# Alluvial Fans and Near-Surface Subsidence in Western Fresno County California

*By* WILLIAM B. BULL

## STUDIES OF LAND SUBSIDENCE

GEOLOGICAL SURVEY PROFESSIONAL PAPER 437-A

*Prepared in cooperation with the California Department of Water Resources.*

*A study of compaction caused by water percolating through certain alluvial-fan deposits for the first time since burial.*

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1964

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

The U.S. Geological Survey Library catalog card for this publication appears after page A71.

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

## FOREWORD

Subsidence of the land surface occurs in three extensive areas in the San Joaquin Valley and in the peat lands of the Sacramento-San Joaquin Delta at the north end of the valley. Subsidence in the three valley areas is related mainly to progressive lowering of the artesian head in confined aquifers. In the Los Banos-Kettleman City area, largely in western Fresno County, more than 1,100 square miles has subsided at least 1 foot, and maximum subsidence in 1960 was about 22 feet. The maximum yearly rate of subsidence is about 1 foot. Locally, on the western and southern flanks of the valley, subsidence also has followed application of irrigation water to certain deposits of subnormal moisture content above the water table. This near-surface subsidence, which exceeds 10 feet in places, is superposed on the subsidence due to compaction of the aquifer system beneath.

The character, extent, and rate of the subsidence in the valley are described in preliminary form in an earlier report (Inter-Agency Committee, 1958) and are being described in detail in U.S. Geological Survey reports now (1964) in preparation.

Subsidence poses serious problems in the construction and maintenance of engineering structures, especially in large canals for water transport, but also in irrigation distribution systems, pipelines, roads, and drainage systems; it also affects land use. Two existing large canals pass through subsiding areas, and the authorized California aqueduct of the State and the San Luis project canal of the Bureau of Reclamation will pass through many tens of miles of subsiding ground. Thus, the extent, magnitude, and rate of past subsidence and the expected amount of future change in altitude of the land surface are of paramount importance in the planning, construction, and maintenance of such major structures. Compaction of aquifer systems, the principal factor in the subsidence, also has an effect on the ground-water yield and causes casing failures.

Because of the problems in water development and distribution caused by subsidence, the Geological Survey in cooperation with the California Department of Water Resources began a study of these subsiding areas in 1956. The objectives of this study are:

1. To provide vertical control on the land surface to measure the extent, rate, and magnitude of subsidence (a vital supporting program by the U.S. Coast and Geodetic Survey).
2. To determine causes of the subsidence, the part attributable to different causes, and the depth range in which subsidence is occurring.
3. To estimate the rates and amounts of subsidence that would occur in the future under assumed conditions; to determine whether any part of the subsidence is reversible, and if so, how much; and to suggest any methods that could be used to decrease or alleviate subsidence.

The first report resulting wholly from the cooperative program with the State is the following paper by W. B. Bull on "Alluvial Fans and Near-Surface Subsidence in Western Fresno County, Calif." Other reports in progress or planned are: Subsidence due to ground-water withdrawal in the Los Banos-Kettleman City area; a summary report on near-surface subsidence; subsidence in the Tulare-Wasco area; and subsidence in the Arvin-Maricopa area.

J. F. Poland,
*Research Geologist*

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# GLOSSARY

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

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

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

**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.

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

**Dry bulk density.** The weight of a deposit dried at 110° C, in pounds per cubic foot.

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

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

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

**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.)

**Flow.** The movement of any fluid, from clear water to viscous mud, in a stream channel or on the fan surface.

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

**Hypsometric (area-altitude) integral.** A measure of the land mass in a drainage basin compared to a reference volume. (Strahler, 1952, p. 1121)

**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.

**Mean slope.** A dimensionless number obtained by dividing the contour interval by the mean width between contour lines.

**Moisture equivalent.** "The ratio of (1) the weight of water which the soil, after saturation, will retain against a centrifugal force 1,000 times the force of gravity to (2) the weight of the soil when dry." (Meinzer, 1923, p. 25; term first used by Briggs and McLane, 1907)

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

**Percentage hypsometric (area-altitude) curve.** A curve controlled by points that relate (1) the ratio of a horizontal cross-sectional area of a drainage basin to the total area of the drainage basin to (2) the ratio of the altitude of the cross section above the basin mouth to the total relief of the basin. (Strahler, 1952, p. 1119)

**Piedmont plain.** A broad sloping plain formed by the coalescence of many alluvial fans.

**Radial line.** A straight line on the fan surface extending from the apex to the toe.

**Radial profile.** A topographic profile along a radial line.

**Relative moisture.** The moisture content of a sample expressed as percent of the moisture equivalent.

**Relief ratio.** "The ratio between the total relief of a basin * * * and the longest dimension of the basin parallel to the principal drainage line." (Schumm, 1956, p. 612)

**Sand-pit density.** Density obtained by filling a pit with sand of a known density.

**Subsidence cracks.** Cracks that form between an area of near-surface subsidence and an area that remains stable. The width and vertical displacement of the cracks may change as the stable-ground boundary moves farther away from the wetted area.

**Thalweg.** The line along the deepest part of the stream channel.

**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)

# ALLUVIAL FANS AND NEAR-SURFACE SUBSIDENCE IN WESTERN FRESNO COUNTY, CALIFORNIA

By William B. Bull


## ABSTRACT

Near-surface subsidence on certain alluvial fans in western Fresno County, Calif., has destroyed or damaged ditches, canals, roads, pipelines, electric-transmission towers, and buildings and has made the irrigation of crops difficult. About 124 square miles has subsided or probably would subside if irrigated. Subsidence of 3–5 feet is common, and subsidence of more than 10 feet has occurred within small areas.

The drainage basins of subsiding fans that were studied have areas of less than 30 square miles and seem to have greater average relief ratios and mean slopes than the drainage basins of nonsubsiding fans. Most drainage basins are underlain by marine sedimentary rocks, but the drainage basins of subsiding fans are underlain chiefly by clay-rich rocks such as mudstone and shale.

Deposition on an alluvial fan is caused mainly by the decrease in depth and velocity of flow that results from the increase in channel width as a flow spreads out on the fan. The deposits occur as mudflows, water-laid sediments, or as types intermediate between mudflows and water-laid sediments. Intermediate and mudflow deposits are most common in subsiding fans, and water-laid sediments are most common in nonsubsiding fans. Mudflows may be more common in present-day deposits than in older deposits because stream entrenchment has made narrow, confining channels that enable mudflows to reach the alluvial fans and because the steep banks provide additional debris for any type of flow.

Voids commonly found in alluvial-fan deposits are intergranular openings between grains held in place by clay bonds; 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 disintegration of entrapped vegetation.

Near-surface subsidence results chiefly from the compaction of deposits by an overburden load as the clay bond supporting the voids is weakened by water percolating through the deposits for the first time. The amount of subsidence is dependent mainly on the overburden load, natural moisture conditions, and the amount and type of clay in the deposits. The amount of compaction due to wetting increases with an increase in overburden load, but most known near-surface subsidence has been caused by compaction in the upper 200 feet of deposits. The moisture condition of the unirrigated parts of subsiding fans is about equivalent to the wilting coefficient, but the moisture condition of nonsubsiding fans may approximate either the field capacity or the wilting coefficient. Montmorillonite is the predominant clay mineral and has more strength at a given moisture content than do other types of clay minerals. The strength of the clay binder also is partly dependent on the moisture conditions. Tests on surface samples under hygroscopic conditions indicate that maximum compaction occurs at a clay content of about 12 percent. At clay contents of less than 12 percent the dry overburden load tends to compact the deposit, but at clay contents of more than 12 percent the deposit tends to resist compaction even when wetted; swelling of the clay also reduces the net compaction. Deposits of subsiding fans have clay contents of about 15–30 percent, but deposits of nonsubsiding fans of the same size have clay contents of about 5–15 percent. More than half the compaction due to wetting occurs as the water front passes through a deposit.


