of known widespread historic near-surface subsidence.

Streamflow within the study area occurs only locally on the fans of Panoche, Los Gatos, and Cantua Creeks, and the frequency of flow is low, with intervals of 2–4 years of no flow being common. The mean total annual runoff of these three streams for the 1889–1929 period has been estimated as about 48,000 acre-feet (California Division of Water Resources, 1930, p. 67). The amount of water derived from streamflow that percolates below the root zone is not known, but Davis and Poland (1957, p. 443) estimated that roughly 60–80 percent, or 30,000–40,000 acre-feet a year, is contributed on the average to the ground-water body. Although water from streamflow as a source of water to cause compaction due to wetting is small in amount and local in its distribution it should be considered as a possible source of water to cause the compaction and the cracking of the fan deposits. Thus, water from both irrigation and streamflow should be considered as possible causes of the wetting.

These sources have historic and prehistoric implications. Extensive irrigation of the fans did not occur until this century and subsidence caused by irrigation waters is considered as historic subsidence. Subsidence resulting from streamflow would be largely prehistoric. The streams have about the same positions on the fans as they did when the first surveys were made in the 1850's. Wetting of the fan deposits when the streams were on other parts of the fans is classed as occurring before the documented history of man in this area.

TIMES OF CRACK FORMATION AND FILLING

If the cracks in the large fans of streams that head in the main Diablo Range were formed as a result of near-surface subsidence, was the subsidence the result of man's activities or of wetting by streams in prehistoric times, or both? For two of the three fans studied, it was the result of both. The presence of small areas of present-day near-surface subsidence show that at least part of the settlement has been caused by irrigation, but strong evidence exists to show that the majority of the settlement resulted from prehistoric stream flows.

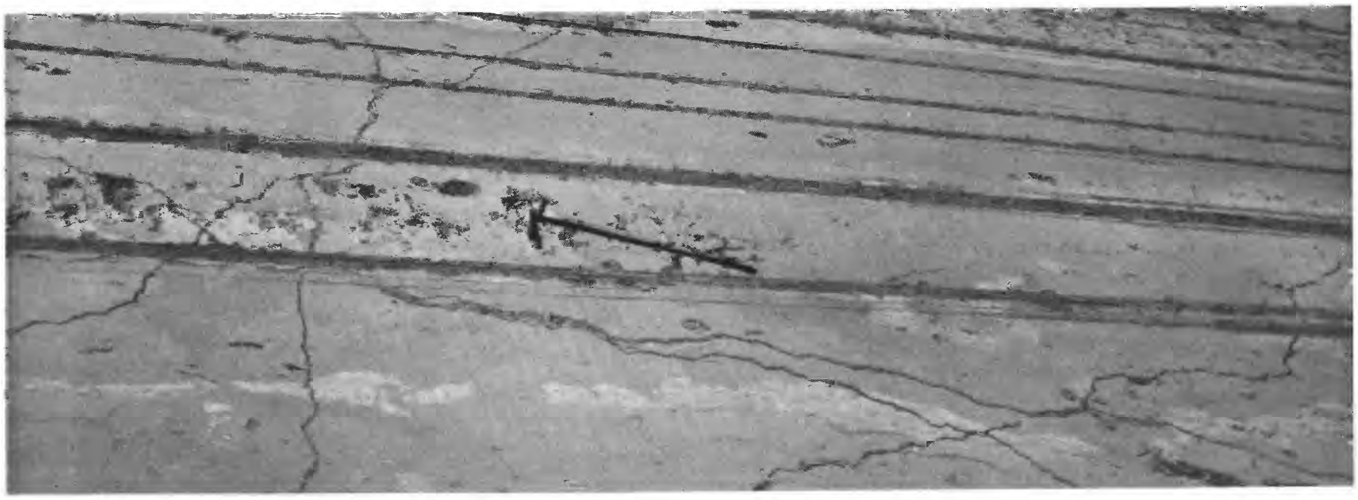
Historic near-surface subsidence is considered as that caused by irrigation waters, and prehistoric near-surface subsidence is considered as the subsidence that occurred as a result of streamflow before 1850. Historic near-surface subsidence has occurred on the Panoche and Los Gatos Creek fans and prehistoric near-surface subsidence has occurred on all three large fans.

Several lines of evidence show that the cracks formed at different times in the history of the fans. Sets of clay-filled cracks at the same locality are truncated at different depths below the fan surface. For example, a trench in the Cantua Creek fan about 2 miles northeast of San Luis Canal station 3480 contains exposures of two intersecting sets of clay-filled cracks. The dominant set of cracks trends about N. 40° E. and is truncated about 7 feet below land surface. The other set of cracks trends about N. 60° W. and is truncated about 3 feet below land surface. The cracks in the trench suggest a sequence of crack opening, filling, and truncation; a period of fan deposition; and a second period of crack opening, filling, and truncation for this part of the Cantua Creek fan. Similar examples can be cited for the Panoche and Los Gatos Creek fans.

Other evidence for different times of crack formation include cracks that extend through preexisting cracks. An example would be cracks that are filled with laminated clay or clean sand and that have cracks passing through them that are filled with massive clay. Crack intersections of differing lithologies show that sufficient time passed between the formation of the first and second sets of cracks for the first set of cracks to be filled before later crack-producing stresses with a different orientation became effective. Different depths of burial of cracks in widely separated parts of a fan also suggest different times of crack formation.

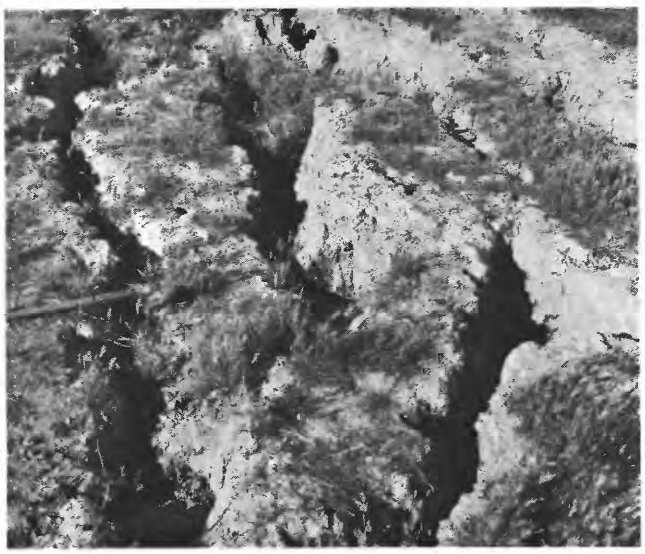
HISTORIC

Although the earlier reports by farmers about small local areas of near-surface subsidence on the Panoche Creek fan were hard to verify and did not agree with the bulk of the information about the fan, it now seems likely that they were correct.

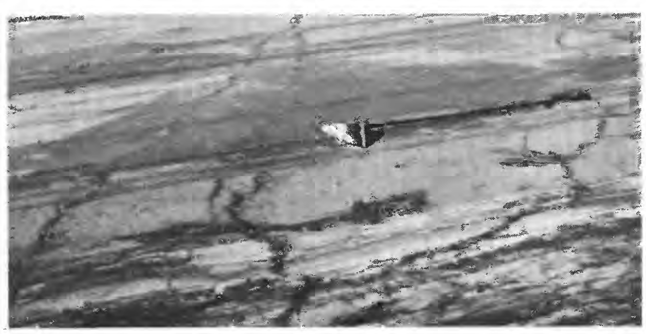


A

FIGURE 47.—Comparison of patterns of clay-filled cracks in the San Luis Canal with patterns of known near-surface subsidence cracks. *A*, Intercepting and intersecting cracks in the Los Gatos Creek fan, San Luis Canal station 4797R.



B, Anastomosing cracks, Mendota test site.



C, Anastomosing cracks, Panoche Creek fan, San Luis Canal station 1923 + 40L. View looking down the trimmed slope.

D, En echelon cracks in the Los Gatos Creek fan, San Luis Canal station 4791 + 25B.

E, Intercepting crack at the Mendota test site.

G, Abrupt widening of crack, note bifurcation of crack at bottom of photograph ; Panoche Creek fan, San Luis Canal station 1921L.

F, En echelon cracks at the Mendota test site.

H, Widening of crack due to secondary slumpage ; bifurcation of crack at top of photograph ; Mendota test site.

A small area of moderate near-surface subsidence is present south of Panoche Creek, about 4½ miles southwest of San Luis Canal station 2060 (Richard Bateman, oral commun., June 1966). Photographs of shallow subsidence hollows in this small near-surface subsidence area are shown in figures 48*A* and 48*B*. Most of the visible settlement is along the alinement of one or two former ditches. Undulating topography occurs in the nearby fields, but some of the breaks in slope visible in the fields are remnants of low terraces of Panoche Creek.

Although the subsidence hollows have been largely filled by agricultural operations, water still floods these low areas when crops are irrigated (fig. 48*A*). In figure 48*B*, the powerline poles in the foreground as well as most of those in the background lean toward the former ditch alinement. It is estimated that as much as 4–5 feet of near-surface subsidence may have occurred locally within this area.

A water-filled subsidence hollow on the Los Gatos Creek fan is shown in figure 48*C*. The photograph is part of an aerial photograph taken in June 1955—the same year that plane-table surveying of the topography was done. The topographic map shows that the central 100 feet of this shallow hollow is slightly more than 5 feet deep. Fallow land is shown in the lower left corner of the photograph. The 160 acres in which the subsidence hollow occurs has been planted with a summer crop such as cotton. The three dark bands near the top of the photograph indicate where the crop is being sprinkler irrigated. The pipeline leading to the sprinklers passes by the right side of the subsidence hollow, and water from a leak in the pipeline is flowing along the pipeline and into the subsidence hollow. The shape of the hollow and the source of the water are similar to those for the hollows on the Tumey Gulch fan shown in figure 2. The slightly larger size of the hollow in figure 48*C*, as compared to the hollows in figure 2, can be attributed in part to gentle slope of the fan in the vicinity of the hollow. The overall fan slope in the vicinity of the hollows shown in figure 2 is four times that of the area shown in figure 48*C*. In figure 48*C*, the overall fan slope is to the northeast, but in the vicinity of the subsidence hollow, the slope has a southerly component (probably caused by subsidence) as is shown by the flow of water from the pipeline leak. By 1967, subsidence had ceased and land-leveling operations had eliminated the hollow shown in figure 48*C*.

Six other historic subsidence hollows of about the same size are shown on the 1955 topographic maps of this part of the Los Gatos Creek fan. These and the subsidence hollows that were on the Los Gatos Creek fan before irrigation began are discussed in the next section.

Historic near-surface subsidence on the Panoche and Los Gatos Creek fans appears to have occurred only in a few places and does not have a magnitude of more than 5–8 feet. Evidence for historic subsidence is lacking on most areas of these fans.

Evidence for historic near-surface subsidence on the Cantua Creek fan was not found. It was concluded that historic near-surface subsidence has not occurred on the fan, or has been so slight that it cannot be detected on aerial photographs or topographic maps, and has not been readily apparent to the farmers in the area.

PREHISTORIC

Abundant evidence exists to show that most of the near-surface subsidence occurred before 1850 and that it was the result of streamflow.

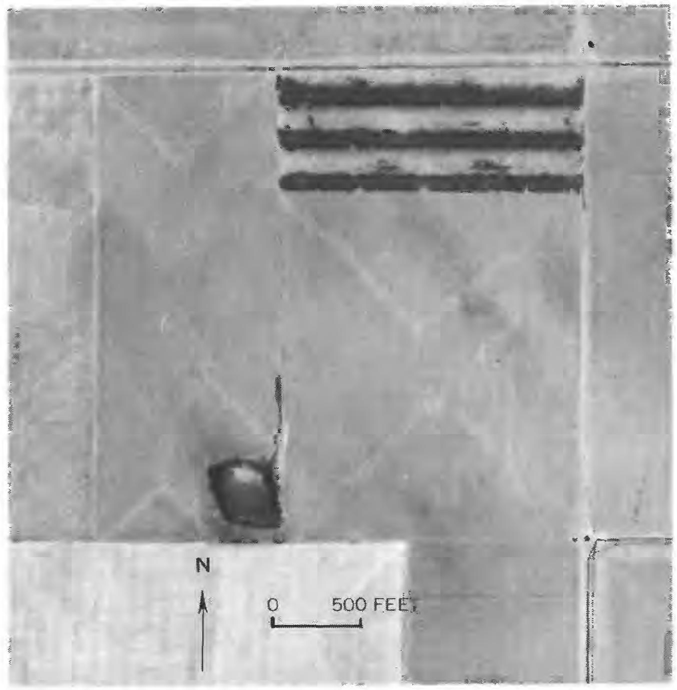
The absence of widespread undulating farmlands and the presence of deposits already wetted to field capacity, even in areas that have not been irrigated, strongly suggests that most of the near-surface subsidence cracks in the canal and streambanks are not the result of modern wetting. In areas of widespread historic near-surface subsidence, undulating farmlands are characteristic of the irrigated areas, and moisture-deficient deposits are characteristic of unirrigated areas.

The fact that the crack fillings are roughly normal to the canal centerline is what one would expect if the subsidence resulted from prehistoric streamflow. Subsidence cracks caused by natural flow along the stream would parallel the channel, which is roughly normal to the fan contours—and to the alinement of the canal—regardless of the part of the fan traversed by the stream.

Orientation of the clay-filled cracks in the Panoche Creek fan is shown in figure 49. The contours are from the 1920 map and indicate the configuration of the fan before appreciable manmade changes such as those caused by subsidence due to artesian-head decline and farming operations. The orientation of cracks, or sets of cracks, is shown diagrammatically. Change in crack orientation is not apparent within short distances, but the change between the fan boundaries is significant. Adjacent to the west boundary of the fan, the trend of the cracks is roughly due north. Near the south boundary of the fan, the trend of the cracks is almost due east. The cracks exposed along the stream channel have an orientation that roughly parallels the present stream course.

A

B



C

FIGURE 48.—Historic near-surface subsidence hollows on the Panoche and Los Gatos Creek fans. *A*, Water in subsidence hollow along old ditch alinement; Panoche Creek fan slope is toward the left. *B*, Powerline poles tilt toward subsidence hollows near old well site. Panoche Creek fan slope is toward the right. Location of hollows in figures 48*A* and 48*B* is about 4½ miles southwest of San Luis Canal station 2060. *C*, Water in subsidence hollow adjacent to sprinkler pipeline on the Los Gatos Creek fan. Location is about 3 miles southwest of San Luis Canal station 4250. Photograph taken by the Topographic Division of the U.S. Geological Survey, June 1955.

The cracks in the Los Gatos and Cantua Creek fans also roughly parallel the former stream courses. On the Los Gatos Creek fan, the general crack orientation along the canal at the west boundary of the fan is roughly due north, and 16 miles to the southeast at the south boundary of the fan, the general crack orientation is roughly due east. The orientation of the cracks in the Cantua Creek fan does not change much from one side of the fan to the other, possibly because the fan contours show little downslope convexity.

Subsidence caused by prehistoric stream flow readily explains patterns of intersecting cracks. Lateral movement of the water from streams in different positions on a fan would account for the intersecting tension-crack alinements.

During a given period of deposition on one part of a fan, the stream channel position may remain approximately constant on the upper part of the fan but may change further downslope. The features shown by the fan contours in figure 52 indicate that the position of Los Gatos Creek channel has remained about constant on the fan upslope from a point halfway between locations *B* and *C*, as is shown by the old channel ridges and stream channels. Downstream from this point, the general stream-channel course has changed by as much as 45°, as is indicated by the former channel features between locations *F* and *H*.

A major shift of the entire stream to another part of the fan would be followed by similar minor changes in stream-channel position as local areas of the fan were made higher than adjacent areas by continuing deposition.

The process of stream-channel shift and the changes of direction of streamflow of as much as 45° on a local part of the fan are in accord with the orientation of the cracks in the large fans. Figure 29 shows that almost half the cracks are within 20°—a total angle of 40°—of being parallel to the radial lines of the large fans. The cracks with deviations of more than about

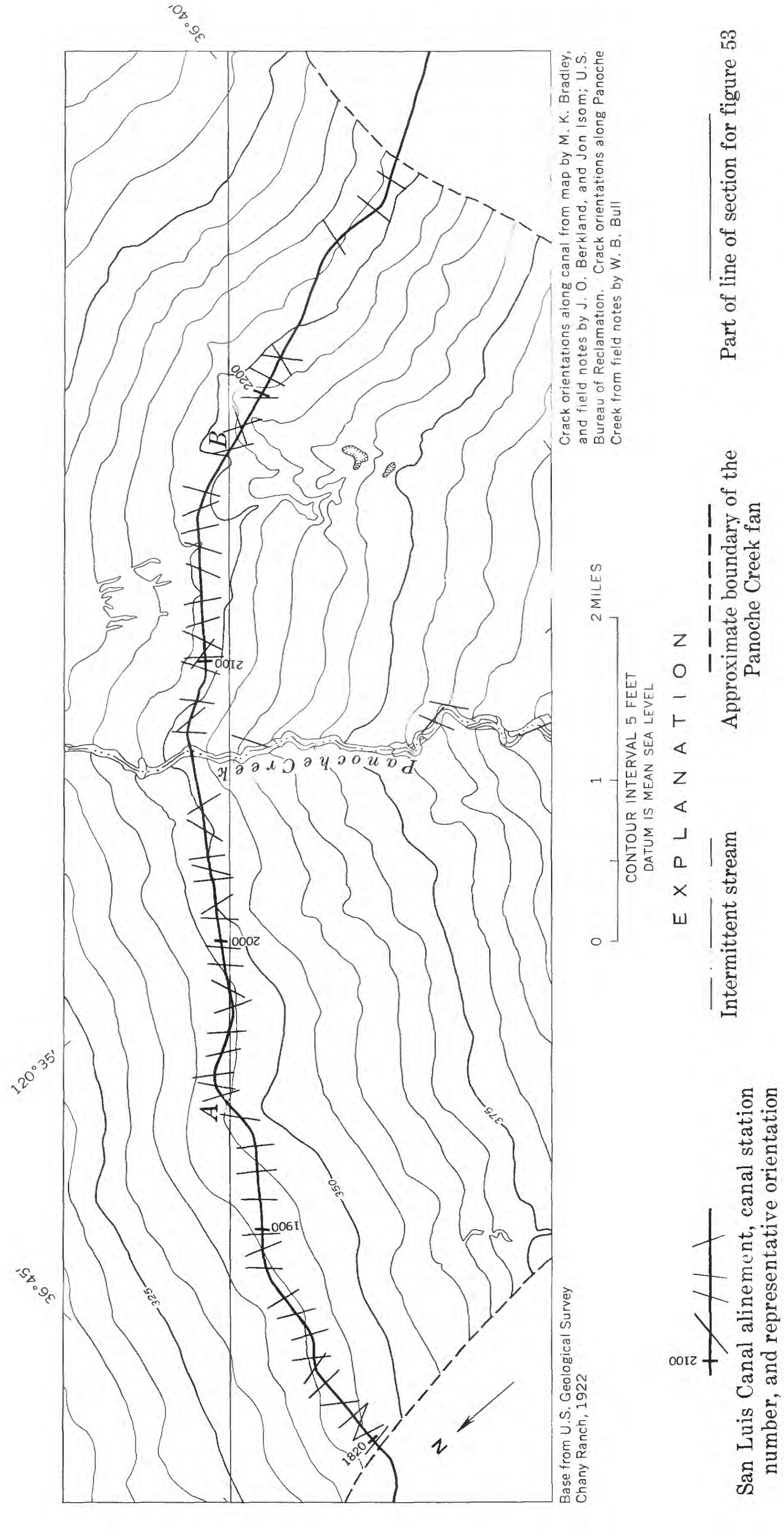


FIGURE 49.—Orientation of clay-filled cracks in the Panoche Creek fan.

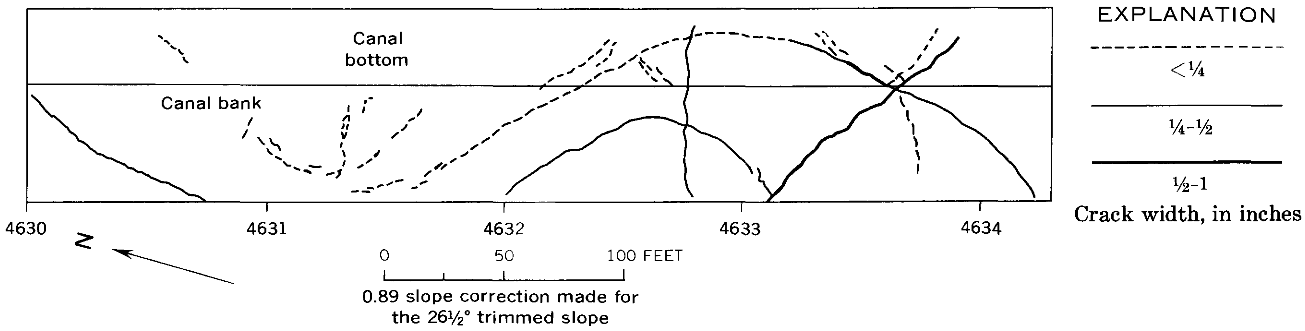


FIGURE 50.—Sinuous pattern of clay-filled cracks in the Los Gatos Creek fan. Right bank of the San Luis Canal, stations 4630 to 4634.

30°–40° are interpreted to be the result of smaller local deviations of prehistoric streamflow, such as would be present in meandering reaches.

Intersecting crack patterns also can be explained by water fronts moving away from and paralleling meandering reaches of prehistoric streams. The water fronts and subsidence cracks would intersect each other on the insides of the curves of the river channel. The present-day stream channels have both meandering and straight reaches (figs. 49 and 52).

The sinuous pattern of clay-filled cracks in figure 50 is suggestive of a meandering stream-channel pattern. Sinuous patterns were not common along the canal, because it is not common for the streams to meander along the contour of the fans. However, the present-day channel of Panoche Creek meanders along th fan contours for short distances. The mean radius of curvature of the sinuous crack pattern shown in figure 50 is 130 feet, which is about the same or slightly larger than the mean radius of curvature of those reaches on the Panoche Creek fan where the stream channel meanders parallel to the fan contour for short distances. The 130-foot radius of curvature would be reasonable for Los Gatos Creek on this part of the fan. The pattern is interpreted as being the result of near-surface subsidence adjacent to a meandering prehistoric Los Gatos Creek stream course.

Some of the best evidence for prehistoric near-surface subsidence is the relation of the cracks to cut-and-fill structures. The general absence of crack fillings in or above buried stream channels and the presence of cracks below buried channels are what one would expect if the cracks were the result of prehistoric subsidence. Prolonged flow concentrated in an entrenched channel might cause sufficiently deep percolation to complete wetting of the moisture-deficient deposits before the channel was backfilled. Truncation of preexisting clay-filled cracks by a buried stream channel can be interpreted only as meaning that the crack fillings are older than the channel fill. Truncation of cracks on those parts of the fans that have not been subject to streamflow since 1850 was by prehistoric streams.

The thin-bedded deposits that occur above many cut-and-fill structures rarely contain crack fillings in excess of one-eighth of an inch wide. This is interpreted as being the result of insufficient overburden load to cause large amounts of compaction due to wetting of the small thicknesses of deposits wetted since cutting and filling of the channel.

The crack fillings found in the banks of streams that were already entrenched by the 1850's also are considered to be prehistoric. The near-surface subsidence that caused these cracks cannot be attributed to irrigation by man because the streams on the upper parts of the large fans had about the same courses in the mid-1850's as in 1967, and irrigation did not begin until the 1880's.

Small fragments of carbonized organic matter were noted in the crack fillings at several locations, but sufficient material for radiogenic dating was available at only one locality. Fragments of carbonized wood were collected from a single crack filling in the south edge of the Cantua Creek fan by J. O. Berkland. A radiocarbon age determination made by Meyer Rubin of the U.S. Geological Survey gave an age of 5,180 ±600 years before present, thereby showing that the crack was prehistoric. The sample site and crack age are discussed in detail on page 78.

About 20 hollows on the Los Gatos Creek fan that are 5–10 feet deep are shown on the topographic maps of quadrangles that were surveyed in 1928 and 1933. Most of these appear to have been unfilled prehistoric near-surface subsidence hollows. The hollows occur chiefly along two radial lines of the fan, which is part of the evidence against the possibility of their being deflation hollows. Seven of the hollows are near the present stream channel, and 11 occur within a radial band on the northwest side of the fan.

The locations of the 11 hollows present in 1928 within a radial band of pronounced hummocky and undulating topography are shown on the map in figure 51. Only the hollows that exceeded 5 feet in depth were shown on the 1928 topographic map of the area. The area in which the hollows occur was not irrigated until after 1940. None of the hollows that are shown on the 1928 map are shown on the 1955 map of the same quadrangle, but six new hollows in different locations within the same radial band of undulating topography are shown on the 1955 map. A photograph of one of the 1955 hollows is shown in figure 48*C*. None of the 1955 subsidence hollows were present in 1967.

The following is a possible history for that part of the Los Gatos Creek fan within the radial band of irregular topography. Deposition of mosture-deficient deposits was followed by an increase in the amount of water infiltrating from streamflow, which caused compaction due to wetting of part of the moisture-deficient deposits. A major shift of stream-channel position from the northwest side of the fan to the middle of the fan occurred before compaction due to

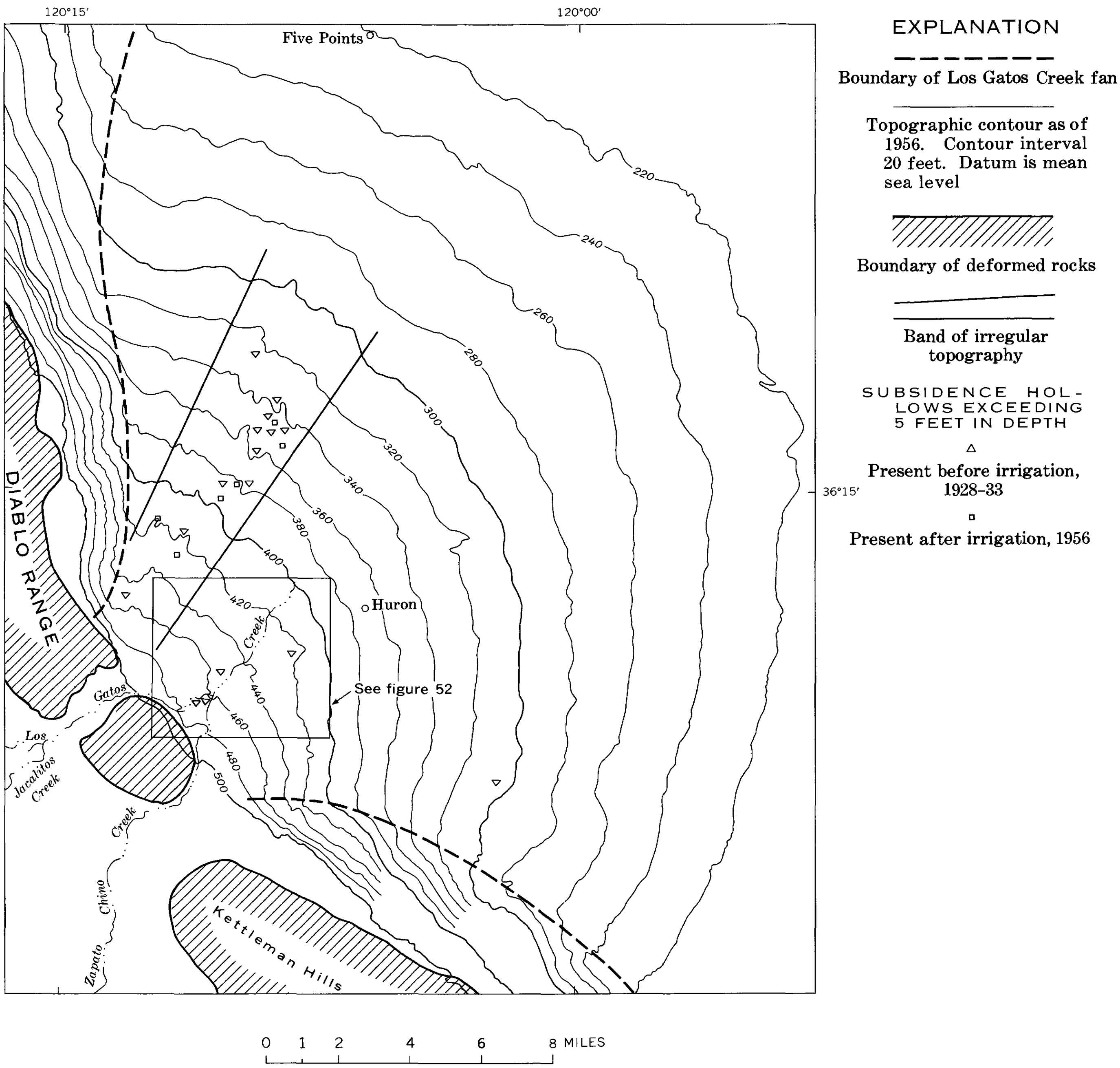


FIGURE 51.—Near-surface subsidence hollows on the Los Gatos Creek fan before and after irrigation.

wetting was complete and before deposition could fill the hollows caused by the partial wetting. Eleven of the deeper subsidence hollows were still unfilled when the 1928 topographic mapping was done. Land leveling associated with farming of the land since 1940 has smoothed much of the irregular topography. Irrigation completed the compaction due to wetting of those deposits that had not been wetted by prehistoric streamflow, and caused the formation of new subsidence hollows of about the same magnitude as the prehistoric subsidence hollows. After compaction due to wetting was complete, land-leveling operations were able to fill the six hollows shown on the 1955 topographic map.

Prehistoric hollows near the channel of Los Gatos Creek are shown in figure 52, which is derived from a 1933 topographic map. Seven irregularly shaped hollows are shown at locations *A*, *B*, *C*, and *D*. Most of the hollows appear to be near-surface subsidence hollows formed as a result of wetting by Los Gatos Creek.

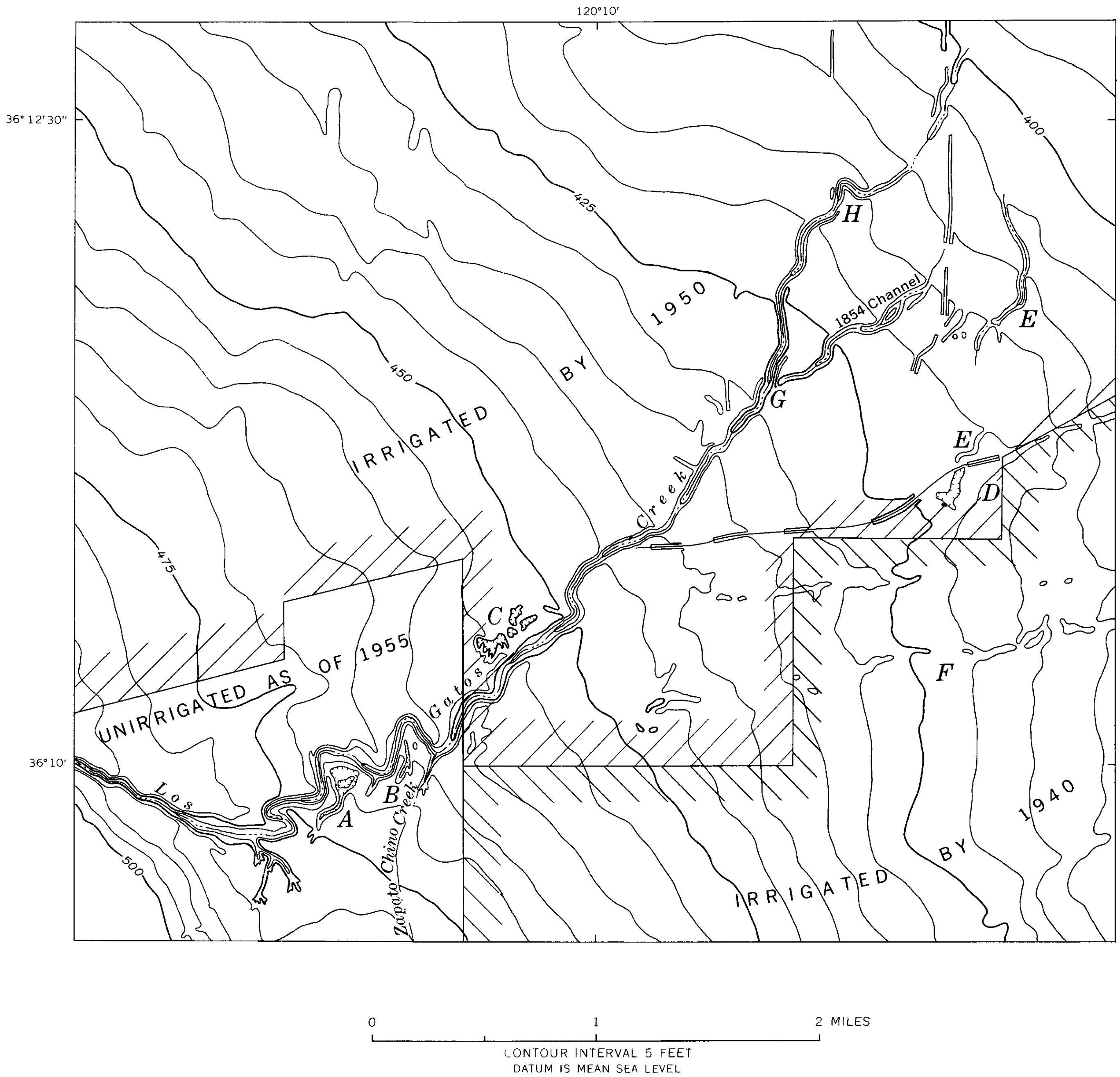


FIGURE 52.—Prehistoric near-surface subsidence hollows, indicated by leters A, B, C, D, near the channel of Los Gatos Creek. For location, see figure 51.

The possibility of the hollows being formed during the course of fan deposition is slight except at locations *A* and *B*. Because the fan surface is depositional, erosional hollows are unlikely. The only way in which a hollow could be formed would be for a reach of a stream channel to be bypassed and then be blocked by deposition from the same stream at its lower end. Such a process hardly seems possible.

The possibility of erosional hollows being formed at the juncture of adjacent streams flowing onto the fan is much more likely. For example, the hollows at *A* and *B* (fig. 52) occur in the vicinity of Zapato Chino Creek on the upper part of the Los Gatos Creek fan. It is possible that these hollows, which exceed 10 feet in depth, formerly could have been part of old gullies, such as the ones southwest of location *A* and northeast of location *B*, that were formed as a result of streamflow from Zapato Chino Creek entering a channel of Los Gatos Creek that was incised below the general depositional area of Zapato Chino Creek. The lower ends of such gullies could be blocked by deposition associated with backfilling of the entrenched channel of Los Gatos Creek. Janda (1965) describes larger hollows of this type in tributaries adjacent to the San Joaquin River. Even if backfilling was the original cause of the hollows at locations *A* and *B*, the hollows would be excellent traps for collecting streamflow from Zapato Chino Creek, which would thoroughly wet any moisture-deficient deposits that might have been beneath them.