## INTRODUCTION

### PURPOSE AND SCOPE

Alluvial fans are widespread topographic features in the arid and semiarid areas of the world, and about one-fifth of California is covered by alluvial-fan deposits. Ground water in many parts of the western conterminous United States is pumped from alluvial-fan deposits. Yet, considering the widespread extent of alluvial fans and the economic importance of alluvial-fan deposits, little detailed work has been done on them. One purpose of this paper is to provide detailed information about certain alluvial fans and their source areas.

The surface of certain alluvial fans in western Fresno County, Calif., subsides when the land is irrigated for the first time. Near-surface subsidence increases the costs of farming and damages engineering structures such as canals, buildings, oil and gas pipelines, power-transmission lines, and highways. Major canals and a highway that have been authorized will cross some of these areas of near-surface subsidence. The maintenance cost for engineering structures is excessively high unless the problems caused by near-surface subsidence

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are considered. Therefore, the economic purpose of the investigation was to study the geology and engineering properties of the alluvial-fan deposits in western Fresno County so that the causes, magnitude, rate, and potential duration of near-surface subsidence will be better understood.

The results of the studies of sedimentary and engineering properties of the fan deposits and of the geology of drainage basins have a direct bearing on the causes and mechanics of near-surface subsidence as well as being essential in the detailed geologic description of the alluvial fans. The types of rocks in a drainage basin partly determine how much a fan subsides, because they partly determine the percentage of clay in the alluvial-fan deposits. The form of the drainage basins that are being eroded to make the alluvial fans is described in the section, "Geomorphology."

Two distinct types of land subsidence are common in western Fresno County. Near-surface subsidence is the result of the compaction of alluvial-fan deposits through which water percolates for the first time since burial. Compaction of deposits as much as 150 feet below the land surface has been measured locally, but the type of compaction that produces the near-surface subsidence generally is not expected to occur below a depth of 200 feet. Subsidence due to artesian-head decline, in contrast to near-surface subsidence, is caused by the compaction of unconsolidated late Cenozoic deposits and is due to the withdrawal of ground water. Subsidence due to artesian-head decline occurs in nearly all the west-side area from Los Banos to Kettleman City (fig. 1) and is coincident with most areas of near-surface subsidence. In this paper, only the near-surface subsidence is discussed, and hereafter the word "subsidence" refers to the near-surface type.

Several different terms have been used in association with subsidence caused by compaction due to wetting. This type of subsidence has been referred to as shallow subsidence (Inter-Agency Comm., 1958; Fuqua and Richter, 1960), and as near-surface subsidence (Bull, 1959; Lofgren, 1960; and Bull, 1961). Compaction due to wetting has been referred to as hydroconsolidation (Krynine and Judd, 1957, p. 107), and as hydrocompaction (Prokopovich, 1963; and Lofgren, 1965).

Compaction of certain loess deposits in Nebraska and Kansas has been noticed when the loess has been wetted and loaded with heavy structures such as dams (Lofgren, 1965). Near-surface subsidence in the San Joaquin Valley is different, in that only wetting is necessary to cause the compaction of the deposits.

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

### ACKNOWLEDGMENTS

The investigation was aided by the cooperation of many agencies and individuals, but the California Department of Water Resources was the principal cooperating agency for this project. In addition to providing financial aid, the Department drilled several core holes and made numerous laboratory tests. The U.S. Bureau of Reclamation and the California Division of Highways tested cores from test holes at the Inter-Agency Committee test plots. Stanford University and the University of California at Davis allowed the author the use of laboratory facilities for making additional tests. The University of California also made the chemical analyses of soils and many moisture-equivalent tests. Ranchers, sheepherders, farmers, and other people living in the area studied gave first-hand accounts of subsidence problems and floods. Stanley N. Davis and George A. Thompson of Stanford University gave advice on certain aspects of the paper and fieldwork. The author also thanks his colleagues in the Geological Survey—L. A. Heindl, B. E. Lofgren, R. H. Meade, J. F. Poland, and F. S. Riley—for their thoughtful discussions and constructive review of the manuscript.

## GEOGRAPHIC SETTING

### LOCATION AND TOPOGRAPHIC FEATURES

The Central Valley of California is divided into a northern part and a southern part—the Sacramento Valley and the San Joaquin Valley, respectively. The area discussed in this paper includes about 1,400 square miles of the west side of the San Joaquin Valley and the adjacent Diablo Range. All of this part of the San Joaquin Valley lies within an area of regional subsidence between Los Banos and Kettleman City. The northern edge of the area studied is about 10 miles south of Los Banos, and the southern boundary is the south side of the drainage basin of Domengine Creek. The alluvial fans studied are in western Fresno County and in a small part of Merced County. The eastern edge of the fans is bounded by the flood plains of the San Joaquin River and Fresno Slough. Figure 1 shows that the drainage basins of these fans extend into San Benito and Merced Counties. The areas of known near-surface subsidence studied are all in Fresno County.

Between the flood plains and the foothills to the southwest is a belt of coalescing alluvial fans 12–19 miles wide. The altitude at the base of this piedmont