The history of changes in stream-channel position on part of the fan is shown by the topography between locations *F* and *H* (fig. 52). The channel ridges mark the location of old distributary stream channels. The general sequence of events was for the stream to deposit part of the fan, backfill the existing channel, move to a nearby part of the fan, and leave channel ridges 2–4 feet above the general level of the terrain on either side of the previous channel location. In some places, the channel changed position before it was backfilled, and the stream channel was preserved, such as downslope from location *G*.

The changes in channel position between locations *F* and *H* may have occurred within the last 150–200 years. Scattered trees (probably cottonwoods) were still growing on the channel ridges at location *F* in 1854 (R. E. K. Whiting, U.S. Surveyor General's Office, written commun., May 12, 1854). In 1854, the stream channel followed the course downstream from location *G;* between 1854 and 1880, it moved to its present position, about half a mile to the north.

None of the hollows shown in figure 52 are in areas that were irrigated before 1940, and, except for the hollow at location *D*, there does not appear to be any possibility of the hollows being the result of wetting by man. The hollow at location *D* is adjacent to a ditch used to divert water for limited agricultural use farther down the fan during years of large flows. However, the hollow at location *D* appears to predate the ditch because the north end of the hollow appears to have been truncated by construction of the ditch. A more likely possibility is that the hollow was formed by prehistoric near-surface subsidence when the stream was on this part of the fan. The ditch occupies remnants of an old stream channel, which branches northward near the end of the ditch. (See letter *E*.)

The four irregular-shaped hollows at location *C* (fig. 52) roughly parallel the stream course. Lateral erosion of the north bank of Los Gatos Creek adjacent to these hollows has removed more than 100 feet of streambank between 1933 and 1967. Abundant clay-filled cracks that extend to the base of the tilled zone can be found in the streambank adjacent to the former position of the largest subsidence hollow at location *C*.

The evidence for prehistoric near-surface subsidence hollows is not good on the fans of Cantua and Panoche Creeks. The Cantua Creek fan has a smooth surface that has few channel ridges, and no indication of the existence of hollows on the fan surface before or after irrigation began.

Most of the Panoche Creek fan surface is smooth except for channel ridges. However, two hollows deeper than 5 feet in a small area of irregular topography such as occurs on the north side of the Los Gatos Creek fan (fig. 51) are shown on the 1920 map of the Panoche Creek fan. The two hollows are shown in figure 49, about 6,000 feet south of San Luis Canal station 2140 in an area that was not farmed until after the 1920 map was made.

POST-SUBSIDENCE BURIAL OF CRACKS

Compaction due to wetting caused by streamflow results in a hollow suitable for ponding of stream water, when available, until the underlying moisture-deficient deposits have been completely wetted and fully compacted. Sediment deposited by the streamflow will tend to fill the hollow, and, after subsidence has ceased, deposition eventually will restore a smooth fan surface.

Where the subsidence hollows are not covered by later fan deposition, irregular topography is present, and the cracks commonly extend to land surface. The best example of irregular topography is on the Los

Gatos Creek fan where it occurs as a radial band extending from the fan apex (fig. 51).

The smooth surface of most parts of the fans and the termination of most cracks below the tilled zone indicate that alluvial-fan deposition has smoothed out the irregular topography that occurred as a result of near-surface subsidence. The clay- and sand-filled cracks observed along the stream channels did not occur within 6–10 feet of the land surface, and the cracks along most of the canal ended within 1–8 feet of the base of the tilled zone. Many cracks were found, though, that extended to the base of the tilled zone about 1–2 feet below the fan surface.

The proximity of the crack tops to the land surface was noted in detail on the Panoche Creek fan where the relation of the depth of burial of the crack tops to the shape of the alluvial fan was evaluated.

A cross-fan profile of the Panoche Creek fan in the vicinity of the San Luis Canal is shown in figure 53. Most of the line of profile is shown in figure 49. The shape of the fan normal to the medial radial line is similar to the shapes of smaller fans in the study area (Bull, 1964c, figs. 73, 74). Channel ridges are common, and the stream is presently flowing on the highest part of the cross-fan profile.

The greatest depth of burial of the crack tops occurs at the points of maximum upward departure from a smooth cross section of a cone. At location *A*, the crack tops are buried to depths of 10–15 feet below the fan surface. The consistent depth of burial of the cracks in the vicinity of location *A* is shown in figure 27. Crack fillings along and near Panoche Creek have tops that are 7–10 feet below land surface. The most pronounced departure from a smooth cross section of a cone on the cross-fan profile shown in figure 53 is at location *B*. Crack fillings are rare on this part of the fan.

Cracks are not common between miles 9 and 11 of the profile either, and the cause of the decrease in crack abundance in this reach may be related to factors other than local burial of the cracks. The cracks between miles 8 and 11 along the profile occur, for the most part, as single cracks or groups of as many as four to six cracks that are spaced 100–400 feet apart. Reaches of as much as 1,000 feet do not have cracks (fig. 49), and some of the cracks pinch out at depths of 20 feet below the land surface.

The decrease in the abundance of crack fillings on the south side of the Panoche Creek fan may be the result of compaction due to wetting earlier in the fan history. A subsequent lack of accumulation of a sufficient thickness of moisture-deficient deposits since the time of wetting would account for the general lack of compaction due to wetting and associated cracking of the fan deposits near the land surface. The steep south side of the cross-fan profile in figure 53 suggests that less deposition has been occurring on the south than on the north side of the Panoche Creek fan. Drilling by the U.S. Bureau of Reclamation prior to canal construction found large amounts of gravel below the canal bottom in this reach (Richard Bateman, oral commun., July 31, 1967). The gravel indicates the presence of material below the canal that would not have undergone large amounts of compaction due to wetting. The gravel also indicates the presence of stream channels that may have concentrated flow sufficiently to thoroughly wet the underlying deposits before deposition of the 25 feet of the fan above the canal bottom.

In summary, the depth of burial and change in abundance of cracks on the Panoche Creek fan agree

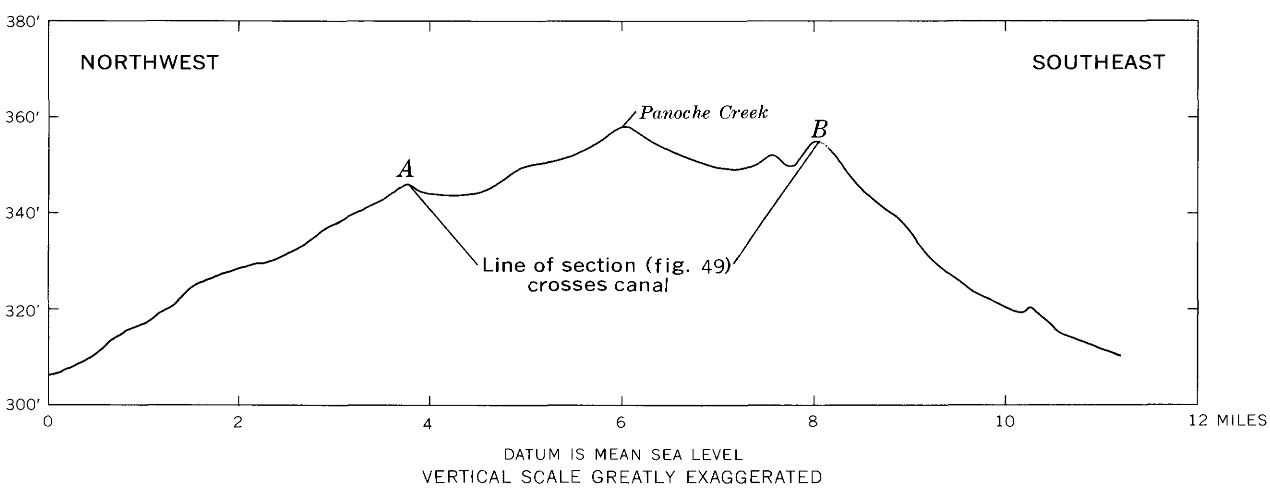


FIGURE 53.—Cross-fan profile of the Panoche Creek fan in the vicinity of the San Luis Canal. For alinement of most of profile, see figure 49.

with the postulated history of deposition of the fan as suggested by the cross-fan profile in figure 53 and by drill-hole information.

ESTIMATED FUTURE NEAR-SURFACE SUBSIDENCE ON THE PANOCHE, LOS GATOS, AND CANTUA CREEK FANS

In addition to subsidence due to artesian-head decline along all of the San Luis Canal in the study area, the potential extent and amount of future near-surface subsidence is of interest to those who will maintain the canal. Although the canal alinement on the fans of Moreno Gulch, Tumey Gulch, Arroyo Ciervo, Arroyo Hondo, and some adjacent smaller fans, was ponded before canal construction, the canal alinement on the fans of Panoche Creek, Los Gatos Creek, and Cantua Creek was not ponded to compact moisture-deficient deposits that might be present.

The evidence in the preceding sections shows that most of the settlement that caused the cracking was near-surface subsidence resulting from prehistoric streamflows. The small areas of historic near-surface subsidence on the Panoche and Los Gatos Creek fans indicate the presence of small pockets of moisture-deficient deposits left as a result of erratic prehistoric percolation from the creeks.

There are several reasons for expecting a lower magnitude of compaction due to wetting in large fans than in the adjacent small fans where near-surface subsidence is widespread and has attained magnitudes of as much as 15 feet. Most of the deposits in the small fans contain considerable clay, whereas the large fans contain many beds of clean sand that have less than 5 percent clay. Sand with less than 5 percent clay and with hygroscopic moisture content underwent only 2–6 percent compaction due to wetting under a simulated overburden load of 50 feet (fig. 4). Sand with little clay binder, and under wilting coefficient conditions, would compact even less when wetted, and might not compact at all.

The maximum possible thickness of moisture-deficient deposits in the large fans is 250–300 feet as compared to the maximum of 300–400 feet of moisture-deficient deposits that have accumulated above the water table in the small fans. Thus, the maximum possible magnitude of compaction due to wetting of the large fans would be less than that of the small fans even if the deposits of the large fans had similar compaction properties.

Large thicknesses of moisture-deficient deposits would not have accumulated if more than one period of prehistoric wetting had occurred. As was shown in figure 3, the effect of overburden load on compaction due to wetting is a linear relation, and the percentage of compaction doubled between 25 and 100 feet of overburden load for a test plot on the Arroyo Ciervo fan.

On the lower part of the large fans, the prehistoric water table was within 50–100 feet of the surface, and prevented the accumulation of large thicknesses of moisture-deficient deposits.

The lack of crack fillings in the fan deposits at the fan apexes indicates that moisture-deficient deposits never had accumulated. The deposits at the fan apexes should not be moisture deficient because the stream remained on this part of the fan regardless of where it traversed the fan downslope from the apex. Thus, the fan apexes have been subject to every large and continuous flow and the deposits at the apexes probably have been wetted repeatedly during the fan history.

PANOCHE CREEK FAN

Widespread percolation of irrigation water on the Panoche Creek fan is demonstrated by comparison of the depth to the water table in 1952 and 1965. The water table in most of the Panoche Creek fan has risen between these dates—the maximum rise being 30 feet.

Along the canal alinement, the probability of future near-surface subsidence is greatest in two fairly small areas in which the water table has remained unchanged or has declined as much as 25 feet between 1952 and 1965. These areas are the 2–3 miles of canal alinement near the south edge, and the 1 mile near the north edge of the fan. Even in these areas, only negligible or minor near-surface subsidence should occur after water is introduced into the canal. The presence of extensive clay-filled subsidence cracks near the north edge of the fan, some of which are truncated by buried stream channels, indicates that considerable prehistoric compaction due to wetting has occurred. Also, both of these areas have been irrigated for at least 7 years. Although this is not as long as the history of irrigation for most of the fan, any deposits that were not wetted by prehistoric flows along Panoche Creek probably have been largely wetted by irrigation.

The distribution systems to be built southwest of the canal may cross pockets of moisture-deficient deposits. Much of the area upslope from the canal has been irrigated for about 10 years, but parts of it have never been irrigated. If these unirrigated lands are underlain by pockets of moisture-deficient deposits, as much as 5–10 feet of near-surface subsidence may occur.

LOS GATOS CREEK FAN

Areas of water-table rise between 1952 and 1965 have not occurred along the canal alinement and in the fan upslope from the canal alinement. Pumping of deeper ground water in much of the fan has caused the water table to decline in spite of percolating irrigation water.

The possibility of near-surface subsidence occurring along most of the canal alinement is slight. The most suspect location would be where the canal crosses the band of irregular topography on the north side of the fan shown in figure 51. Prehistoric and historic hollows within this band were discussed in a previous section. However, the lack of subsidence hollows in this area by 1967 suggests that wetting of residual pockets of moisture-deficient deposits had been completed by percolating irrigation water. Thus, little or no near-surface subsidence should occur along the canal, even in the reach described above, after water is introduced into the canal.

The distribution systems to the southwest of the canal probably are in deposits that have been completely wetted by prehistoric streamflow or irrigation water. Some of the fields adjacent to the foothills have been irrigated for only a few years, but the soil is highly permeable and should have permitted percolation of irrigation waters to the water table after several years. Also, the thickness of the Los Gatos Creek fan decreases rapidly adjacent to the foothills.

CANTUA CREEK FAN

Historic near-surface subsidence has not occurred on the Cantua Creek fan, as is shown by the reports of farmers and examination of aerial photographs and topographic maps. Future irrigation and transport of water across the fan should not cause near-surface subsidence because the fan deposits appear to have been wetted completely before man irrigated the fan.

CONCLUSIONS REGARDING THE CRACKS IN THE ALLUVIAL FANS OF PANOCHE, LOS GATOS, AND CANTUA CREEKS

The cracks in the canal and streambanks are the same as known near-surface subsidence cracks. Both:

1. Consist of tension cracks between blocks of alluvium that have rotated and settled in response to stresses produced by compaction of the adjacent alluvium.
2. Have undergone tensional opening followed by compressional closing of the cracks and have little or no offset bedding where uniform wetting of the moisture-deficient deposits has occurred.
3. Are vertical; discontinuous; have a rough hackly fracture along their sides; have a highly variable density of spacing; occur in parallel sets; and anastomosing, intersecting, and en echelon patterns.

Most of the cracks are filled with clay that contains minor amounts of silt-size particles less than 20 microns in size. The clay may be massive, laminated or may contain medial parts of sandy and silty material or have medial partings or compressional folds. Some cracks are filled with clean well-sorted sand.

Most of the cracks have truncated tops. The undisturbed tops of clay-filled cracks consist of a widening of the crack to 2–18 inches in the upper 1–3 feet of the crack. The material in the top may consist of water-laid sediment or debris that has slumped into the crack. The tops of sand-filled cracks do not have a change in width; instead, they end abruptly at an overlying sand bed that has a lithology similar to that filling the crack.

Stream-transported material is the only logical source for the crack fillings. Material that has slumped into, or overlies, the tops of most cracks would permit only the finest particle sizes to infiltrate into the crack and coat the crack sides with clay. Multiple periods of deposition would result in matching laminae of clay in the crack. Sand-filled cracks appear to have been filled with saturated sand furnished directly from the stream in a single period of deposition.

The cracks may open, be partly or completely filled, and be closed during a single winter rainy season. Winters of above-normal and prolonged streamflow would be times of sufficient water to cause deep percolation of water in moisture-deficient deposits and compaction due to wetting. The streamflow would also furnish a supply of clay and sand to fill the cracks.

The widths of the cracks are a function of the intensity of temporary differential subsidence, and the stage of rotation of the blocks of alluvium between the cracks at the time of filling. The width of a crack filling is in part a function of how much material is deposited in the crack before rotation of the adjacent blocks of fan deposits tends to close the crack.

The spacing of the cracks is a function of the thickness of the moisture-deficient deposits that remain temporarily above a seepage bulb and the strength of the alluvium.

Crack patterns are a function of the amount of differential settlement, the geometry of the seepage bulb(s), and the relative positions of multiple seepage bulbs occurring at different times that may be necessary to complete wetting of the deposits. The smaller crack patterns are mainly a function of factors affecting secondary fracturing of the deposits after the primary cracks have opened.

The cracks have formed at different times during the depositional history of the fans, and most of them were caused by prehistoric streamflows. Evidence supporting the prehistoric nature of the near-surface subsidence includes the absence of widespread historic near-surface subsidence in irrigated areas, deposits already wetted to field capacity in unirrigated areas, the dominance of cracks that parallel the former stream courses on any part of the fans, truncation of crack fillings by buried stream channels, the presence of crack fillings in the streambanks that were entrenched decades before irrigation started, and the variable depth of burial (0–15 feet) of the tops of the crack fillings on the different parts of the fans.

The magnitude of compaction due to wetting of the large fans never approached the magnitude of compaction of the small fans because the thickness of moisture-deficient deposits was less than the 200–350 feet of moisture-deficient deposits that commonly occur in the small fans. Also, many of the water-laid sands in the large fans have such a low clay content that there would be little decrease in the strength of the material when it was wetted under overburden load for the first time since burial.

The amount of prehistoric near-surface subsidence may have been larger on the middle of the fans than at the fan apexes, or near the fan toes. The thickness of the deposits at the fan apexes is less than further downslope, and appreciable thicknesses of moisture-deficient deposits are unlikely to accumulate at the fan apex, because the stream crosses the fan apex regardless of where it transverses the fan farther downslope. Thus, the fan apex would be subject to possible wetting by every streamflow that would reach the fan from the source area.

The prehistoric depth to the water table below the middle and upper parts of the fans was about 100–300 feet. The water table on the lower parts of the fans probably was within 50 feet of the surface, and in parts of the area the toes of the fans were areas of ground-water discharge. Thus, the potential for accumulation of large thicknesses of moisture-deficient deposits, and large amounts of compaction due to wetting, would be slight on the lower parts of the fans.

Future near-surface subsidence is not expected on most parts of the large fans. However, the areas that have not been irrigated yet, or have been irrigated for only a few years, may have small pockets of moisture-deficient deposits left by the erratic percolation of water from the streams. Several feet of near-surface subsidence may occur in these local areas.

CRACKS IN THE ALLUVIAL FANS OF MORENO GULCH, TUMEY GULCH, ARROYO CIERVO, AND ARROYO HONDO

The small fans of Moreno Gulch, Tumey Gulch, Arroyo Ciervo, and Arroyo Hondo, in contrast to the large fans of Panoche, Los Gatos, and Cantua Creeks, are derived entirely from the foothill belt of the Diablo Range. In addition to the differences in fan and source-area characteristics shown in table 1, the most notable feature of the small fans is their higher overall clay content. The predominant mode of deposition ranges from mudflows for the Arroyo Ciervo fan to water-laid sediments for the Arroyo Hondo fan.

The cracks were found only in the banks of the San Luis Canal. The general features, orientations and patterns, and crack fillings will be described; the times of formation will be discussed, and the cracks will be compared with those in the fans of Panoche, Los Gatos, and Cantua Creeks.

Comparison of the cracks in the small and large fans is interesting. The basic cause of the settlement and many of the features of the cracks is the same as for the cracks in the large fans, but important differences exist. Compaction due to wetting of the fans derived from the foothill belt has caused widespread historic near-surface subsidence, and as much as 15 feet of near-surface subsidence has occurred on these fans.

GENERAL FEATURES OF THE CRACKS

The cracks are vertical, or near vertical, tension fractures with rough hackly breaks or undulating sides. They are filled with a variety of material ranging from clay to gravel, but some cracks are unfilled or partly filled.

The width of the cracks ranges from less than 1/32 of an inch to more than 12 inches, but most are 1/2- to 3-inches wide. Crack width commonly remains constant for 100 feet or more, but cracks that change in width with horizontal distance and narrow or widen vertically are common. Changes in crack width in part of the Tumey Gulch fan are shown on plate 2*C*. Of the 35 cracks that occur in this 6,000-foot reach of the canal, six cracks narrow upslope, four cracks narrow downslope, and 25 cracks do not have an appreciable change in width as exposed on the slope.

Some cracks have irregular widths such as the one in the Moreno Gulch fan shown in figure 54. A rough hackly break of the deposits adjacent to the crack is apparent where the tape crosses the crack filling. Abrupt widening of a crack such as in the foreground of figure 54, commonly is the result of secondary

FIGURE 54.—Variation in width of crack filled with clayey sand in the Moreno Gulch fan. San Luis Canal station 1702 + 60L. Paired arrows end at sides of crack.

slumpage into primary cracks. Clay lines the edges of the crack, but the bulk of the crack filling consists of clayey sand.

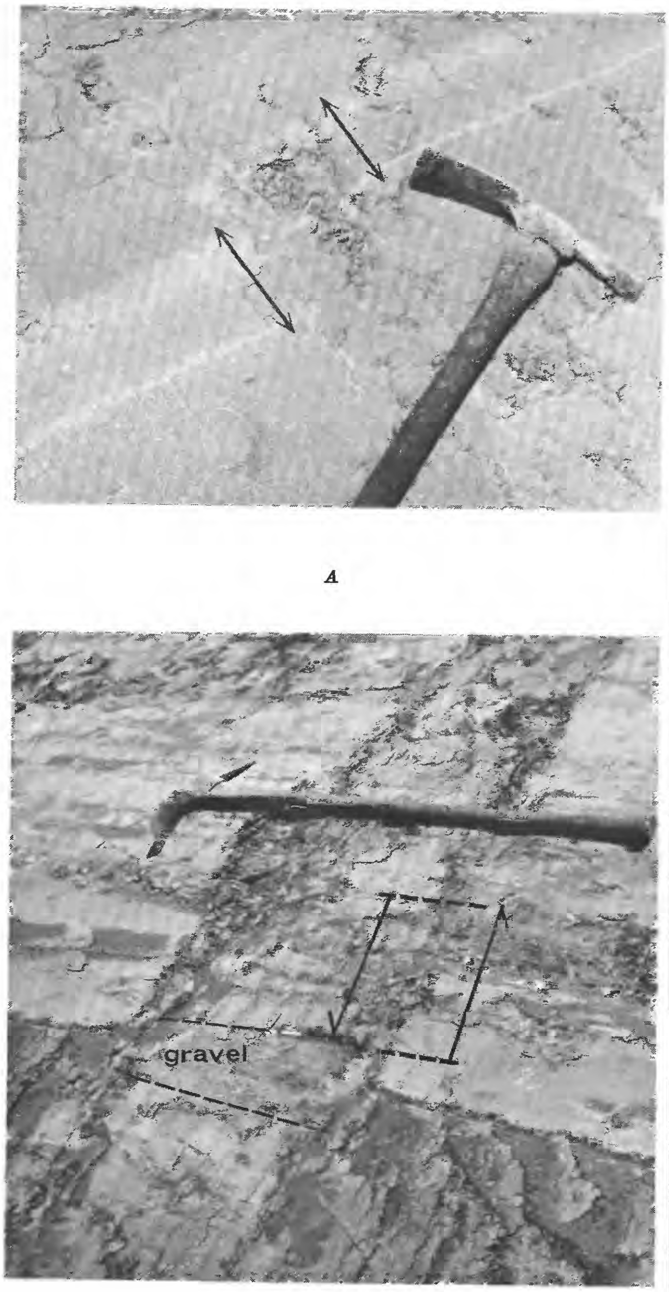
Most of the cracks have truncated tops at about the top of the undisturbed fan deposits. The distance of the top of the bedded fan deposits below the original fan surface was more difficult to determine than for cracks in the large fans, where the canal alinement was not ponded before canal construction. For most of the canal reaches on the small fans, the disturbance of the bedded fan deposits during the excavation required to build the ponds was 1–3 feet deeper than the base of the tilled zone. Thus 2–5 feet of deposits below the original fan surface have been disturbed by plowing, pond construction, or both.

Undisturbed crack tops were found only in parts of the Tumey Gulch fan and were not common there. The funnel tops consisted of an upward widening of the cracks from 1/2 to 3 inches to as much as 30 inches in a vertical distance of 2–6 feet. In the larger funnel tops, the bedding of the fan deposits adjacent to the funnel top curved downward at the sides of the funnel top.

Most of the cracks do not have offset bedding on opposite sides of the crack (figs. 55, 58, and 61). Figure 55 is a typical crack in the Arroyo Hondo fan. Most of the cracks in this fan occur as sets or single cracks that commonly are spaced more than 1,000 feet apart. The primary crack shown in figure 55 is 5 inches wide and is filled with silty clay that has 15 percent sand. (See sample 28 in fig. 63 and table 3.) The crack filling contains fragments of reeds and other organic matter. A closer view of area *A* is shown in figure 56*B*.

The few cracks that had offset bedding rarely had more than a few inches of offset bedding as exposed on the 2-to-1 slopes. Offset bedding in the Arroyo Ciervo and Arroyo Hondo fans is shown in figure 56. Offset

FIGURE 55.—Five-inch wide clay-filled crack with no primary offset bedding. Secondary cracking at *A* is shown in figure 56*B*. Arroyo Hondo fan, San Luis Canal station 2992.



A

B

FIGURE 56.—Offset bedding adjacent to cracks. *A*, Offset bedding on opposite sides of a primary crack in the Arroyo Ciervo fan, San Luis Canal station 2820 + 20L. Lengths of double arrows indicate differences in apparent thickness on opposite sides of the crack. *B*, Offset bedding associated with a secondary slump in a primary crack in the Arroyo Hondo fan, San Luis Canal station 2992L.

bedding on opposite sides of a primary crack in the Arroyo Ciervo fan is shown in figure 56*A*. The offset, as exposed on the trimmed canal bank, is about half a foot and extends for more than 20 feet along the crack. The difference in apparent thicknesses of the beds (shown by the arrows) indicates differing amounts of rotation of the blocks on opposite sides of the crack—a situation similar to that shown in figure 23.

Offset bedding that is a result of secondary slumpage into a primary crack is shown in figure 56*B*. A view of the entire exposed crack is shown in figure 55. The bed of gravelly sand downslope from the mattock handle has been downdropped to the top of the dark clay-rich bed in the foreground. The positions of the contacts between the dark clay bed and the overlying light-colored sand bed in the foreground indicate that primary offset of the bedding on opposite sides of the downdropped block has not occurred.

Buried stream channels in the small fans are much smaller than those in the large fans (pl. 2*A*). Also, instead of being filled with gravelly sediments, they generally are filled with fine-grained bedded deposits, which range from mudflow deposits to water-laid sediments and that are similar to the adjacent fan deposits.

The crack fillings that occur below the buried stream channels extend through the stream channels and into the overlying fan deposits. Examples are the cracks at station 2568+50 on plate 2*C*, and in figure 64*D*. The presence of cracks in the buried channel fills indicates that prehistoric streamflow in the channel did not percolate below the root zone and cause compaction due to wetting. Wetting occurred after the channel had been backfilled, and after additional deposition had covered the channel. Compaction due to wetting occurred within the clayey channel fill as well as in adjacent deposits.

Most of the cracks extend to within 3 or 4 feet of the former land surface. Many cracks appear to have extended above the top of the undisturbed deposits prior to disturbance resulting from construction.

Cracks that end below the top of the bedded fan deposits were most common in the Tumey Gulch fan. For example, between stations 2545 and 2552—a distance of 700 feet—five out of six cracks end about 5 feet below the top of the bedded fan deposits (about 7–10 ft. below the undisturbed fan surface).

The distribution of the cracks on the various parts of the fans is not known outside of the canal. Although the channels of the streams in the small fans are entrenched 20–40 feet, a search of the walls of the arroyos did not reveal any crack fillings or cracks similar to those in the canal. The entrenched reaches of the stream channels are in unirrigated areas on the upslope third of the fans. A few manmade pits and trenches on the middle and downslope parts of the fans were examined, but crack fillings were not found, possibly because of the wide spacing of the cracks in the small fans.

The density of crack spacing is highly variable and changes abruptly; in general, the cracks are widely spaced. The density of crack spacing shown on plate 2*A* and *C* is representative of the four fans studied. Parts of the Moreno Gulch fan have a mean density of spacing of about 10 cracks per 100 feet. On the central part of the fan, only 30 cracks were mapped in the left bank in 5,500 feet (Merrit Bradley, oral commun., July 1966).

The abundance of crack fillings in the Tumey Gulch fan is about the same as in the central part of the Moreno Gulch fan. On plate 2*C*, 35 cracks are shown in the right bank of the canal in 6,000 feet—a density of spacing that is representative of the fan. The cracks commonly occur in sets of two to four cracks with large distances of no cracks between the sets, but isolated single cracks occur also.

The density of spacing of cracks in the Arroyo Ciervo fan is similar to that of the Tumey Gulch fan.

The Arroyo Hondo fan has the lowest density of crack spacing of any fan studied. Most of the fan has only four to five cracks per 1,000 feet, and intervals of more than 1,000 feet between cracks are common. The abundance of cracks in the Arroyo Hondo fan increases markedly adjacent to the Cantua Creek fan: several hundred cracks occur in the 1,000 feet adjacent to the Cantua Creek fan. This anomalous increase in density of crack spacing is discussed in detail later.

The orientation of most of the cracks is roughly parallel to the radial lines (normal to canal alinement) of the fans on which they occur (pl. 2*A*, *C*). A few cracks parallel the canal alinement, but most deviate less than 45° from the radial lines of fans.

The orientations of the cracks for two sites in the Tumey and Moreno Gulch fans is shown in figure 57. The proportion of cracks having deviations of 20° or less from a bearing normal to the fan contours is about the same as for the cracks in the large fans (table 2). For the reach studied in the Tumey Gulch fan (pl. 2*C*), 42 percent of the cracks have deviations of 20° or less; and for the reach on the Moreno Gulch fan (pl. 2*A*), the percentage was 38. About 85 percent of the cracks in the Tumey Gulch fan reach and 71 percent of the cracks in the Moreno Gulch fan reach have deviations of 50° or less. The patterns shown in figure 57 have much less statistical significance than the pattern for 415 cracks shown in figure 29, because of the small number of orientation measurements made of cracks in the small fans.

Although the orientation of most cracks on the small fans is roughly normal to the canal centerline, many cracks have an orientation that is either north-south or east-west. Examples would be the cracks in the left bank of the canal in the Moreno Gulch fan at station 1797 (pl. 2*A*). Cracks with these orientations are uncommon on the large fans, except where the canal alinement trends east or south (stations 1820–1850 on pl. 2*A*). The north-south and east-west cracks on the small fans commonly are near former ditches that paralleled section-line farm roads.

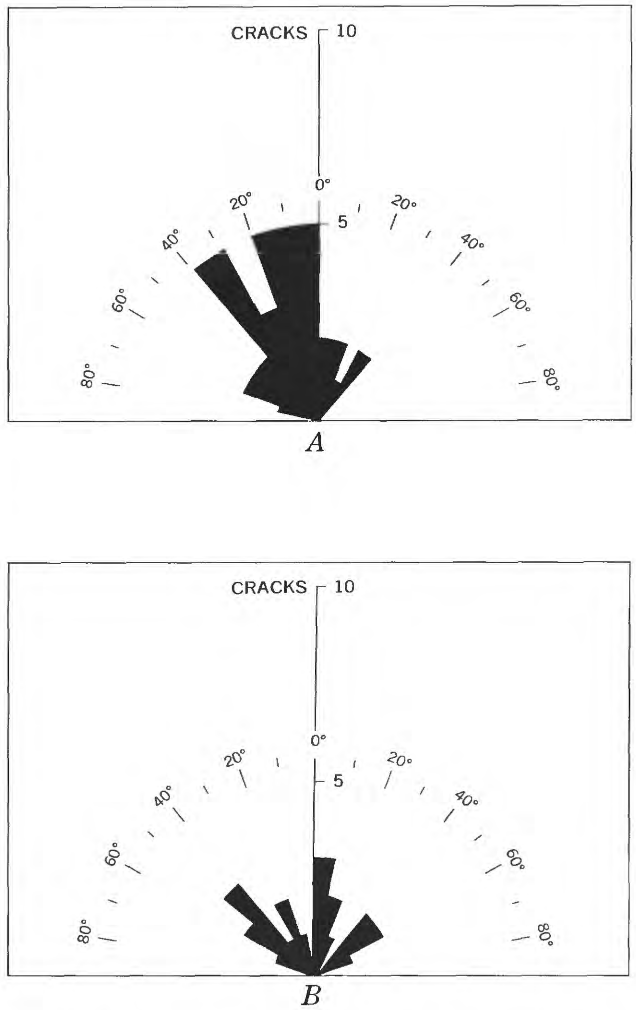


Figure 57.—Deviation of crack strikes from bearings normal to the fan contours. Tumey Gulch and Moreno Gulch fans. *A*, Tumey Gulch fan, stations 2525–2585. *B*, Moreno Gulch fan, stations 1790–1818.

The crack patterns are the same as those in the large fans. Parallel sets are the most common pattern. Intersecting and intercepting cracks are not common, and offset of intersecting cracks was not observed. En echelon cracks were fairly common on the Tumey Gulch fan, but were rare on the other fans.

LITHOLOGY OF THE CRACK FILLINGS

Most of the cracks are filled with clay that contains large amounts of silt and sand, but some are filled with a variety of materials ranging from clay to gravel.

Partly filled cracks were found on all the fans. On the Moreno Gulch fan, partly filled cracks were found 25 feet below the fan surface. On the Arroyo Ciervo fan open and partly filled cracks were noted at station 2808+15 to 70R. About 32 uniformly spaced cracks were counted in 55 feet. The cracks were thin, 1/32- to 1/4-inch wide, and some of them were filled with clayey sand.

The crack fillings may be massive, laminated, contain medial partings or lithologies and show internal folding. Some cracks are filled with bedded sand or gravel. Most of the crack fillings are massive. A massive crack filling consisting of sandy clay is shown in figure 58. The particle-size distribution of a sample from the crack filling is shown in table 3 and figure 63 (sample 26). The crack width changes abruptly along the strike and ranges from 1 to more than 3 inches wide. The bedding on opposite sides of the crack is not offset.

Many of the cracks, particularly in the Tumey Gulch fan, contain more sand near the land surface than at depths of more than 10 feet. Six of the 35 crack fillings on plate 2*C* change from sandy clay in the lower part of the trimmed slope to clayey sand or sand in the upper part of the slope. One of these cracks is shown in both figure 59*A* and *B*. In figure 59*A*, a 2- to 4-inch crack is filled with sand-silt-clay. Above the mattock, the crack filling becomes progressively more sandy, and on the far side of the finger drain

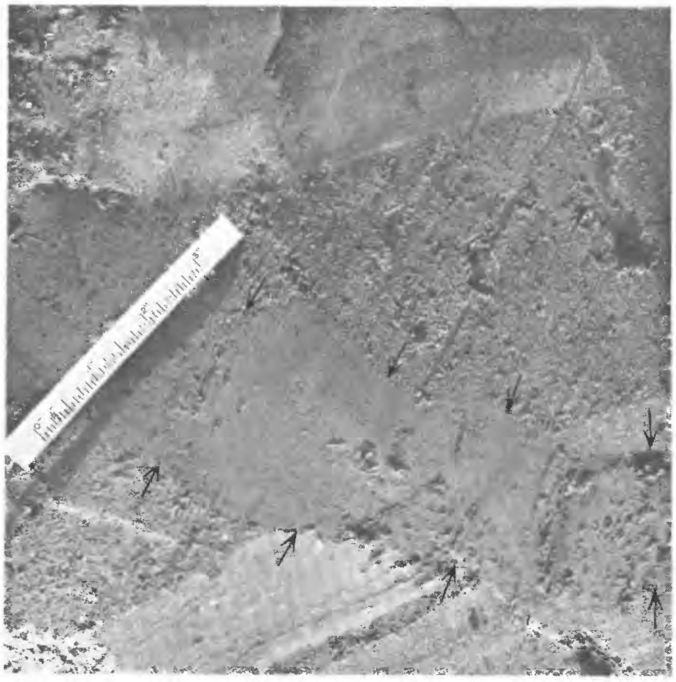


FIGURE 58.—Crack filled with massive sandy clay, Tumey Gulch fan. San Luis Canal station 2530 + 70R. Paired arrows end at sides of crack.