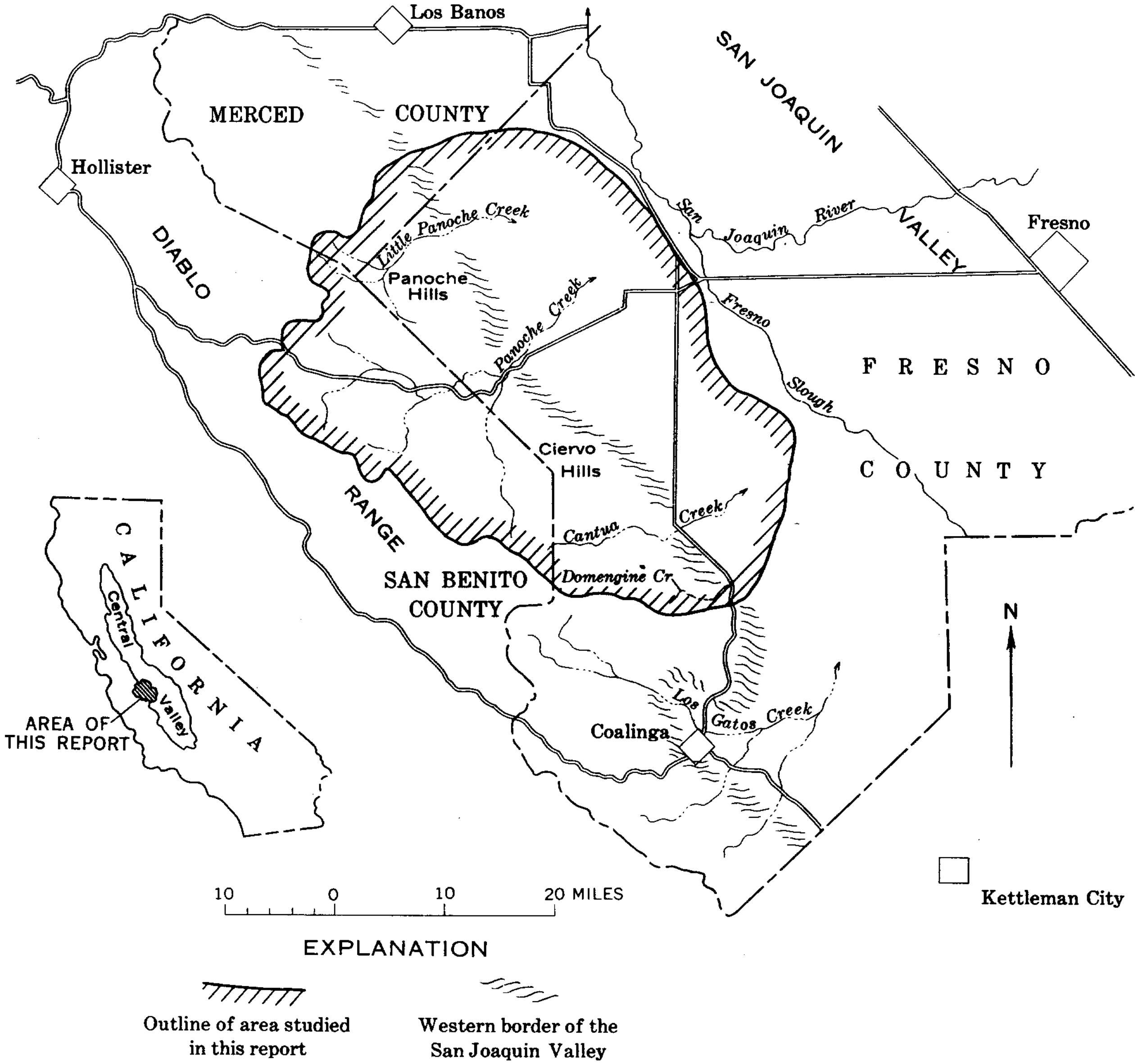



FIGURE 1.—Map of parts of Fresno, Merced, and San Benito Counties, Calif., showing area discussed in this paper.

plain ranges from 130 to 175 feet, from which the alluvial fans rise to altitudes of about 340–900 feet at their apexes. The slopes of the fans range from about 10 feet per mile near the base of the larger ones to about 150 feet per mile on the upper slopes of some of the smaller ones. Local relief on the fans generally is less than 5 feet, except on the upper parts where the stream channels are incised about 10–40 feet.

The Diablo Range in the southwestern part of the area consists of several groups of foothills that fringe the San Joaquin Valley and the main range, which is generally about 10–15 miles from the western margin of the valley (pl. 1). The larger foothill groups are the Ciervo Hills, whose highest point is about 3,400 feet, and the Panoche Hills, which rise to an altitude of about 2,700 feet. The main Diablo Range has several peaks higher than 5,000 feet. Both the foothill belt and the main Diablo Range have a rugged terrain cut by many steep canyons. Plate 1 shows the rugged nature of this part of the Diablo Range. The streams of subsiding fans head in the foothill belt.

Many place and stream names are used throughout the paper, and the location of most of these features can be found on plates 1 and 2; the reader should refer to plate 1 for place names of ranches, canals, and mountains. Specific drainage basins and their associated alluvial fans can be located by using the alphabetical arrangement on plate 2, which shows the complete section-line grid for all section references. Features that are not shown on plates 1 and 2 have a text reference to the figure in which they can be located.

The approximate boundaries of the alluvial fans were determined from aerial photographs and contour maps and by gypsum-content determinations. The average gypsum content of fans whose streams head in the foothill belt is five times that of fans whose streams head in the main Diablo Range (table 15).

Drainage basins in the foothill belt and in the main Diablo Range were studied. Those in the foothill belt are generally less than 10 miles long and, in some places, tend to be closely spaced. The streams that head in the main Diablo Range and cross the foothill belt are Little Panoche Creek, Panoche Creek, and Cantua Creek. The length of the drainage basins of the larger streams ranges from 14 miles for Cantua Creek to 22 miles for Panoche Creek. Plate 2 shows that the basins of the larger streams extend around the smaller basins to drain the west side of the foothill belt. In general, the streams flow toward the northeast at right angles to the trough of the San Joaquin Valley.

The streams may be classed as intermittent or ephemeral. As the streams in the area studied do not receive enough water from underground sources such as springs and bank storage to sustain a continuous flow from source to mouth during the dry season, there are no perennial streams. Little Panoche, Panoche, and Cantua Creeks are intermittent streams that receive enough ground water to flow along their entire lengths for a few weeks after most winter rainy seasons; but the channels of the ephemeral streams are always above the water table, and the streams, therefore, flow only in direct response to rainfall.

During the summer and autumn, dry stretches alternate with reaches with flow on the intermittent streams, but in the winter the streams may have a flood flow of several hundred cubic feet per second. Flash floods are not common on the larger streams.

The ephemeral streams flow during flash floods. These floods are controlled by the areal distribution, intensity, and duration of rainfall, and by the vegetative cover, lithology, and slopes of the drainage basin. The resulting flow may range from clear water to viscous mud.

### CLIMATE AND VEGETATION

Nearly all the precipitation within the area occurs as rainfall. The average annual rainfall is 15–20 inches for most of the main Diablo Range, which intercepts much of the moisture brought into the area by storms and creates a rain shadow across the foothill belt and the west side of the San Joaquin Valley. The average annual rainfall in the foothills is about 8–15 inches,

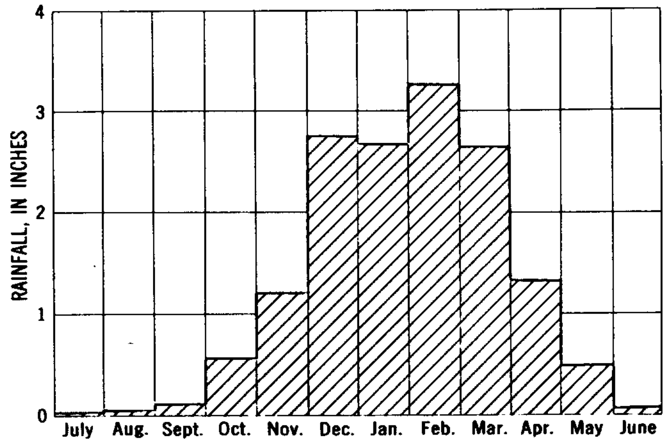



FIGURE 2.—Average monthly rainfall, 1919–58, at New Idria.

and that in the valley is about 6½–8 inches. The annual rainfall decreases slightly from north to south.

Most of the rainfall occurs from December through March (fig. 2). Precipitation at the New Idria station, at an altitude of 2,650 feet in the Diablo Range, is typical of the precipitation of the area. The winter rains are carried by cyclonic storms that move across the Pacific coast and cover large areas; the spring and rare summer rains also generally result from cyclonic storms, but some are scattered thunderstorms.

The weather stations do not record rainfall intensities, but daily amounts of rainfall of 3–4 inches have been measured in both the mountains and the San Joaquin Valley. Residents note that the most intense rains generally occur from March through May and are not necessarily of the thunderstorm type. The rainfall of a given storm can be sporadic. Most of the large farms in the valley have several rain gages, and the daily rainfall at one gage may be but a fraction of that at another gage 2 miles away.

Temperatures in the area are characteristically hot in the summer and mild in the winter. The daily temperature range is often 30°–40° F, particularly during the summer. Table 1 shows some mean temperatures

TABLE 1.—*Selected mean temperatures at the Coalinga and Panoche Junction weather stations*

[Data from U.S. Weather Bur. annual summaries]

| Station | Month | Temperature, °F | | |
|---|---|---|---|---|
| | | Mean minimum | Mean maximum | Mean |
| Coalinga, 1913–58 | December | 33.9 | 58.7 | 47.0 |
| | January | 34.3 | 57.9 | 46.0 |
| | July | 63.1 | 102.3 | 82.5 |
| | August | 60.7 | 100.5 | 80.5 |
| Panoche Junction, 1942–58. | December | 39.3 | 56.9 | 47.9 |
| | January | 36.9 | 54.4 | 45.5 |
| | July | 63.4 | 100.1 | 81.7 |
| | August | 61.3 | 96.8 | 79.2 |

at Coalinga (fig. 1) and Panoche Junction, which are weather stations near the foothills. The humidity is low throughout much of the year.

Prevailing winds are from the northwest. Occasional dust storms may be formed by winds from the north, west, or south.

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 the higher altitudes. Soils of the foothill belt and the alluvial fans support a different type of vegetation. Shadscale is a common bush, and the grasses are short types such as downy chess and red-stem filaree.

The vegetation of the foothills and San Joaquin Valley is sparse, particularly during dry years, but it is usually more luxuriant on the parts of the alluvial fans subject to flooding. This growth on the alluvial fans may be renewed in a dry year following a flood year because some moisture is left in the ground to support above-normal growth. The dryness and hot temperatures discourage the growth of many plants at the low altitudes during the summer.

## GEOLOGY OF THE ALLUVIAL FANS

### REGIONAL GEOLOGY

The east flank of the Diablo Range consists chiefly of a thick sequence of marine sedimentary rocks that dip toward the San Joaquin Valley. The Franciscan formation of Late Jurassic to Late Cretaceous age, which forms the core of the range, comprises deformed and slightly metamorphosed shale and graywacke. Cretaceous mudstone, shale, and sandstone form most of the marine section, and in several places the Cretaceous rocks are more than 20,000 feet thick. Tertiary marine and continental sediments are found mainly in the foothill belt and in basins such as the Vallecitos. Pleistocene and recent alluvial-fan deposits extend eastward from the foothill belt.

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

### THE COAST RANGE OROGENY

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

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

The age of the upper part of the Tulare formation provides a general date for the Coast Range orogeny in western Fresno and Merced Counties. The Tulare has been folded and faulted, particularly near the mountain front. A widespread lacustrine clay (the Corcoran clay member) in the upper part of the Tulare formation has been monoclinally folded along the mountain front near Laguna Seca Creek where it dips 30°–50° E. (written commun., J. S. Long and D. W. Carpenter, U.S. Bur. Reclamation, 1963).

Potassium-argon dating, by G. B. Dalrymple, of a volcaniac ash associated with the Corcoran permits a reassignment of the age for the Tulare formation, which has been considered of Pliocene and Pleistocene(?) age. Pumice pebbles exposed near Friant in eastern Fresno County, which are correlated with volcanic ash immediately overlying the Cocoran, contain sanidine crystals that were dated at 600,000±20,000 years (Janda, R. J., Pumice from the Friant formation: its age and stratigraphic position in the San Joaquin Valley, California, unpub. data). A date of 600,000 years indicates that part of the Tulare was deposited during Pleistocene time; therefore, the Tulare formation will be referred to in this report as being of Pliocene and Pleistocene age.

"The deposition of these late Pliocene and early Pleistocene beds [the Tulare formation] was brought to a close by an even more important and widespread diastrophic event [the Coast Range orogeny] than that through which they originated" (Taliaferro, 1943, p. 148). Although the age of the Coast Range orogeny is generally considered to be middle or late Pleistocene (Eaton, 1928; Reed and Hollister, 1936; Stille, 1936;

Putnam, 1942; Bailey, 1943; Taliaferro, 1943), within the area studied it can be dated only as post-Tulare. The Tulare generally is accepted as being of Pliocene and Pleistocene age; therefore, the foothill belt and probably the main Diablo Range were elevated during Pleistocene time.

Middle to late Pleistocene fossils have been found in tilted and folded strata in southern California, and some of these beds have been tilted by minor earth movements since the Coast Range orogeny. Movements younger than the Coast Range orogeny probably also affected the Diablo Range and the deposition of alluvial fans.

During Pliocene and early Pleistocene time the Tulare probably covered the site of the present-day foothill belt, as indicated by remnants of flat-lying Tulare beds on the highest parts of the Panoche Hills. The uplift of the foothill belt must have occurred after the deposition—and as part of the deformation—of the Tulare formation, because the foothill belt now separates the Tulare from the source areas of some of the debris that composes it.

Streams that now head in the main Diablo Range either maintained their original courses through the rising foothill belt or took courses around the areas of maximum uplift. Deposition of alluvial fans then took place east of the foothill belt on alluvial-fan deposits of the Tulare formation.

The fans whose streams now head in the foothill belt did not exist before the Coast Range orogeny. The orogeny formed the foothills and started the deposition of new alluvial fans to the east. This means that the fans which now show the effects of near-surface subsidence began to form in the Pleistocene and may be of middle Pleistocene age or younger. The younger, upper parts of these fans are the deposits that are being compacted to cause the subsidence.

## GEOLOGY OF THE DRAINAGE BASINS

The drainage basins are the source areas for the sediments of the alluvial fans. Geomorphic and lithologic properties of the drainage basins directly affect the type, texture, and rate of deposition of the alluvial-fans deposits, which in turn affect the near-surface subsidence.

### GEOMORPHOLOGY

The geomorphology of the drainage basins can be discussed in two ways that supplement each other—their evolution can be described in generalized terms, and their features can be discussed in quantitative terms. This section emphasizes the quantitative approach because numbers provide a more precise way of comparing drainage basins than do words. For example, every man has his own idea of what is meant by the term "rugged mountains," but the mean slope of a mountainous area is a number and as such can have only one meaning.

Two types of quantitative numbers are used to describe some of the drainage basins in western Fresno County. The first gives the dimensions of the area, in square miles, and the relief of the drainage basins, in feet. The other type of number is dimensionless and includes ratios of dimensions or angles, which are independent of the size of the drainage basins and thus are useful in the comparison of certain features of basins of different sizes.

The dimensionless numbers used in this report are the relief ratio, the mean slope, and the area-altitude integral. Other dimensionless features such as stream order, drainage density, or basin shape could have been obtained, but they would probably have a less direct bearing on the amount and type of deposition on the alluvial fans than the numbers used.

The drainage basins are classified in three groups: *A*, those associated with nonsubsiding fans; *B*, those associated with subsiding fans; and *C*, those associated with fans that might subside if irrigated. Nonsubsiding fans have been irrigated but do not subside. Subsiding fans have distinct evidence of near-surface subsidence. Potentially subsiding fans seem to have