(linear feature normal to the trimmer marks), the crack is filled with clayey sand and sand. The hard hat in figure 59*A* is near the upper end of the crack. A view of the sand-filled part of the crack in the vicinity of the hard hat is shown in figure 59*B*. The crack width is about 2 inches in the foreground, but the crack pinches out rapidly upslope from the hard hat.

The particle-size distribution of samples collected from two parts of the crack shown in figure 59 are shown in figure 60 and table 3. The lower part of the crack consists of a poorly sorted mixture of sand, silt, and clay (sample 24). The upper part of the crack consists mainly of fairly well sorted sand, but about one-fourth of the sample from the crack filling consisted of poorly sorted silt and clay (sample 25). The massive nature of both the sand-silt-clay and the clayey sand suggests that the crack was filled rapidly after it opened.

Some of the crack fillings consist of extremely poorly sorted material, such as samples 22 and 28 in table 3 and figure 63. The crack filling from which sample 22 was obtained is shown in figure 61. This crack is as much as 6 inches wide, and the sides of the crack are lined with clay that is darker than the silty clay that fills the center of the crack. Although the crack cuts beds containing coarse grained sand and gravel, the crack filling does not contain particles larger than 0.5 mm (millimeter).

Fragments of organic matter were found in the cracks in several of the small fans. Fragments of cotton plants were found in some of the crack fillings in the Moreno Gulch fan. Pieces of reeds and unidentified organic fragments were found in the crack filling at station 2992B in the Arroyo Hondo fan and in a crack filling at station 2449+20 in the Tumey Gulch fan. The large pieces of organic matter commonly are surrounded by blue-green reduced clay.

Many of the cracks in the Arroyo Hondo and Arroyo Ciervo fans are filled with clay or sandy clay that contain mica oriented parallel to the crack sides. Even the cracks that had no visible laminations commonly had oriented mica. The mica was distributed uniformly both across and along the crack. The source of the mica most likely is mica-rich rocks within the source areas of the fans. The Etchegoin, Jacalitos, and parts of the Temblor Formations contain visibly large amounts of mica. These formations are common in the source areas of the Arroyo Hondo and Arroyo Ciervo fans, but are thin or absent in the source areas of the Tumey Gulch and Moreno Gulch fans. The presence of abundant mica in the crack fillings of some fans but not of others and the relation of the abundance of mica to

A

B

FIGURE 59.—Crack filling in the Tumey Gulch fan that changes from sand-silt-clay where exposed on the lower part of the slope to sand on the upper part of the slope. *A*, Crack filled with sand-silt-clay at station 2529 + 66R. *B*, Crack filled with clayey sand at station 2529 + 85R.

source-area lithologies indicates that the clay as well as the mica was derived from the same source materials as the fan deposits.

Medial partings, or stringers of sand or pebbly sand, are common in the clay-filled cracks of the small fans. An intermittent sand filling as much as 1½-inches wide in the center of a clay-filled crack is shown in figure 62. Parts of the clay seams on either side of the sand-filled center have medial parts of clayey sand. The clay contains mica that is oriented parallel to the crack sides.

Cumulative curves of a variety of crack-filling lithologies are shown in figure 63. Although the samples are from only the Tumey Gulch (samples 22, 23, and 26) and Arroyo Hondo (samples 28 and 29) fans, they are representative of the crack fillings in all four of the fans derived from the foothill belt. The only crack lithology not shown is gravel. Although cracks, or parts of cracks, that are filled with gravel were noted in all four fans, they are rare. Almost all of the crack fillings consist of poorly sorted materials and the main differences between fillings are the variations in the proportions of sand, silt, and clay. The proportions of sand, silt, and clay for eight samples of crack fillings are listed in table 3.

CAUSE OF THE CRACKS

As was true for the large fans, compaction due to wetting is the only hypothesis that fits the facts presently available for the cracks in the small fans. The arguments for the near-surface subsidence hypothesis,

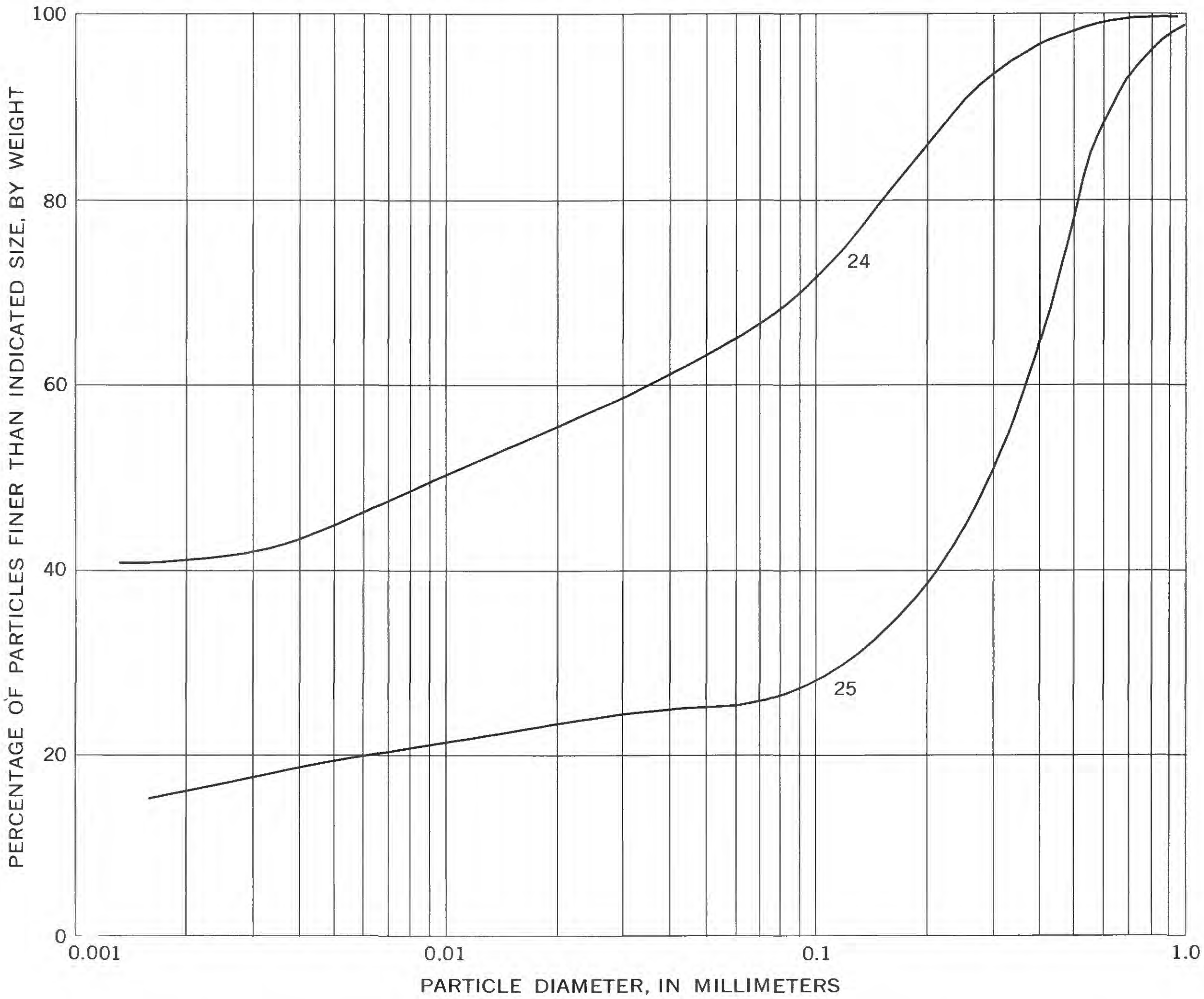


Figure 60.—Change in the particle-size distribution of material filling a single crack in the Tumey Gulch fan. Numbers adjacent to curves refer to samples in table 3.

and against the other hypotheses, are the same as those considered in detail in the section, "Possible Causes of the Cracks."

The following features of the cracks in the small fans were considered characteristic of near-surface subsidence cracks: the vertical nature of the cracks; the tendency of the cracks to narrow downward, narrow upward, or have parallel sides; the rough hackly break along the crack sides; the lack of offset bedding; the compressional forces that occur after the tensional forces; the change in the abundance of cracks on adjacent fans; the abrupt variation of density of spacing of cracks within a fan; the presence of parallel sets, and anastomosing, intercepting, intersecting, and en echelon crack patterns that have dimensions and frequency of occurrence similar to known near-surface subsidence cracks.

COMPARISON WITH THE CRACKS IN THE LARGE FANS

Most of the features of the cracks in the small fans are the same as those in the large fans. The main purpose of this section will be to discuss the differences in a few of the features. Features that generally are similar in both categories of fans are:

1. The occurrence of the cracks as vertical tension fractures with hackly breaks or undulating surfaces along their sides.
2. The orientation of most of the cracks roughly parallel to the radial lines of the fans in which they occur.
3. The variability and abrupt changes in the density of spacing of the cracks.
4. The predominance of clayey materials in most of the crack fillings, and the occurrence of sand in only a few cracks.

FIGURE 61.—Wide crack filled with silty clay. Tumey Gulch fan, San Luis Canal station 2311 + 26L.

FIGURE. 62.—Discontinuous sand filling in the center of a clay-filled crack. Arroyo Ciervo fan, San Luis Canal station 2820 + 80L.

5. The occurrence of cracks in parallel sets, and in anastomosing, intercepting, intersecting, and en echelon patterns.

The most striking difference between the cracks in the small and large fans is the difference in abundance of cracks. A density of spacing of one crack per 100 feet, or less, is common along the canal alinement in the small fans, whereas a density of spacing of five cracks per 100 feet is common along the canal alinement in the large fans.

Several alternative explanations are possible for the lower abundance of the crack fillings in the small fans. The possible explanations presented here will explain the differences in abundance primarily by postulating differences in the infiltration of water in different types of moisture-deficient deposits in the small fans, as compared to the large fans. Possible differences in the infiltration of water under both historic and prehistoric conditions will be considered. The time of wetting is discussed in the next section.

If most of the cracks on the small fans are the result of wetting of the moisture-deficient deposits during the past few decades, the infiltration of irrigation water to the fan deposits would contrast markedly with the infiltration of water to the large fans by prehistoric streamflow. Large areas on the small fans have been brought under irrigation at the same time. When a field that is a square mile in size is irrigated for the first time, the deposits tend to be wetted uniformly, and minimum differential settlement will occur. Differential settlement within the field is largely the result of differences in the permeability of the surficial materials, which partly control the rate of advance of the moisture front. Maximum differential settlement occurs along the ditches used to supply the fields because they contain water for a greater length of time than do the fields. Even in sprinkler-irrigated fields, the maximum differential settlement will be near the borders of the fields because the borders of the fields commonly are the boundaries between areas that are undergoing compaction due to wetting and areas that are not. The end result would be for a few cracks to open within a field, and for a greater abundance of cracks to open near the borders of fields that are being irrigated for the first time.

In contrast, the abundance of cracks would be much greater on the large fans, because large equidimensional areas would not be wetted at one time, and the wetting would require many periods of streamflow. Different sections of the fans would be wetted along radial lines as the stream changed position on the fan. Abundant cracks would form between the narrow wetted areas and the areas that remained stable.

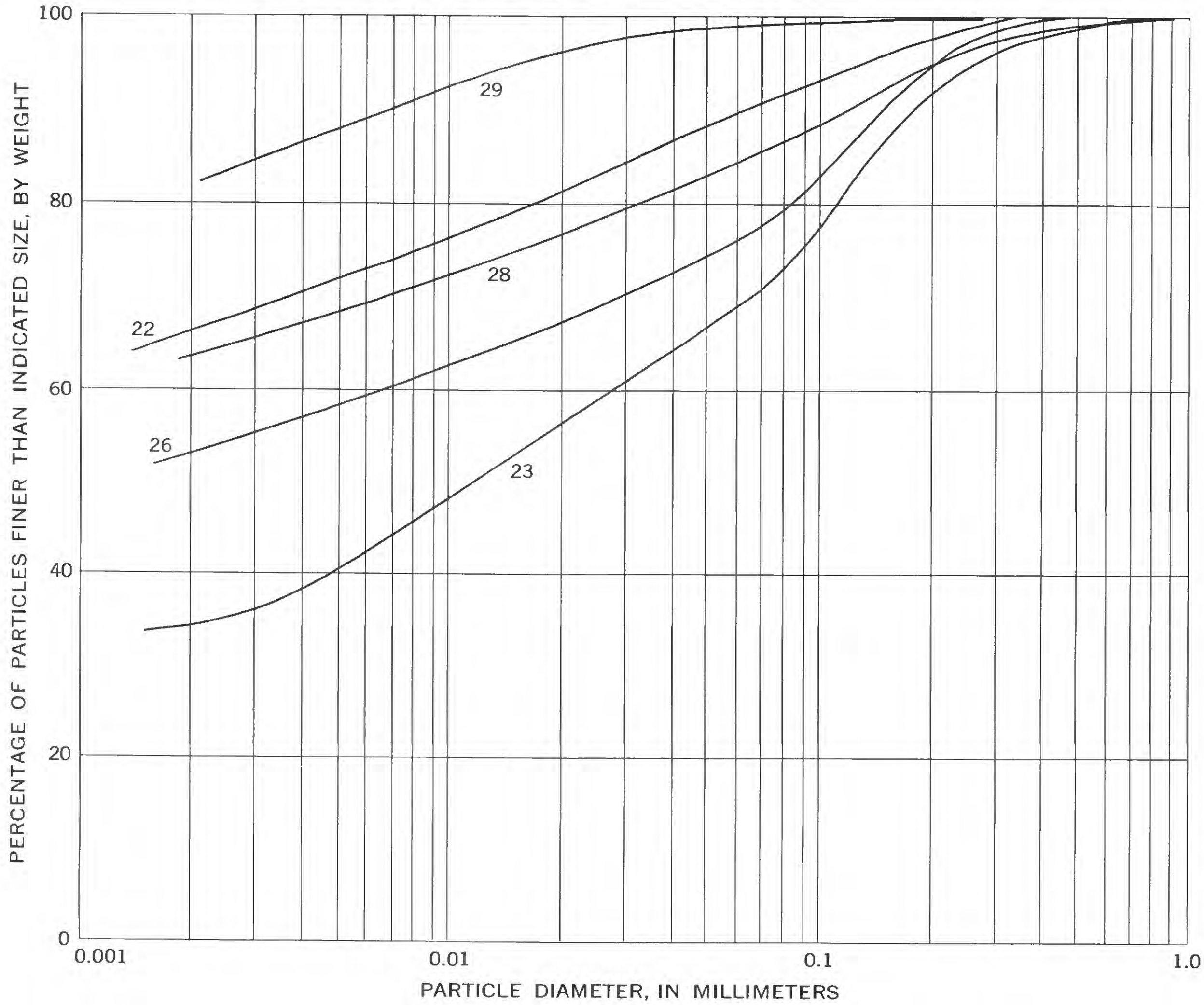


FIGURE 63.—Particle-size distribution of samples from cracks in the small fans. Numbers adjacent to curves refer to samples in table 3.

Consideration of the application of water by prehistoric streamflow to the moisture-deficient deposits of the small fans also can explain the low density of crack spacing. The presence of widespread historic near-surface subsidence and moisture-deficient deposits to depths of more than 300 feet indicate that little or no complete wetting of the deposits of the small fans occurred until the area was irrigated by man. However, some prehistoric cracks do exist in the fans, as will be shown in the next section. Local infiltration of prehistoric streamflow below the root zone, that wetted the deposits to sufficient depth to cause cracking, would account for many of the widely spaced cracks in the small fans.

Another possibility for the low abundance of crack fillings in the small fans might be that many historic cracks may open and close without being exposed to a source of sediment to fill them. Cracks that have closed adjacent to test plots commonly cannot be seen in excavations made across the crack, even when the trace of the rupture still is discernible on the surface.

Intersecting crack patterns are not as common in the small fans as in the large fans. The possibility of cracks intersecting is in part a function of crack abundance, which is low in the small fans. The difference also might be the result of more uniform application of water from irrigation, as compared to the nonuniform infiltration of water from prehistoric meandering stream channels on different parts of the large fans.

The crack fillings are distinctly wider in the small fans than in the large fans. Most of the crack fillings in the small fans are 1/2 to 3 inches wide and most crack fillings in the large fans are 1/8- to 1-inch wide. The reason for the difference in crack-filling widths of the two categories of fans is not known. The width of the cracks is, in part, a function of the magnitude of subsidence, and the width of the crack fillings is in part a function of the amount of deposition of material that occurs before the crack is closed by the compressional forces tending to rotate the blocks of alluvium between the cracks.

The strength of the alluvium also may affect crack width. The higher clay content of the deposits of the small fans may make the alluvium stronger than the deposits of the large fans. Evidence in support of this idea is the similarity of total crack width per 100 feet in the small and large fans. One 2-inch crack filling per 100 feet in the small fans would be the same as four 1/2-inch crack fillings in the large fans—both would be 2 inches of crack filling per 100 feet. Thus, the differences in the strength of the alluvium may partly explain the differences in both width and spacing of the crack fillings in the small and large fans.