TABLE 2.—*Quantitative geomorphic properties of some of the drainage basins*

| Stream | Area (sq mi) | Total relief (ft) | Relief ratio | Approximate mean slope | Area-altitude integral |
|---|---|---|---|---|---|
| ***A*. Nonsubsiding fans** | | | | | |
| Laguna Seca Creek | 11.1 | 1270 | 0.033 | 0.20 | 0.47 |
| Wildcat Canyon | 11.4 | 1140 | .028 | .16 | .44 |
| Little Panoche Creek | 104.0 | 3150 | .032 | .24 | .38 |
| Panoche Creek | 296.0 | 4550 | .043 | .27 | .33 |
| Cantua Creek | 49.4 | 4610 | .067 | .35 | .41 |
| Salt Creek | 25.2 | 3480 | .083 | .39 | .42 |
| Martinez Creek | 8.9 | 3230 | .113 | .26 | .35 |
| Domengine Creek | 11.2 | 3500 | .084 | .33 | .46 |
| Average | 64.6 | 3110 | .060 | .27 | .41 |
| ***B*. Subsiding fans** | | | | | |
| Moreno Gulch | 11.7 | 1830 | 0.054 | 0.45 | 0.59 |
| Marca Canyon | 1.9 | 1500 | .087 | .48 | .40 |
| Capita Canyon | 2.6 | 1760 | .067 | .50 | .49 |
| Sec. 15, T. 15 S., R. 12 E | 0.5 | 770 | .130 | .37 | .44 |
| Tumey Gulch | 29.1 | 2590 | .052 | .30 | .50 |
| Arroyo Ciervo | 8.0 | 2740 | .077 | .34 | .47 |
| Arroyo Hondo | 25.7 | 2550 | .044 | .29 | .41 |
| Average | 11.4 | 1960 | .073 | .39 | .47 |
| ***C*. Fans that might subside if irrigated** | | | | | |
| Gres Canyon | 0.18 | 620 | 0.118 | 0.33 | 0.41 |
| Chaney Ranch Canyon | .53 | 620 | .078 | .29 | .46 |
| Dosados Canyon | .93 | 1520 | .132 | .41 | .39 |
| Escarpado Canyon | .56 | 1130 | .107 | .39 | .38 |
| Average | .55 | 970 | .109 | .36 | .41 |

slopes. Thus, steep slopes seem to be more conducive to the occurrence of flash floods and mudflows. Sheepherders and ranchers have reported flash floods on many of the streams, and most of these reported floods have occurred in drainage basins with a mean slope of 0.29 or more; only one flash flood was reported from drainage basins that have a mean slope of less than 0.29 (Little Panoche Creek, 1958).

The third dimensionless number used is the area-altitude integral, which is a measure of the distribution of the land mass within a basin. The term "area-altitude" is synonymous with the term "hypsometric" (Langbein and others, 1947; Strahler, 1952).

The area-altitude integral is derived from the percentage area-altitude curve, which is constructed by plotting the relative height, $h/H$, against the relative area, $a/A$. The relative height is the ratio of the height of a given contour above the lowest point in the basin to the total basin height or relief. The relative area is the ratio of the horizontal area above a given contour to the area of the entire basin. Both these dimensionless numbers are converted to percentages and then plotted against each other to give the percentage area-altitude curve. A description of the percentage area-altitude curve is given by Strahler (1952, p. 1119), and figure 4 shows two contrasting percentage area-altitude curves. The area-altitude integral is measured as the ratio of the area below the area-altitude curve to the area of the entire square.

The area-altitude curves in figure 4 show two types of landmass distribution. In the Moreno Gulch basin the divides and valley floors are narrow, and the original surface has been dissected except for a small area of flat-lying Tulare formation in the highest part of the basin. The undissected part of the Tulare does not greatly influence the area-altitude curve because it amounts to about 1 percent of the area of the basin. The Panoche Creek basin has a broad valley bordered by rugged mountains. Parts of the mountains have altitudes of more than 5,000 feet, but only 3 percent of the area has an altitude of more than 3,500 feet. This 3 percent of the area has a distinct influence on the area-altitude curve, as is shown in figure 4, where the left side of the Panoche Creek curve swings abruptly upward. If the area-altitude integral is used to define the stage of basin evolution (Strahler, 1952, p. 1128–1138), the Moreno Gulch basin has just entered the equilibrium stage, and the Panoche Creek basin is approaching the monadnock phase of the equilibrium stage.

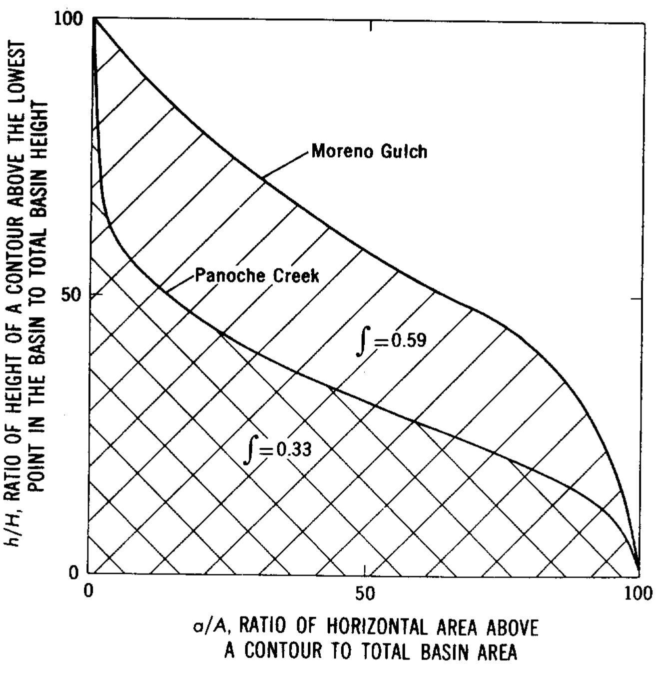



FIGURE 4.—Area-altitude curves for the drainage basins of Moreno Gulch and Panoche Creek.

Area-altitude curves for some of the drainage basins are shown in figure 5. The curves for the basins of nonsubsiding fans have a greater variety of shapes than the curves for the basins of subsiding fans. Only two curves have irregularities that reflect contrasting lithologies within the drainage basins; the curves for the rest of the basins are smooth.

The area-altitude integral of two basins may be the same, but the shape of the curves may vary. A basin would have an area-altitude integral of 0.50 if the curve was a straight line from the upper left corner to the lower right corner. A variety of S-shaped curves could also have an integral of 0.50 if the area below the curve was 50 percent of the reference square.

The average area-altitude integral does not vary much for the three classes of drainage basins studied. The average area-altitude integral for the drainage basins of subsiding fans is only 0.06 larger than the average integral of the basins whose fans do not subside. The average integral of the basins of nonsubsiding fans is the same as the average integral of the basins of fans which might subside if irrigated. The integrals for each basin are listed in table 2.

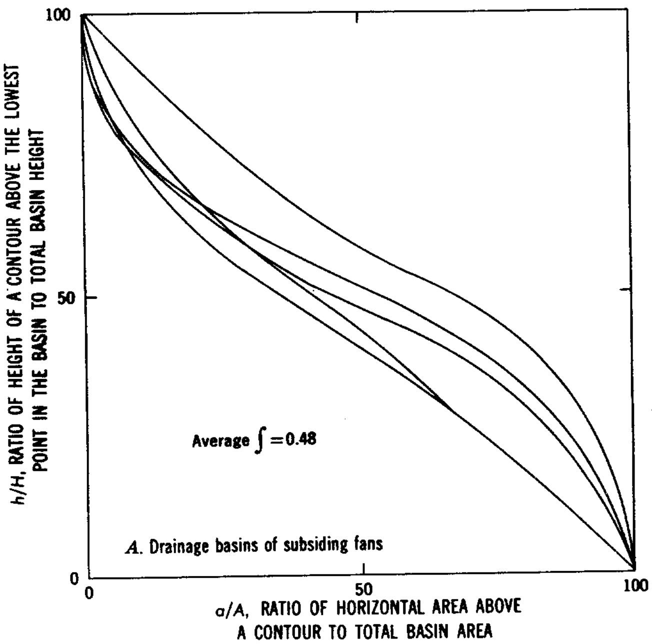
## STRATIGRAPHY

Studies of fan size and slope (Bull, 1964a) show that the fans derived from mudstone- or shale-rich drainage basins are thicker and almost twice as large areally as the fans derived from sandstone-rich drainage basins. Thus, the type of source rock partly controls the areal extent and total amount of near-surface subsidence in western Fresno County, because subsiding fans are associated with drainage basins that have abundant clay-rich rocks.

Marine sedimentary rocks of Cretaceous and Tertiary ages are exposed in all the drainage basins studied. The basins that head in the Diablo Range are underlain in part by rocks of the Franciscan formation and serpentinized ultrabasic rocks.

The rocks in the area studied are subdivided into four stratigraphic units: Franciscan formation and ultrabasic intrusive rocks, Cretaceous marine sedimentary rocks, Tertiary marine sedimentary rocks, and upper Cenozoic continental deposits. The Cretaceous and Cenozoic units consist of more than one formation in some of the basins. The location and distribution of the units and their subdivisions are shown on plate 1.

The area of 12 selected drainage basins and the percentage of each that is underlain by the individual stratigraphic units are shown in table 3. The first four drainage basins have fans that are known to subside; in the others, subsidence of the fans either is not apparent or does not occur.



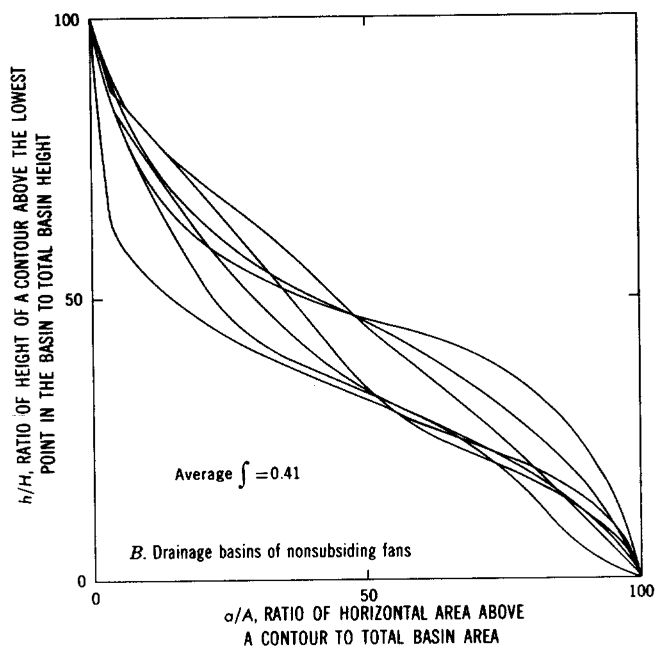




FIGURE 5.—Area-altitude curves for selected drainage basins of subsiding and nonsubsiding fans. *A*, Drainage basins of subsiding fans; *B*, Drainage basins of nonsubsiding fans.

TABLE 3.—*Area of selected drainage basins and percentage of each underlain by given geologic units*

[The stratigraphic data are from a variety of sources. Data for the Little Panoche Creek, Panoche Creek, Cantua Creek, Salt Creek, and Domengine Creek basins are from Davis (1961), who obtained his data by planimetering geologic maps by Jenkins (1938) and Kundert (1955). Data for the basins of Laguna Seca Creek and Wildcat Canyon were obtained from a map by Briggs (1953, pl. 1). Data for the basins of Moreno Gulch, Tumey Gulch, Arroyo Hondo, and Martinez Creek were obtained from a geologic map of the California Division of Mines, compiled by Jennings and Strand (1958). The percentages of the units for the Arroyo Ciervo basin are from a map by the author (pl. 3)]

| Stream | Area of drainage basins (sq mi) | Percentage of selected drainage basins underlain by indicated geologic units | | | |
|---|---|---|---|---|---|
| | | Franciscan formation and ultrabasic intrusive rocks | Cretaceous marine sedimentary rocks | Tertiary marine sedimentary rocks | Upper Cenozoic nonmarine deposits |
| Drainage basins of subsiding fans: | | | | | |
| Moreno Gulch | 12 | ---------- | 82 | 3 | 15 |
| Tumey Gulch | 29 | ---------- | 10 | 87 | 3 |
| Arroyo Ciervo | 8 | ---------- | ---------- | 87 | 13 |
| Arroyo Hondo | 26 | ---------- | | 86 | 14 |
| Drainage basins of nonsubsiding fans: | | | | | |
| Laguna Seca Creek | 11 | ---------- | 82 | 5 | 13 |
| Wildcat Canyon | 11 | ---------- | 86 | 1 | 13 |
| Little Panoche Creek | 104 | 41 | 25 | ---------- | 34 |
| Panoche Creek | 296 | 17 | 26 | 42 | 15 |
| Cantua Creek | 49 | 13 | 52 | 35 | ---------- |
| Salt Creek | 25 | ---------- | 68 | 32 | ---------- |
| Martinez Creek | 9 | ---------- | 47 | 46 | 7 |
| Domengine Creek | 11 | ---------- | 59 | 41 | ---------- |

The formations discussed in this paper are not shown on plate 2, where the formations have been grouped according to age and environment of deposition. The relationship between the lithologic units on plate 2 and the formations described is shown below.

| Lithologic group | Formation | Age |
|---|---|---|
| Upper Cenozoic nonmarine deposits. | Tulare | Pliocene and Pleistocene. |
| | Etchegoin | Pliocene. |
| | Jacalitos | Early Pliocene. |
| Tertiary marine sedimentary rocks. | Santa Margarita | Miocene. |
| | Temblor | Early and middle Miocene. |
| | Tumey formation of Atwill (1935). | Oligocene. |
| | Kreyenhagen shale | Eocene and Oligocene (?). |
| | Domengine sandstone | Middle Eocene. |
| | Lodo | Paleocene and Eocene. |
| | Moreno shale | Late Cretaceous and Paleocene(?). |
| Cretaceous marine sedimentary rocks. | Moreno | Late Cretaceous and Paleocene(?). |
| | Panoche | Late Cretaceous. |
| | Wisenor formation of Briggs (1953). | Early Cretaceous. |

The Franciscan formation underlies about 40 percent of the Little Panoche Creek drainage basin, and serpentinized ultrabasic rocks underlie 13 percent of the Cantua Creek basin. According to Briggs (1953, p. 11), about 80 percent of the Franciscan in this part of the Diablo Range consists of graywacke sandstone, black slaty shale and siltstone. Minor rock types include crystalline chert, greenstone, gabbro, glaucophane schist, and volcanic rocks (Briggs, 1953, p. 14–19). Minor amounts of serpentine occur in the Panoche Creek and Little Panoche Creek Basins. The ultrabasic rocks probably were emplaced after the formation of the Franciscan formation.

The Cretaceous rocks comprise the Upper Cretaceous Panoche formation and the lower part of the Moreno shale; the upper part of the Moreno formation is of Paleocene(?) age. The Lower Cretaceous is partly represented by an 1,800-foot section of marine shale and thin-bedded sandstone in the Little Panoche Creek basin. These rocks were called the Wisenor formation by Briggs (1953, p. 20, 22). The Panoche formation consists of concretionary sandstone, sandy shales and mudstones, and conglomerate (Anderson and Pack, 1915, p. 46–54; Payne, 1951, p. 7–11). All the above authors note the characteristic organic siliceous nature of parts of the Moreno shale.