In the large fans, cut-and-fill structures truncate the crack fillings beneath them in most places, but in the small fans, crack fillings extend through cut-and-fill structures in most places. Truncated crack fillings show that the cracks formed before the stream channel attained its deepest entrenchment. This truncation suggests that the cracks were formed and filled as a result of streamflow. Crack fillings that pass through buried stream channels show that compaction due to wetting did not occur as a result of streamflow during the course of channel entrenchment and that the compaction due to wetting occurred after the channel was backfilled by an aggrading stream. In many places, the crack fillings extend upward 5–10 feet into the bedded fan deposits overlying the buried stream channel.

Open cracks indicate a more recent time of crack formation than do completely filled cracks. Open or partly filled cracks in the large fans are virtually nonexistent. Open or partly filled cracks are rare in the small fans also, but they were found at several places in each of the small fans.

The crack fillings in the small fans contain coarser particles than do the crack fillings in the large fans. Even the massive crack fillings in the small fans that contain 55–85 percent clay generally contain coarse-grained silt and medium-grained sand. The finest-grained crack filling sampled from the small fans contained 86 percent clay and had a coarsest percentile of 65 microns. A possible reason for this crack filling not having sand is discussed on pages 71–72. In contrast, the samples of the five crack fillings from the large fans that did not have medial parts of sand and silt consisted entirely of clay and fine-grained silt. The coarsest percentile of these five samples ranged from 3.7 to 14 microns, and none of the samples contained particles larger than 20 microns.

The difference in the particle size of the materials in the crack fillings in the small and large fans may be the result of different crack widths and sources of materials to fill the cracks. The fine material filling the narrow cracks in the large fans has been concentrated by a process such as filtering of the sediment made available by the streams. The coarser grained material filling the wide cracks in the small fans is similar to finer grained sediments being deposited on the fans at the present time (Bull, 1964a, table 17, samples 7, 8, 10, 14, 42, 64, 65, 84, and 85). Sediment carried by irrigation water also may account for the types of materials found in the 1/2- to 3-inch cracks. Regardless of the mode of deposition of the crack fillings, it is apparent that they could be derived readily from local sources and be deposited in the cracks without filtering, in contrast to the material filling the cracks in the large fans. A partial filtering process may be responsible for part of the fine-grained nature of the crack fillings, but the extent of such filtering is not known.

AGE OF THE CRACK FILLINGS

The cracks in the small fans are both historic and prehistoric, but the proportions of both ages of cracks in individual fans cannot be determined with the same degree of certainty as for the large fans. Individual cracks can be shown to be historic or prehistoric, but the age of many cracks cannot be determined. One problem is that the proximity of the crack tops to the former land surface is not as well defined as for the large fans. Construction of ponds to eliminate near-surface subsidence before the canal was built resulted in disturbance of the fan deposits to variable depths.

Historic cracks are considered as those that resulted from infiltration of irrigation water, or from infiltration of water from ponding prior to canal construction. Prehistoric cracks are considered as those that resulted from natural streamflow before agricultural development of a fan.

HISTORIC

Evidence that some of the cracks have formed during the past few decades includes the following characteristics:

1. Fragments of cotton plants and reeds in the crack fillings.
2. Cracks that parallel former ditches.
3. Most of the cracks extend to the top of the bedded fan deposits.

4. No subsidence hollows are shown on the 5-foot contour interval maps made of all four small fans before agricultural development on the fans.
5. Crack fillings were not found in the banks of arroyos in the unirrigated areas of the small fans, even where the streams are entrenched as much as 40 feet into the fans.
6. Almost all the crack fillings are not truncated by the buried stream channels; instead, the cracks extend through the buried stream channels and into the overlying bedded fan deposits.
7. Open or partly filled cracks occur as much as 25 feet below the former land surface.

Description of most of these characteristics has been presented in the preceding sections, and most of the points need little additional comment.

The presence of reeds in the crack fillings is considered as evidence for historic near-surface subsidence because the environment was not suitable for growing reeds on the small fans until the last few decades. Sufficient water may have flowed on the small fans in prehistoric times to cause the formation of hollows that could have been filled with water. However, the seasonal nature of the rainfall would make water available for aquatic plants only during the winter months when low temperatures would not favor growth of reeds.

The ponds used to wet any remaining moisture-deficient deposits before canal construction were choked with lush growths of reeds and seem to be a much more likely source of the reed fragments found in the crack fillings in the Arroyo Hondo and Tumey Gulch fans. The preconstruction ponding caused 2–4 feet of near-surface subsidence along much of the canal alinement, and locally caused as much as 8 feet of near-surface subsidence (Richard Bateman, oral commun., May 26, 1967). The particle-size distribution of one of the crack fillings that contained reeds is shown in figure 63 and is listed in table 3 (sample 28). The preconstruction ponding resulted in both near-surface subsidence to account for the stresses to cause the cracks and a source of reeds to supply the organic matter found in the crack fillings.

The parallelism of the cracks with the alinements of former ditches was noted in many places, but many crack orientations do not have any apparent relation to former ditches. An example of a crack that parallels ditches is the crack at station 1797 on the Moreno Gulch fan (pl. 2A), which turns from a north-south strike to an east-west strike. This crack occurs near a former corner of a field that was irrigated with ditches and furrows. Clay-filled cracks that trend north-south in the Tumey Gulch fan, and which are less than 1 inch wide, are shown on plate 2C at stations 2542R and 2573R. These cracks are about the only cracks in 6,000 feet that roughly parallel the canal alinement. They also parallel and are near the alinement of a ditch that trended north-south in 1956. The clay-filled crack at station 2583+50R and the sand-filled crack at station 2565 also trend roughly north-south, and also may have been caused by subsidence related to flow in the same ditch.

PREHISTORIC

Despite the abundant evidence to show that many of the cracks have been formed and filled within the past few decades, there is good evidence that some cracks in the small fans were formed and filled as a result of prehistoric streamflow. Evidence for the prehistoric time of formation of some of the cracks includes:

1. The presence of individual cracks or sets of cracks that end below the top of the bedded fan deposits.
2. The orientation of most of the cracks is parallel to the radial lines—and the trend of the prehistoric stream courses—of the fans.
3. The presence of abundant cracks in that part of a small fan adjacent to a large fan.
4. The presence of cracks that end at the base of buried stream channels and are filled with bedded sand and gravel derived from the former stream channel.

The presence of cracks that end in funnel tops below the top of the bedded fan deposits shows that the cracks were formed before the area was irrigated and plowed. Examples of cracks with buried funnel tops in the Tumey Gulch fan are shown on plate 2C at stations 2568+62R, 2569+18R, and possibly 2584+20R.

Although most cracks extend to the top of the bedded fan deposits, sets of cracks can be found that terminate below the top of the bedded fan deposits. Sets of such cracks were observed in the Moreno Gulch and Tumey Gulch fans but not in the Arroyo Ciervo and Arroyo Hondo fans. Examples of buried sets of cracks in the Tumey Gulch fan are shown on plate 2C between stations 2545 and 2552, and stations 2566 and 2576. In each of these sets, one crack extends to the top of the bedded fan deposits.

Examples of cracks that are roughly normal to the canal centerline in the Moreno Gulch and Tumey Gulch fans are shown on plates 2*A* and 2*C*. However, some cracks that parallel former ditch sites, or contain organic matter such as reeds, also are roughly normal to the canal centerline, so this criterion should be used with caution when attempting to establish the ages of individual cracks.

The deposits in the small fans adjacent to the large fans were examined to determine whether prehistoric streamflow of the large streams had caused compaction due to wetting of the deposits in the adjacent small fans. Four locations where this type of prehistoric near-surface subsidence could have occurred are: the Moreno Gulch-Little Panoche Creek fan boundary. the Moreno Gulch-Panoche Creek fan boundary, the Tumey Gulch-Panoche Creek fan boundary, and the Arroyo Hondo-Cantua Creek fan boundary (pl. 1). The abundance and width of the cracks near the boundaries of the small fans were similar to the abundance and width of the cracks in the central parts of the small fans, except at the Arroyo Hondo-Cantua Creek fan boundary.

The Arroyo Hondo fan adjacent to the Cantua Creek fan contains hundreds of clay-filled cracks. For 2,000 feet adjacent to the Cantua Creek fan, the Arroyo Hondo fan has a density of crack spacing ranging from 10 to more than 50 cracks per 100 feet of canal alinement. The abundance of cracks in this reach is anomalous because the rest of the fan had fewer cracks than any other fan studied. The mean density of spacing of cracks in the rest of the Arroyo Hondo fan along the canal alinement is less than one crack per 200 feet. The cracks extend to the top of the bedded fan deposits.

The abundance of cracks in the Arroyo Hondo fan adjacent to the Cantua Creek fan is the result of a complex history of channel cutting and filling and of intertonguing deposition by the streams of both fans. The series of photographs in figure 64 shows the general relations at the fan boundary, the details of some of the channel cutting and filling, and clay-filled cracks. Two large buried channels are shown in figure 64*A*. Both channels are of a size typical of the buried channels observed in the Cantua Creek fan at this distance from the mountain front, and both are much larger than the channels of Arroyo Hondo found in the trimmed canal banks. Channel A was cut by Cantua Creek and was backfilled with sand and gravel containing serpentine fragments typical of 12 percent of the Cantua Creek source area. The top of the bedded fan deposits is approximately at the top of the finger drains. Location X is the same on all four photographs in figure 64.

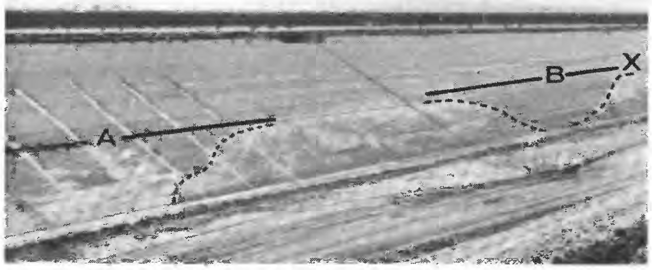
Channel B in figures 64*A* and 64*B* also was cut by Cantua Creek, as is indicated by its size and shape. The channel has been backfilled with material that is distinctly different than the material that fills channel A in figure 64*A*. Instead of water-laid sands and gravels, channel B is filled with clayey deposits, many of which appear to have been deposited by a more viscous mode of transport than the water-laid mode of deposition that filled channel A. Serpentine fragments were not found in the channel fill, although the bottom of the channel below the canal bottom may contain lag gravels with serpentine. The type of deposits indicates that the exposed part of the channel was filled with deposits from Arroyo Hondo.

Details of the channel and the cracks near location X in figure 64*B* are shown in figures 64*C* and 64*D* (the shovel shows the scale). A smaller cut-and-fill structure that has a size typical of the channels of Arroyo Hondo along the canal alinement occurs beneath the side of the larger channel cut by Cantua Creek. Both fine-grained channel fills are cut by many clay-filled cracks, as is the coarse-grained fill of channel A (fig. 64*A*).

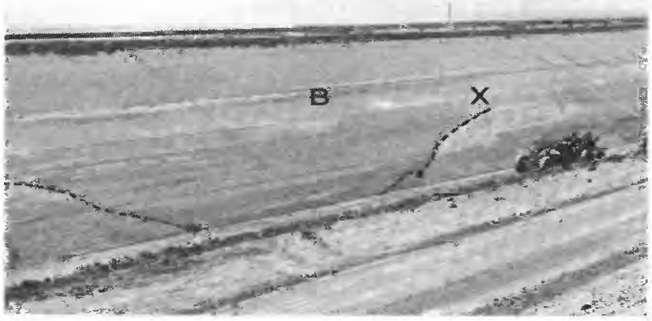
Not all channel entrenchment results in percolation of streamflow below the root zone of the plants growing in the channel bottom. For example, the channels of four of the small fans susceptible to wide-spread historic near-surface subsidence have been entrenched 20–40 feet during the past century (Bull, 1964c), but near-surface subsidence has not been observed along the channels.

The following history is postulated for this part of the Arroyo Hondo fan. Deposition by Arroyo Hondo of water-laid sediments, and deposits intermediate between water-laid sediments and mudflows, was interrupted occasionally by channel entrenchment (foreground of fig. 64*D*). Deposition by Arroyo Hondo was followed by encroachment of Cantua Creek. A period of channel cutting and filling by Cantua Creek made the cut-and-fill structure (fig. 64*A*, channel A). A second period of channel cutting by Cantua Creek made the channel shown in figure 64*B*; however, the channel was backfilled principally by Arroyo Hondo. The presence of clay-filled cracks in all the buried channel fills shown in figure 64 indicates that compaction due to wetting did not occur as a result of streamflow during the channel cutting and backfilling. The stream channels probably were cut by flashy flows of short duration that did not percolate down to moisture-deficient deposits.

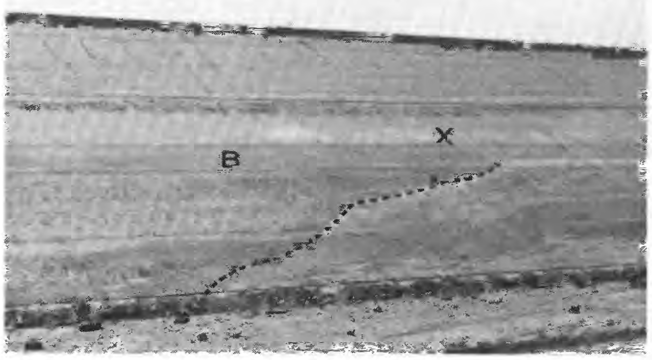
Backfilling of the second channel (channel B) was followed by deposition of about 10 feet of bedded fan deposits that covered all the preexisting channel fills. Most of the bedded fan deposits are fine-grained and appear to have been deposited by Arroyo Hondo. Near the end of the period of deposition of the bedded fan deposits, Cantua Creek again encroached onto the Arroyo Hondo fan but did not become incised into



A

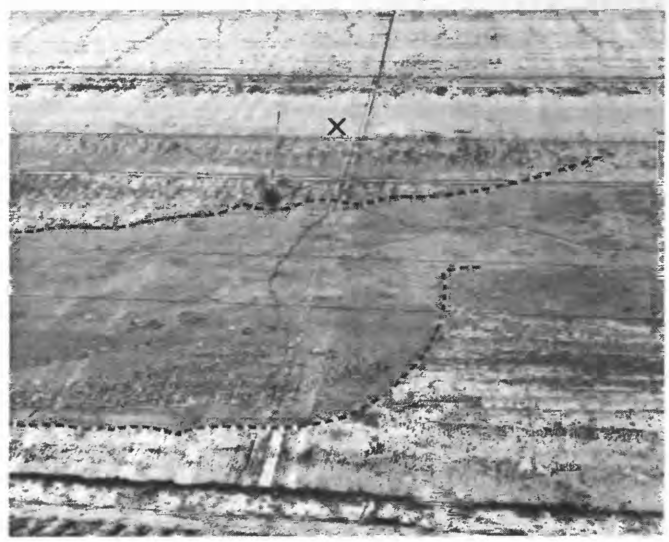


B



C

the fan—apparently the end of the fanhead trench of Cantua Creek was upslope from the canal alinement during this second period of encroachment. Periods of flow from Cantua Creek were sufficiently long to cause percolation of water below the root zone and compaction of the deposits. Near-surface subsidence lowered the surface of the Arroyo Hondo fan. This subsidence permitted Cantua Creek to encroach farther onto the fan. The present slope of the Arroyo Hondo fan surface, normal to the contours, is about 10 feet in 2,000, but small amounts of subsidence



D

FIGURE 64.—Prehistoric buried stream channels and near-surface subsidence cracks at the Arroyo Hondo-Cantua Creek fan boundary. Boundaries of buried channels are dotted. The point X is common to all four photographs. *A*, Buried channels cut by Cantua Creek. *B*, Channel cut by Cantua Creek and backfilled by flows from Arroyo Hondo. *C*, Multiple cut-and-fill structures made by Cantua Creek and Arroyo Hondo. *D*, Clay-filled cracks extending through multiple cut-and-fill structures.

would probably cause a substantial shift of the stream along the fan contour.

The particle-size distribution of a sample from a crack filling in the Arroyo Hondo fan near the Cantua Creek fan is indicative of a Cantua Creek source. Sample 29 (table 3) was the only sample analyzed from the small fans that had a lithology similar to that of the clay-filled cracks in the large fans. The sample contained 86 percent clay and had a coarsest percentile of only 65 microns.

Apparently the deposits were wetted to the water table which, in 1967, was about 200 feet below the land surface. Evidence supporting the depth of wetting and the prehistoric nature of the cracks is shown by the lack of visible subsidence due to agricultural operations on this part of the Arroyo Hondo fan, and the fact that this was the only part of the fan that did not subside as a result of preconstruction ponding along the canal alinement (Richard Bateman, oral commun., May 26, 1967). The surface of the area shown in figure 64 has a gentle slope typical of the Cantua Creek fan, and the contours merge smoothly with the Cantua Creek fan. However, Arroyo Hondo is depositing in this area again as is shown by aerial photographs taken in 1940 before agricultural development.

The last type of evidence for prehistoric cracks in the small fans is the presence of cracks that extend downward from the sides or bottoms of stream channels that are filled with bedded sediments similar to those in the buried channel. The only cracks of this type were found in the Tumey Gulch fan.