Tertiary marine rocks from the Moreno, Lodo, Temblor, and Santa Margarita formations, the Kreyenhagen shale, the Domengine sandstone, and the Tumey formation (Atwill, 1935). Most of the Tertiary marine formations are exposed in the drainage basins south of Arroyo Ciervo, but only minor amounts of them occur north of Panoche Creek. In the Ciervo Hills the most widespread formations are the Kreyenhagen shale of Eocene and Oligocene(?) age, the Temblor formation of early and middle Miocene age, and the Lodo formation of Paleocene and Eocene age. The Kreyenhagen is a brown to maroon diatomaceous shale whose exposed surface weathers to a characteristic white color. The upper part of the Kreyenhagen is a punky white diatomite at several localities. The Temblor is mainly massive sand and sandstone which have abundant fossils at some localities. Shale and sandstone of the Lodo formation underlie a large area of the Tumey Gulch and Arroyo Hondo drainage basins. The Santa Margarita formation of Miocene age has a maximum thickness of about 400 feet (Anderson and Pack, 1915, p. 94) and consists of a basal conglomerate overlain by a pebbly sandstone.

Upper Cenozoic nonmarine deposits include the Etchegoin, Jacalitos, and Tulare formations as well as all younger alluvium. The Pliocene Etchegoin and Jacalitos formations are exposed chiefly south of Panoche Creek, and their lithology includes gravel, reddish-brown and blue-green silts, sands, and marls. The Tulare formation of Pliocene and Pleistocene age is exposed in most of the drainage basins. Its varied lithology includes sand, gravel, silt, marl, limestone, and gypsum.

Most of the alluvial fans are composed of fragments of the rock types that predominate in the present-day drainage basins. The only exceptions are the fans of Laguna Seca Creek and Wildcat Canyon whose drainage basins head in the foothill belt north of Little Panoche Creek. According to Briggs (1953, p. 55, 56), the foothill belt north of Little Panoche Creek was imperfectly planed in early Pleistocene time before the thin mantle of the Tulare formation was deposited. Post-Tulare erosion may have formed alluvial fans composed chiefly of detritus from the Tulare. At the present time much of the Tulare mantle has been removed by erosion, and more than 80 percent of each of these basins is underlain by Cretaceous rocks. Many of the ridges of Cretaceous rocks have a common summit altitude that suggests the approximate position of the pre-Tulare erosion surface.

I. E. Klein, U.S. Bureau of Reclamation (written commun., 1958) has shown that the sand-size fraction of samples from subsiding fans contains 16–50 percent opaline shale as compared to 5–8 percent for the sand-size fraction of samples from nonsubsiding fans. The source of the opaline shale is the diatomaceous sections of the Moreno shale and the Kreyenhagen shale.

The significance of the clay content of the alluvial-fan deposits is mentioned at this time to give the reader an idea of the value of the lithology of the drainage basins as one criterion in appraising the potential for near-surface subsidence of the correlative alluvial fans. Diatomaceous shale fragments show that there is a source of clay, and, of course, clay may be eroded from nondiatomaceous mudstones, shales, siltstones, and other rock types. Clay controls to a large extent the engineering properties of the alluvial-fan deposits. In general, clay has a high dry strength compared to its wet strength, and if enough clay is present, it may act as a binder between the sand grains. Dry clay helps deposits to withstand overburden loads until water percolates through them, but as the clay adsorbs water it loses part of its strength and allows the overburden load to compact the deposit and produce subsidence. The effect of clay content on near-surface subsidence is discussed in detail in the section "Causes and mechanics of near-surface subsidence."

The principal source of clay is the marine sedimentary rocks and the soils formed on them. It is difficult to estimate from a generalized geologic map the amount of shale and mudstone in an area because the lithology of the formations changes along the strike. Marine sedimentary rocks occur in about 90 percent of the Martinez Creek basin, but the average clay content of 10 samples from a 70-foot core hole in the Martinez Creek fan is only 6 percent. Marine sedimentary rocks are exposed also in about 85 percent of the Moreno Gulch basin, but surface and core-hole samples indicate that the deposits have a clay content of about 20–25 percent.

Geologic sections were studied in 19 drainage basins to estimate the percentage of clay-rich rocks. The sediments included in the estimates shown in table 4 are mudstone, shale, and clay. Detailed maps and sections provided stratigraphic information for 50 square miles of the drainage basins. Publications used for the compilation of table 3 and Payne's (1960) guidebook of the type Panoche formation provided the maps from which the areas of each formation were planimetered and provided records of measured sections. The amount of mudstone and shale in the various formations in the remaining 550 square miles of drainage basins was estimated from field studies of representative stratigraphic sections in each basin. The accuracy of the estimates varies with the amount of published information and with the accessibility and exposure of the sections studied. The estimated maximum error, shown as a plus or minus range, is also listed in table 4.

TABLE 4.—*Area of selected drainage basins, estimated percentage of each underlain by clay-rich rocks, and estimated range of error*

| Stream | Area (sq mi) | Estimated percent underlain by clay-rich rocks | Estimated range of error (percent) |
|---|---|---|---|
| *A.* **Nonsubsiding fans** | | | |
| Laguna Seca Creek | 11.1 | 48 | ±7 |
| Wildcat Canyon | 11.4 | 42 | ±7 |
| Little Panoche Creek | 104.0 | 35 | ±10 |
| Panoche Creek | 296.0 | 32 | ±10 |
| Cantua Creek | 49.4 | 32 | ±10 |
| Salt Creek | 25.2 | 41 | ±10 |
| Martinez Creek | 8.9 | 34 | ±10 |
| Domengine Creek | 11.2 | 38 | ±10 |
| Average | 64.6 | 38 | |
| *B.* **Subsiding fans** | | | |
| Moreno Gulch | 11.7 | 67 | ±7 |
| Marca Canyon | 1.9 | 60 | ±7 |
| Capita Canyon | 2.6 | 67 | ±7 |
| Sec. 15, T. 15 S., R. 12 E | 0.5 | 86 | ±7 |
| Tumey Gulch | 29.1 | 67 | ±10 |
| Arroyo Ciervo | 8.0 | 68 | ±4 |
| Arroyo Hondo | 25.7 | 52 | ±10 |
| Average | 11.4 | 67 | |
| *C.* **Fans that might subside if irrigated** | | | |
| Gres Canyon | 0.18 | 57 | ±7 |
| Chaney Ranch Canyon | .53 | 40 | ±7 |
| Dosados Canyon | .93 | 63 | ±7 |
| Escarpado Canyon | .56 | 60 | ±7 |
| Average | .55 | 55 | |

Clay-rich rocks are almost twice as abundant in the drainage basins of subsiding fans as in the drainage basins of nonsubsiding fans, and the drainage basins of fans that might subside if irrigated have an intermediate amount of clay-rich rocks. Thus, large amounts of clay-rich rock seem to be associated with subsiding fans, even if the extremes of the estimated ranges of accuracy are used.

Two variables must be considered in the evaluation of the above relations. The first variable is the rate of erosion of different rock types. The soft clay-rich rocks of a drainage basin are eroded more rapidly than the resistant sandstone, and this results in the removal of a proportionately larger amount of clay-rich material. The proportion of clay-rich material removed changes as areas of soft rocks are eroded to a low relief and areas of resistant rocks are eroded to a greater relief.

The second variable is that the products of erosion of clay-rich sediments are markedly different for various rock types. Clay or punky Kreyenhagen shale is deposited on the alluvial fans as clay-size particles and as larger fragments and slaty shale of the Franciscan formation or porcellaneous Kreyenhagen shale is deposited on the fans mainly as sand- and gravel-size fragments. Most drainage basins have both hard and soft clay-rich rocks, but soft clay-rich rocks are predominant in the drainage basins of subsiding fans.

## GEOLOGY AND VEGETATION OF THE ARROYO CIERVO DRAINAGE BASIN

The evidence discussed in the two preceding sections indicates that, in general, the drainage basins of subsiding fans are more rugged and have more clay-rich rocks than the basins of nonsubsiding fans. The following description of a basin of a subsiding fan provides detailed information about most of the factors controlling erosion, which in turn directly affects the amount, rate, and type of deposition on the fan.