Near station 2545 in the Tumey Gulch fan (pl. 2*C*), two cracks are associated with a buried stream channel, the top of which is buried by 8 feet of bedded fan deposits. A clay-filled crack at station 2545+30 extends a few feet above the bottom of the channel fill and is truncated. At about the same level as the truncated top, a second crack at station 2545+40 extends to the side of the buried channel, but not into the channel fill. The upper 5–8 feet of the southern crack is filled with bedded clayey sand and gravel similar to the channel fill. Farther down the trimmed slope, the crack is filled with sandy clay. The following sequence of events at this site seems likely. Streamflow percolated deep enough to produce compaction and cause the crack that extends upward into the channel fill. Sandy clay derived from subsequent streamflows filled the crack. Continuing compaction caused the second crack to open at the side of the channel at about the same level as the truncated top of the first crack. Fine and then coarse water-laid sediment was carried directly from the stream into the open crack. The channel was then backfilled and covered with bedded fan deposits.

A crack filling that extends down from the side of a buried channel at station 2548 +75 is shown in figure 65 and plate 2*C*. The channel is narrow near its deepest part, but widens near its top and extends to the top of the bedded fan deposits. The bottom of the channel is filled with lag gravel, and clayey bedded deposits fill the rest of the channel. Upslope from the mattock (to the left), a bed of clayey sand in the channel is exposed in arcuate fashion on the trimmed slope, and is overlain by bedded clayey gravel. In the foreground, to the right of location A, the arcuate bed of clayey sand is breached and a crack filling extends down the canal slope past the bottom of the buried channel. The top of the crack is filled with clayey gravel that is similar to that in the channel immediately above the crack top. The crack filling under the clayey gravel consists of sandy clay, and the crack filling at the base of the canal bank consists of sand-silt-clay. A sample of sand-silt-clay with 22 percent sand was collected from the crack filling at location B (fig. 65). The particle-size distribution of the sample is shown in table 3 (sample 27).

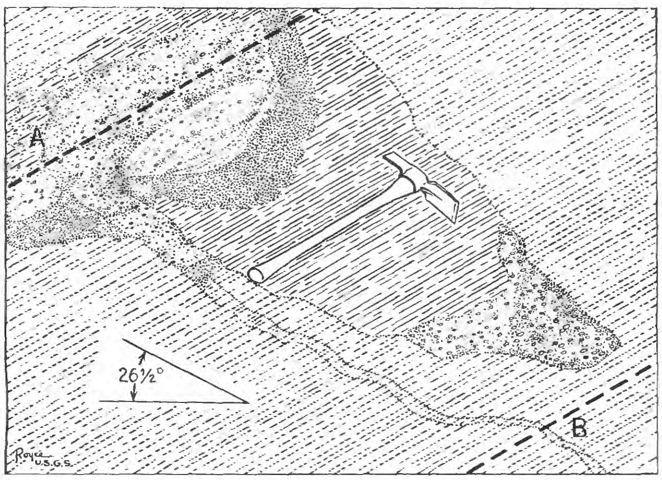
The following sequence of events is postulated for the near-surface subsidence crack shown in figure 65. The channel was entrenched and backfilled to the top of the arculate clayey sand bed above the mattock. Compaction associated with infiltration that occurred during the trenching and partial backfilling caused a crack several inches wide to open and rupture the arcuate clayey sand bed. Subsequent flows in the channel allowed bedded sediments to be deposited in the crack. Movement of water-transported material down the crack rounded the lip of the arcuate sand bed adjacent to the crack. Clayey gravel was deposited in the stream channel and the top of the crack, and backfilling continued to the fan surface.

Because the channel at station 2548 +75 extends to the top of the bedded fan deposits and the buried channel at station 2545 +25 extends to within 8 feet of the top of the bedded fan deposits, the possibility of crack formation after agricultural development of the area should be considered. The topographic surveys of 1921 show that these stations are at the south side of the area of 1921 deposition on the Tumey Gulch fan. The end of the Tumey Gulch fanhead trench in 1921 was 4 miles due west of the canal stations. Downstream from the end of the fanhead trench, a network of braided distributary channels 2–4 feet deep spread out on the fan. One of the braided distributary channels extended to within 3,000 feet of the buried channels at the canal stations, and the backfilled downslope extension of the distributary channel extended downslope as a channel ridge that passed directly over the buried channel at station 2545+25.

It appears that the two buried channels discussed above were part of former distributary channels that were entrenched temporarily during a wet period and then were largely or completely backfilled. The period of wetting was sufficiently long to cause local compaction of the fan deposits and to produce the cracks. The cracking occurred before the agricultural development of the area in the late 1940's, and it is concluded that the cracks associated with the channels are prehistoric.

In summary, good evidence exists to show that some cracks, or sets of cracks, in the small fans are historic, and that others are prehistoric. However, the time of formation of many cracks cannot be determined with confidence. In contrast to the cracks in the large fans, which are virtually all of prehistoric origin, large numbers of both historic and prehistoric cracks occur in the deposits of the small fans. Also, the proportion of identifiable historic to prehistoric cracks in each of the small fans appears to be different. Prehistoric

A



B

FIGURE 65.—Crack filling extending down from the side of buried stream channel in the Tumey Gulch fan, San Luis Canal station 2548 + 75. *A*, View looking diagonally down the trimmed canal bank. Three-foot mattock handle is parallel to overall fan bedding. Arrows end at sides of crack and funnel top. *B*, Isometric diagram of channel and crack filling; heavy lines are parallel to canal centerline. Drawn by M. E. Royce from photographs.

cracks appear to be more abundant in the fans of Moreno and Tumey Gulches, and historic cracks appear to be more abundant in the fans of Arroyo Ciervo and Arroyo Hondo (excluding that part of the Arroyo Hondo fan adjacent to the Cantua Creek fan).

Prehistoric near-surface subsidence may partly explain the hummocky, irregular topography that is typical of fields in areas of historic subsidence after several years of agricultural operations. Even partial prehistoric wetting and compaction of moisture-deficient deposits, and subsequent filling of local subsidence hollows, would tend to produce high areas in fields in which all the deposits are now being wetted.

HISTORY OF ACCUMULATION AND WETTING OF THE MOISTURE-DEFICIENT DEPOSITS

The presence of near-surface subsidence implies a long period of deposition, during which water from streamflow or rainfall does not percolate below the root zone, followed by a period during which water percolates below the root zone. The occurrence of more than 200 feet of moisture-deficient deposits in the small fans indicates that water did not percolate below the root zone during times of glacial and lacustrine expansion during the Pleistocene.

The thickness of moisture-deficient deposits needed to cause a given amount of near-surface subsidence can be estimated by laboratory and field tests, and the age of the deposits can be estimated on the basis of rates of accumulation of the alluvial-fan deposits. The times of wetting of the deposits to cause the subsidence and the cracking in the small and large fans is evaluated mainly by study of the depth of burial of the cracks.

THICKNESS OF MOISTURE-DEFICIENT DEPOSITS NEEDED TO CAUSE THE ESTIMATED NEAR-SURFACE SUBSIDENCE IN THE LARGE FANS

Evidence for prehistoric subsidence in excess of 5 feet was found in the Los Gatos and Panoche Creek fans, and it is probable that as much as 10 feet of near-surface subsidence occurred on the large fans as a result of water percolating from prehistoric streamflows. A minimum of 5 feet of prehistoric near-surface subsidence will be used to estimate the minimum thickness and age of the formerly moisture-deficient deposits in the large fans. Consideration of the effect of overburden load and lithology on the magnitude of compaction due to wetting provides a means of estimating the number of feet of moisture-deficient deposits necessary to cause 5 feet of near-surface subsidence on the large fans.

The magnitude of near-surface subsidence is in part dependent on the amount of overburden load present when water percolates through the moisture-deficient deposits for the first time since burial. Compaction due to wetting does not occur until a critical overburden load is present. The deposits are thoroughly wet when first deposited, but an overburden load is not present. The amount of voids in a deposit of a given lithology is largely a function of the moisture content and lithology. A freshly deposited sediment rapidly attains an equilibrium condition regarding its volume of voids between its high moisture content favoring the collapse of voids and low load favoring preservation of voids. Post-depositional drying of the fan deposits reduces the moisture content, and increases the competence of the deposits to retain the voids still remaining. If the deposits have been covered by only a few feet of subsequent deposition, compaction due to wetting will not occur if the deposits are wetted again. For example, initial wetting of test plots caused the surface to rise slightly for 1–3 days because of unconfined swell of clay in the surficial deposits. As the water percolated to greater depths, the overburden load increased and eventually a depth was reached—the critical depth—where the overburden load was sufficient to cause a net compaction of the deposits being wetted. Below the critical depth, deposits of a given intergranular porosity and clay content will undergo a greater percentage of compaction due to wetting with increasing overburden load.

The best means of estimating the thickness of moisture-deficient deposits necessary to cause the minimum of 5 feet of prehistoric compaction due to wetting on the large fans is the graph showing the effect of overburden load on compaction due to wetting (fig. 3). The percentage of compaction due to wetting at Inter-Agency test plot B on the Arroyo Ciervo fan increased from 5½ percent for the 25- to 60-foot depth zone to 9 percent for the 75- to 100-foot zone. The graph shows that about 65 feet of deposits were wetted in order to cause 5 feet of near-surface subsidence.

The estimate of 65 feet as the minimum amount of moisture-deficient deposits needed to cause 5 feet of near-surface subsidence in the large fans has to be evaluated regarding the difference in the overall clay content of the deposits beneath test plot B and those in the large fans. The deposits beneath test plot B contained about 18–22 percent clay, as compared to a mean clay content of 10–20 percent for the deposits of the large fans along the canal alinement.

The effect of clay content on the general magnitude of compaction due to wetting (fig. 4) shows that, under hygroscopic moisture conditions, deposits with clay contents of 10–20 percent undergo more compaction due to wetting than deposits with 18–22 percent clay. The values of compaction due to wetting in figure 4 are minimum values because large voids or zones of weakness, such as buried but unfilled polygonal cracks and rodent burrows filled with loose debris, could not be tested in the consolidometer. The samples tested in the consolidometer were taken from the areas of present-day deposition on both the small and large fans.

The curve in figure 4 is the air-dry end member of a family of curves relating compaction due to wetting, clay content, and moisture conditions. The change in load from surficial loading conditions to a simulated overburden load of 50 feet represents a constant change in load for the samples tested. The other end member of the family of curves would be at a moisture condition of about field capacity where 100 percent of the compaction due to wetting should have occurred. The moisture condition of the moisture-deficient deposits in western Fresno County is about half of field capacity—at about the wilting coefficient. Deposits with wilting-coefficient moisture content will compact less when wetted than will deposits with hygroscopic moisture content, assuming a given clay content and overburden load. The peak of the curve in figure 4 indicates that the optimum clay content for compaction due to wetting, when the moisture condition is changed from hygroscopic to field capacity, is roughly 12 percent clay. The peak of the curve for compaction due to wetting when the moisture condition is changed from wilting coefficient to field-capacity conditions is of smaller magnitude, and occurs at a larger clay content than the peak of the curve shown in figure 4. A shift in the peak of the curve shown in figure 4 from about 12 to about 18 percent, as a result of the difference between the compaction properties of deposits with hygroscopic and wilting coefficient conditions would make the unit compaction of the moisture-deficient deposits in the two classes about the same. The mean compaction due to wetting for deposits with 10–20 percent clay would be slightly to the left of the peak of the curve, and the mean compaction due to wetting for deposits with more than 20 percent clay would be slightly to the right of the curve. On the basis of this assumption, it is concluded that 65 feet is a reasonable approximation of the minimum thickness of moisture-deficient deposits needed to cause 5 feet of near-surface subsidence on the large fans.

Another reason for regarding the 65-foot thickness approximation as a minimum is that the large fans contain beds of clean sand that have less than 5 percent clay—beds that will compact only to a minor extent upon wetting. In contrast, clay is more uniformly distributed in the small fans and most of the sand beds contain more than 5 percent clay, and therefore undergo larger amounts of compaction due to wetting for a given overburden load.

AGES OF THE MOISTURE-DEFICIENT DEPOSITS IN THE LARGE AND SMALL FANS

The time required to deposit 65 feet of moisture-deficient deposits can be estimated by determining the rates of alluvial-fan deposition above the Corcoran Clay Member of the Tulare Formation. Fortunately, the age of the top of the Corcoran lake clay, the age of a young lake clay, and the thickness of the fan deposits have been determined. The mountain uplift and the dating of the deposits that have accumulated during the last 600,000 years are described in detail by W. B. Bull in a manuscript on prehistoric soil moisture and late Quaternary climatic changes in central California. The rates of deposition are summarized briefly here.

Uplift of the Diablo Range has increased the rate of alluvial-fan deposition since Corcoran time, as is shown by the depths to radiogenically dated lake clays (Janda and Croft, 1967; Croft, 1968). The mean rate of alluvial-fan deposition along the canal alinement for the last 600,000 years was about 1.0 foot per thousand years. The mean rate near the valley trough during the last 27,000 years was about 1.8 feet per thousand years—a rate that was almost twice the mean rate for the past 600,000 years.

The boundaries of the alluvial fans have shifted eastward since Corcoran time. Immediately after Corcoran time, the Diablan fans had only 60 percent of their present area, and Sierran alluvium was being deposited within 10 miles of the present eastern boundary of the Coast Ranges. The increases in fan area and rate of deposition indicate a fivefold to eightfold increase in the sediment yield of the Diablo Range since Corcoran time.

By using several different types of data, Bull estimated the changes in the rates of accumulation of the 400–900 feet of fan deposits above the Corcoran. For most of the purposes of this paper, however, only approximate dates are needed for the time required to accumulate deposits less than 100 feet thick.

The short-term rates of deposition while a stream is on a given radial line of a fan are much larger than the long-term rates for the entire fan. During winters of repeated flooding, as much as 1–2 feet of deposition may occur locally on the fans. A row of heavy metal fence posts across the depositional area on the Arroyo Hondo fan was buried as much as 5 feet during the 1924–64 period. This burial of the posts indicates a local rate of deposition of as much as 1.2 feet per decade. A radiocarbon age determination (Rubin and Corrine, 1960, p. 156, sample W–793) from a hearth near the apex of the Arroyo Hondo fan at a depth of 10.5 feet gave an age of 1,040 ± 200 years. The date indicates a mean rate of deposition of about 1.0 foot per 100 years. Studies by Bull (1964a, p. 38, 39) indicate that the Arroyo Ciervo basin is being denuded at a rate of about 2 feet per thousand years—a rate that is compatible with the mean depositional rate on the fan of 1.0–1.5 feet per thousand years during the last 600,000 years. The fan is larger than the drainage basin (table 1).

The mean rates of accumulation of deposits on the small fans (1.0–1.5 feet per 1,000 years) have been more rapid than the mean rates of deposition on the large fans (0.8–1.2 feet per 1,000 years) during the last 600,000 years. The differences in the rates of accumulation appear to be the result of differences in the erodibility of the rocks, degree of vegetative cover, and the amounts of tectonic uplift within the two types of source areas.

Along most of the canal alinement on the large fans, the mean rate of deposition during the last 600,000 years has been between 1.0 and 1.25 feet per thousand years. Because of the accelerating depositional rates, a rate of 1.4 feet per thousand years was arbitrarily selected as the maximum rate of deposition for the upper 100 feet of fan deposits in the areas in which the cracks were studied.

The minimum time needed to deposit 65 feet of moisture-deficient deposits on the large fans is estimated to be roughly 45,000 years. This is the minimum estimated time needed to accumulate 65 feet of deposits to cause 5 feet of prehistoric near-surface subsidence. The time needed to accumulate sufficient deposits to cause 10 feet of subsidence on the large fans would approach 100,000 years. The minimum date shows that the moisture-deficient deposits on the large fans are much older than 10,000 years and therefore were accumulating on the fans of the present-day intermittent streams during periods of glacial and lacustrine expansion during the Wisconsin Glaciation.

The time needed to accumulate the known thicknesses of moisture-deficient deposits on the small fans is even larger, despite the more rapid rates of deposition on the small fans. Thicknesses of moisture-deficient deposits in the Arroyo Ciervo and Tumey Gulch fans exceed 300 feet. Using a large arbitrary depositional rate of 1.5 feet per thousand years, 200,000 years would be necessary to accumulate the moisture-deficient deposits on the small fans. This is one-third of the time since the Corcoran pluvial period, and includes much of late Pleistocene time.

CHANGE IN STREAMFLOW ON THE LARGE FANS

Uplift of the Diablo Range also has tended to change precipitation runoff, and streamflow characteristics, particularly in the main range which forms the crest of the Coast Ranges. At least 2,000 feet of uplift of parts of the Diablo Range would tend to increase the mean annual precipitation in the drainage basins of the large fans. Storm durations would be longer at the higher altitudes than before uplift, and increased runoff from overland flow during and immediately after rainstorms would cause longer periods of streamflow than before uplift. The increase in mean annual precipitation, and the increase in the proportion of precipitation falling as snow, would increase the amounts of water infiltrating into the hillslopes and eventually contributing to an increased base flow of the streams of the large fans.

A change in streamflow characteristics caused the prehistoric near-surface subsidence. The presence of moisture-deficient deposits in the large fans in the past indicates that earlier in the fan history, streamflow was ephemeral instead of intermittent. As uplift of the Diablo Range continued, streams that were ephemeral gradually tended to become intermittent in their flow characteristics. A recent climatic change, perhaps in part locally due to the increased height of the mountains, initiated deep percolation of streamflow into the large fans to cause the prehistoric compaction due to wetting. At the present time, streamflow on the large fans is intermittent—the streams flow across the fans for weeks at a time during some winters of above-normal precipitation.

A gradual overall trend toward greater aridity in the San Joaquin Valley part of the study area is suggested by decreasing moisture in the accumulating moisture-deficient deposits during the last 200,000 years. It is not known how much of this trend toward greater aridity is the result of regional climatic change and how much is the result of rain-shadow effects created by the rising Diablo Range. However, the evidence presently available indicates that the net effect of several concurrent changes has been an increase in precipitation in the drainage basins of the large fans, and an increasing tendency toward intermittent streamflow.

Superimposed on the long-term trends of increasing precipitation and streamflow have been short-term variations of precipitation and streamflow. Changes in stream discharge have caused repeated temporary channel entrenchment, lasting for a few decades or centuries (Bull, 1964c). Changes in the magnitudes of discharges during the different periods of channel entrenchment can be evaluated on the basis of stream-channel geometries in the upper 30 feet of fan deposits as exposed in the canal banks. Major changes in channel width and depth were noted between adjacent fans, but within a given fan, the channel depth and apparent width are remarkedly uniform. Thus, the magnitudes of stream discharges during times of channel entrenchment appear to have been roughly the same during the time of deposition of the upper 30 feet of deposits.

TIMES OF WETTING OF THE MOISTURE-DEFICIENT DEPOSITS IN THE LARGE AND SMALL FANS

The period associated with the wetting of the large fans was wetter than the wet periods during most or all of Wisconsin Pleistocene time, because it was sufficient to cause compaction due to wetting—an event that streamflows were unable to do during the accumulation of the moisture-deficient deposits. At least several thousand years were needed to wet the large fans, because of the large thicknesses of deposits to be wetted, and because of the time involved between shifts of the stream from one part of the fan to another. Wetting was largely completed by the time man began agricultural operations in the area, as is indicated by the small areas affected by historic near-surface subsidence on the large fans.

The best indication of the times of wetting of the large fans is the proximity of the tops of the cracks to the land surface. Along most of the canal alinement, the cracks are buried 4–8 feet below the land surface, but locally they are buried as deeply as 10–15 feet. In other reaches, they extend to the base of the tilled zone. The variable depth of burial also indicates that considerable time was needed to wet the fan deposits.

Because the cracks are buried to depths of only 4–15 feet along most of the canal alinement on the large fans, depositional rates cannot be used to provide accurate dates of the times of burial of the cracks at individual sites. Short-term depositional rates could account for 10 feet of deposition at a single locality in a time span of 1,000 years, or less.

Although 15 feet of deposition can occur along a single radial line within a short time, the rates of overall deposition on the fan are much slower because of the time needed to lay down a fanwide relatively uniform thickness of material by successive deposition along many radial lines as the stream channel shifts to different parts of the fan.

Long-term rates of deposition are more appropriate than short-term rates for estimating the maximum time needed to accumulate the small thicknesses of deposits above the crack tops. The occurrence of depths of burial of more than 5 feet on many parts of the large fans precludes the possibility that wetting began only a few centuries ago. The lack of depths of burial of more than 15 feet suggests that wetting began in recent geologic time.

In the following discussion, reasonable estimates of the times of wetting will be made for the large and small fans, and the times of probable wetting will be compared with a radiocarbon age determination for the time of wetting of a crack in the Cantua Creek fan.

The time of earliest wetting on the large fans is indicated by the maximum depth of burial for cracks over a reach of 1,000 feet or more. The maximum depth of burial was on the Panoche Creek fan and was 10–15 feet below the land surface (fig. 27). This part of the Panoche Creek fan is a topographic high, as is shown by the cross-fan profile in figure 53. The maximum depth of burial of cracks for those parts of the fan that do not have channel ridges is about 8–10 feet. If the mean rate of deposition was between 1.1 and 1.4 feet per thousand years, the cracks whose tops are 10 feet below present land surface had been opened, filled, and truncated between 7,000 and 9,000 years before present. Thus, we can conclude on the basis of mean rates of deposition for entire fans, that the time of initial wetting is not older than 10,000 years, and may be much less than 10,000 years if locally the rates have exceeded the long-term mean rates of deposition.

The presence of variable depths to the top of the zone of cracking, that range from the base of the tilled zone to depths of as much as 15 feet, indicates that wetting has continued to the present time, as the loci of streamflow and deposition shifted on the large fans.

A radiocarbon age determination of carbonized wood from a crack filling also provides evidence for compaction due to wetting since 9,000 years ago, as well as showing that a particular crack is prehistoric. The crack is at station 3485 + 50R, in the zone of coalescence between the alluvial fans of Cantua and Salt Creeks. The crack top is truncated about 3 feet below the precanal-construction land surface. Aerial photographs taken before agricultural development of the sample location do not reveal the presence of former braided distributary channels. The lack of channels indicates that sufficient time has passed since the stream last flowed on this part of the fan to permit obliteration of the shallow stream channels. The poorly sorted material filling the crack includes pieces of diatomaceous shale and fragments of carbonized wood in a matrix of sand and clay. The age of the carbonized wood fragments that were washed into the crack provides an approximate date of the time of rupture of the enclosing deposits. The enclosing deposits do not contain visible carbonaceous material. Fragments of carbonized wood were collected from the crack filling at depths of 13–18 feet below the land surface by J. O. Berkland. A radiocarbon age determination, made by Meyer Rubin of the U.S. Geological Survey, shows that the carbonized wood is 5,180 ± 600 years old. The carbonized wood is U.S. Geological Survey Radiocarbon Laboratory sample W–2086. The large plus-minus figure is the result of dilution of the sample that was necessary to make the analysis.

The oldest prehistoric cracks in the small fans appear to be roughly the same age as the oldest cracks in the large fans. Most of the cracks extend to the top of the bedded fan deposits, which makes it difficult to determine whether they are historic or prehistoric. The maximum depth of burial below the top of the bedded fan deposits is only 8–10 feet and is under a channel ridge. The maximum depth of burial of crack tops on those parts of the fans not under channel ridges is 6–7 feet below the top of the bedded fan deposits. If 2–4 feet is used as an estimate of the distance between the top of the bedded fan deposits and the former land surface, the oldest cracks occur 8–11 feet below the fan surfaces. A mean depositional rate of 1.5 feet per thousand years was used for the overall rate of fan deposition for these deposits along the canal alinement. The estimate of the earliest time of wetting on the small fans would be sometime between 6,000 and 9,000 years before present.

Other than the cracks that are buried about 8–11 feet below land surface in the small fans, very few cracks are found that terminate below the top of the bedded fan deposits; almost all the cracks extend to the top of the bedded fan deposits. Thus, in contrast to the large fans, there is no evidence of continued wetting as a result of streamflow between the time of initial wetting and the time represented by the deposits in the 2- to 4-foot-thick zone below the present surface that has been disturbed by man's activities.

The occurrence of one brief period of wetting of the small fans is in accord with the fact that nearly all of the near-surface subsidence on these fans has been the result of man's activities, and that only small local areas of the fans experienced prehistoric near-surface subsidence.

The estimates of the time of initial prehistoric wetting of the moisture-deficient deposits on the large and small fans suggested that the period of increased streamflow may have occurred in the early part of post-Wisconsin time. If the time of initial wetting occurred in the early post-glacial times, compaction due to wetting would have begun on the fans during the humid, cool Anathermal time (7,500–10,000 years before present) of Antevs (1955).

The presence of a dated crack at 5,180 ± 200 years before present, not only shows times of wetting after Anathermal time, but also indicates at least one period of sufficient wetness to cause compaction due to wetting during the warm dry Altithermal time (4,000–7,500 years before present) of Antevs. Data collected by other workers (Martin, 1963; Mehringer, 1967) suggest that postglacial climatic variations may be more complicated than suggested by the simple three-part classification of Antevs. Mehringer (oral commun., Jan. 30, 1969) also has found evidence for a period of higher effective moisture in the Mojave desert of California, starting about 5,000 years ago, as indicated by radiocarbon and pollen data.

SUMMARY AND CONCLUSIONS

The practical importance of this study of tension cracks in alluvium was to determine their origin and time of occurrence, as an aid for construction and maintenance plans for the San Luis Canal and other parts of the California Aqueduct. It is concluded that the cracks were the result of near-surface subsidence—a type of subsidence that has proved very costly to agricultural and engineering operations within 100 square miles of the study area. However, the evidence summarized below provides ample proof that the cracks in the large fans are not the result of man's activities, but instead are prehistoric; being the result of compaction due to wetting caused by water percolating from prehistoric streamflows. The possibility of future near-surface subsidence causing serious damage to the San Luis Canal section of the California Aqueduct is slight, because almost all the cracks in the large fans are prehistoric, and because the canal alinement on the small fans was wetted thoroughly by ponding before construction of the canal. The small pockets of moisture-deficient deposits left in the large fans as a result of erratic prehistoric percolation from the streams probably have been wetted and compacted during the 20 years of irrigation, as is indicated by water-table rise in part of the area.

In an earlier paper of this series (Bull, 1964a), the magnitude, extent, and rate of compaction of certain small fans due to wetting by man were described in detail, but the cracks associated with near-surface subsidence were described only as exposed on the land surface, or in shallow excavations. In this paper, the amounts of compaction due to wetting are only estimates, even in areas of widespread historic near-surface subsidence, and the cracks studied are not exposed on the land surface. Construction associated with the San Luis Canal section of the California Aqueduct, and channel entrenchment by Los Gatos Creek during the past decade provided ample opportunity to study the filled cracks to depths of as much as 30 feet below land surface. As a result, our knowledge of near-surface subsidence has been increased greatly, and the earlier hypothesis concerning the process of cracking has been confirmed and expanded. The earlier paper discussed the subsidence; this paper adds to the fundamental background regarding near-surface subsidence in western Fresno County by discussing the filled subsidence cracks, and the extent and times of prehistoric near-surface subsidence.

One major conclusion of this paper is that extensive prehistoric near-surface subsidence occurred on the large alluvial fans—fans that in previous studies did not appear to have been subject to widespread historic compaction due to wetting.

The near-surface subsidence cracks in both the large and the small fans:

1. Consist of tension cracks between blocks of alluvium that have rotated and settled in response to gravitational stresses produced by compaction of the underlying and adjacent alluvium.
2. Have undergone tensional opening followed by compressional closing and have little or no offset of the bedding on opposite sides of the cracks, where uniform wetting of the moisture-deficient deposits has occurred.
3. Are vertical and discontinuous; have rough hackly fractures along their sides; have a highly variable density of spacing; occur in parallel sets; and have anastomosing, intersecting, and en echelon patterns.

Crack widths and patterns are functions of factors such as the magnitude of subsidence and the strength of the dry deposits overlying the seepage bulb. The width of a crack filling is, in part, a function of the amount of material deposited in the crack before rotation of the adjacent block of fan deposits closes the crack. Crack spacing is a function of the thickness of moisture-deficient deposits above the seepage bulb at the time of cracking, and the strength of the alluvium. Crack spacing increases with increasing thickness of the moisture-deficient deposits above the seepage bulb, and with increasing overall strength (clay content) of deposits.

The mean crack spacing in the small fans generally is less than one crack per 100 feet, and even in reaches of moderately abundant cracks, the spacing is only about one to two cracks per 100 feet of canal length. The total crack width per unit distance is similar to the total crack width per unit distance in the large fans, because the mean crack width in the small fans is several times that in the large fans (one 2-inch crack filling per 100 feet in a small fan would have the same total crack width as four ½-inch crack fillings in a large fan). The greater strength of the more clay-rich alluvium in the small fans may partly explain some of the differences in width and spacing of crack fillings in fans of different lithologies.

The primary crack patterns are largely a function of the depth and position of one or more seepage bulbs. Intersecting cracks are the result of compaction associated with more than one seepage bulb. Differences in the depths of burial of the tops of two sets of intersecting cracks are indicative of different times of wetting, and the inability of a single period of wetting to completely wet the moisture-deficient deposits. En echelon cracks are indicative of torsional forces, and commonly are near changes in direction of cracks. Intercepting cracks may be either primary or secondary.

Secondary crack patterns are mainly the result of fracturing and slumpage after the primary cracks have opened. Anastomosing patterns form as a result of fracturing of most of a block between two primary cracks. Abrupt changes in crack width occur as a result of part of the material adjacent to a crack being downdropped as a secondary block into the crack.

A significant difference between the cracks in the large and small fans is the lithology of the crack fillings. Most of the cracks are filled with clayey materials. However, the cracks in the large fans commonly do not contain particles larger than 20 microns, whereas the crack fillings in the small fans commonly have 15–35 percent sand distributed throughout the silty clay. The fine-grained material in the narrow cracks of the large fans appears to be illuviated clay derived from stream-transported sediment. The coarser grained material filling the wide cracks in the small fans may have been selectively concentrated to varying degrees, but is similar to the sandy clay being deposited at times of low flow at the present time.

The magnitude of the prehistoric near-surface subsidence on the large fans (about 5–10 feet) was less than 10–15 feet of historic near-surface subsidence observed locally on the small fans. The main reasons for lower magnitudes of near-surface subsidence on the large fans include: (1) the comparatively shallow depth to the water table, particularly on the downslope parts of the fans, (2) accumulation of moisture-deficient deposits over a shorter time span than on the small fans, and (3) greater variation in clay content in a sequence of beds than in the deposits of the small fans. Beds of silty clay, and sand with less than 10 percent clay, undergo little or no net compaction due to wetting when the moisture condition is changed from wilting coefficient to field capacity or wetter conditions.

The cracks are both historic and prehistoric. Nearly all the cracks in the large fans are prehistoric. Evidence for prehistoric times of cracking include: (1) The dominance of cracks that parallel former stream courses, (2) crack fillings truncated by buried stream channels, (3) crack fillings in the banks of streams that were entrenched decades before agricultural development of the area, (4) the variable depth of burial (0–15 ft) of the crack tops, (5) the absence of widespread historic near-surface subsidence in irrigated areas, and (6) the presence of deposits with field capacity moisture conditions in unirrigated areas.

A study of 415 crack orientations at six sites on the large fans shows that 45 percent of the cracks are within 20° of being parallel to the radial lines of the fans, and that 80 percent are within 50° of being parallel to the radial lines. The orientations of most cracks are roughly the same as the orientation of present-day streams on the large fans.

Many of the cracks in the small fans are prehistoric also. However, evidence also exists to indicate that many of the cracks in the small fans are the result of man's activities. Such evidence includes: (1) Fragments of cotton plants and reeds in the crack fillings, (2) cracks that parallel former ditch alinement, (3) extensive reaches where the cracks extend to the top of the bedded fan deposits, (4) cracks that extend through buried stream-channel fills into the overlying fan deposits, (5) the absence of crack fillings in the banks of the streams presently entrenched into the small fans, and (6) open, or partly filled, cracks as much as 25 feet below land surface.

Stream-transported sediment is the logical source of the crack fillings, particularly in the large fans. Filtering of sediment allows only material that is finer than 20 microns to infiltrate into many of the cracks and coat the sides of the crack with clay. Multiple periods of illuviation result in laminated crack fillings. Cracks filled with clean sand in the large fans appear to have been filled with saturated sand furnished directly from the stream during a single period of deposition. The material filling the wide cracks of the small fans has been filtered to a lesser degree, or has been deposited directly from irrigation or streamflows.

The history of accumulation and wetting of the fan deposits has consisted of a long period of accumulation of moisture-deficient clayey deposits, followed by a period during which water percolated below the root zone for the first time since burial. Moisture-deficient deposits have been accumulating for at least 200,000 years on the upslope parts of some of the small fans where the thickness of moisture-deficient deposits exceed 300 feet. The 5–10 feet of near-surface subsidence on the large fans indicates a minimum of 65 feet of accumulation of formerly moisture-deficient deposits, which would have required at least 45,000 and perhaps as much as 100,000 years to accumulate. The occurrence of these moisture-deficient deposits on both the large and small fans shows that water from streamflow or rainfall did not percolate below the root zone, even during times of glacial and lacustrine expansion during the Pleistocene.

The character of the streamflow changed during late Quaternary time. The presence of formerly moisture-deficient deposits indicates that ephemeral streamflow prevailed during much of the histories of the fans. At the present time, the streamflow is intermittent—the streams flow across the large fans for weeks at a time during some winters of above-normal precipitation. The change to intermittent streamflow may have been largely the result of continuing uplift of the Diablo Range—uplift that tended to increase the mean annual precipitation and the streamflow. A Holocene climatic change, perhaps in part local due to the increased height of the mountains, initiated deep percolation of the streamflow into the large fans.

The maximum depth of burial of the filled cracks below the land surface can be used to estimate the time of initial wetting. The maximum depth of burial on both the large and small fans is about 10 feet. Mean rates of deposition for entire fans indicate that the time of initial wetting is not older than 10,000 years, and may be much less than 10,000 years if locally the rates of deposition have exceeded the long-term mean rates.

On the large fans, the variable depths to the zone of cracking, that range from the base of the tilled zone to depths of as much as 15 feet, indicate that wetting has continued to the present time. A radiocarbon age determination of carbonized wood from one crack was dated at 5,180 ± 600 years before present.

On the small fans only a few cracks were buried; most of the cracks extend to the base of the zone of surficial disturbance by man. The single depth of burial of the cracks indicates that local wetting may have occurred on the small fans at some time between roughly 6,000 and 9,000 years ago, and that compaction due to wetting by streamflow has not occurred during the last 6,000 years.

Wetting of the moisture-deficient deposits by prehistoric streamflow was incomplete on most fans and absent on others. A comparative degree of prehistoric wetting for the fans studied can be assigned subjectively on the basis of the amount of historic near-surface subsidence on the large fans, and the proportion of prehistoric cracks in the small fans. Near-surface subsidence of the Cantua Creek fan appears to be entirely prehistoric, whereas the cracks in the Arroyo Ciervo fan appear to be entirely historic. The following sequence is assigned in order of decreasing proportion of prehistoric near-surface subsidence on the fans of the following streams: Cantua Creek, Los Gatos Creek, Panoche Creek, Tumey Gulch, Moreno Gulch, Arroyo Hondo, and Arroyo Ciervo.

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