Arroyo Ciervo heads on 3,400-foot Ciervo Mountain, and the basin is underlain by a variety of Cenozoic marine and continental rocks. The basin was chosen for study for the following reasons:

1. The alluvial fan of Arroyo Ciervo subsides.
2. Most of the formations do not change in lithology along the strike within the basin.
3. The basin is of an intermediate size compared to other basins studied.
4. The Inter-Agency Committee did more coring and testing on the Ciervo fan than on any other fan.
5. Sediments were deposited on the Ciervo fan each year from 1955 to 1960, and these deposits can be

related to the drainage-basin characteristics. (See sections "Mudflow deposits" and "Amount and rate of deposition.")

The oldest formation in the basin is the punky diatomaceous Kreyenhagen shale of Eocene and Oligocene (?) age. The Oligocene Tumey formation (Atwill, 1935) overlies the Kreyenhagen in part of the basin. The Tumey formation has a sandstone member and a shale member, and the shale has the same lithology as the Kreyenhagen shale. Therefore, the Kreyenhagen shale and the shale of the Tumey formation were mapped as one unit, but the Kreyenhagen accounts for nearly all the diatomaceous shale in the basin. The Kreyenhagen shale and the shale of the Tumey formation underlie 60 percent of the drainage basin, as is shown in table 5; and plate 3 shows that most of the landslide areas are also in the Kreyenhagen.

TABLE 5.—*Lithology of the Arroyo Ciervo drainage basin*

| Formation or unit | Lithology | Area (sq mi) | Percent of total area |
|---|---|---|---|
| Landslides | Shale, diatomaceous, punky | 0.69 | 8.6 |
| Dune sand | Sand, well-sorted | .20 | 2.5 |
| Tulare | Sand and silt, brown to yellowish-white. | .27 | 3.4 |
| Etchegoin, upper part | Sand and silt, red- and green-hued; blue-gray sand bed at top. | .24 | 3.0 |
| Etchegoin, lower part | Sand and silt, green-blue and red-hued. gravel lenses and marl beds common. | .17 | 2.2 |
| Jacalitos | Sand and silt, green-blue and red-hued; gravel lenses and marl beds common. | .15 | 1.9 |
| Santa Margarita | Conglomerate and sandstone | .01 | .1 |
| Temblor formation and sand of Tumey formation (Atwill, 1935). | Sandstone, coarse-grained; fine grained sand in upper part. | 1.45 | 18.3 |
| Kreyenhagen shale and shale of Tumey formation. | Shale, diatomaceous, punky | 4.77 | 60.0 |
| Total | | 7.95 | 100.0 |

The sand of the Tumey formation (Atwill, 1935) and the Miocene Temblor formation overlie the diatomaceous shales. The lower part of the Temblor and the sand of the Tumey formation are coarse-grained locally very fossiliferous sandstones. Again, the units were not mapped as separate formations because the purpose of the mapping was to determine the amount of the different lithologic types within the basin. The upper part of the Temblor formation consists of fine-grained sand and sandy silt. The Temblor formation and the sand of the Tumey formation are exposed in 18 percent of the Arroyo Ciervo drainage basin; the sandstones occur as patches that cap the higher hills.

The Santa Margarita formation, which is exposed in only 0.1 percent of the basin, thins to the northwest and consists of interbedded conglomerate and sandstone. The conglomerate is fossiliferous and has clasts of serpentine.

Of the continental deposits that underlie 10.5 percent of the drainage basin, the Jacalitos is the oldest. This unit has a varied lithology composed mainly of green-blue and reddish-brown fine-grained sand and silt beds; gravel lenses and marly beds are common. The Jacalitos is exposed in only 2 percent of the drainage basin. The approximate contact between the Jacalitos and Etchegoin formations is from a map by Green and Cochran (1958).

The Etchegoin formation is divided into two parts on plate 3 on the basis of lithology. The lower part has the same general lithology as the Jacalitos, but the upper part consists of reddish- and greenish-gray fine-grained sands and silts and a few marly beds; a conspicuous gray-blue sand bed is exposed below the contact with the Tulare formation. The gravel lenses in the Jacalitos and the lower part of the Etchegoin commonly cap the hilltops and dip slopes, where the gravel retards the erosion of the softer deposits. Thus, a more rugged topography is formed on the Jacalitos and the lower part of the Etchegoin than on the upper part of the Etchegoin, which has no gravel lenses and underlies gently rolling hills.

The Tulare formation is predominantly brown to yellowish-white sand and silt. There is also some gravel and a little gypsite.

Two types of landslides occur on the steeper slopes in the clay-rich rocks throughout the Ciervo Hills: one is characterized by the downward movement of blocks of rock and soil that may be rotated slightly; the other is an actual flowage of rock and soil. The first type of movement is a slump (Sharpe, 1938, p. 66, 67), and the second is an earthflow (Sharpe, 1938, p. 53). Earthflows are usually accompanied by slumping near the upslope end. Many landslides continue to move downhill for years and probably should be referred to as slowly moving earthflows. Putnam and Sharp (1940, p. 594) note that the downslope movement of a similar type of earthflow near Ventura, Calif., during 1 year was in many places only 6–7 feet.

In the Arroyo Ciervo area, comparison of aerial photographs shows that cracks have opened in some of the earthflows and slumps since 1940. Many of the earthflows and slumps are probably the result of the rejuvenation of adjacent stream channels (pl. 3) in which accelerated downcutting has removed part of the material near the base of the slope and has created an unstable mass of soil and rock on the higher slopes. Rainwater seeping along bedding planes probably weakened the mass enough to start the slump. Occasional floods clear the debris out of the stream channel and allow more material to creep down the slope and into the channel. This type of mass wasting supplies large quantities of debris to flood waters and probably is conducive to mudflow deposition on the alluvial fan.

About 2.5 percent of the basin is covered by dune sand that has formed from the sand of the Temblor and the Tumey formations. The dunes are on or near the sandstone caps of the higher hills and are thickest on the lee sides of the hills.

The lithology of a geologic unit partly controls the type of soil, which influences the type and amount of vegetation. In the Arroyo Ciervo basin, shaly soils generally support a poorer growth of grass and bushes than do sandy soils.

Other factors that control vegetative density are the amount of rainfall and the direction toward which a slope is facing. The average annual rainfall ranges from about 7 inches at the edge of the San Joaquin Valley to about 15 inches above the 3,000-foot contour.

FIGURE 6.—Difference in vegetative cover on the north and south slopes of Arroyo Ciervo.

North-facing slopes have a good vegetative cover of grass and bushes, but the south-facing slopes are barren (fig. 6); the lithology is the same on both sides of the valley. The Kreyenhagen shale and shale of the Tumey formation (foreground, fig. 6) are overlain by the sand of the Tumey formation and the Temblor formation. The sandstone on the barren side of the valley supports a few scattered shrubs.

The vegetative cover partly controls the amount of runoff from a drainage basin and the type of deposition on the alluvial fan. Runoff will be larger and faster on a barren slope than on a grassy slope, which slows the flow of water and allows part of it to soak into the soil.

Probably the most significant effect of vegetative cover is its ability to reduce the splash erosion of raindrops. Raindrop-impact erosion is most serious on slopes that have little or no vegetation and less serious on slopes where the vegetative cover is dense enough to intercept the falling raindrops. Ekern (1953, p. 23), in his discussion of raindrop impact erosion, says "* * * the kinetic energy * * * for falling rain ranges from 1,000 to 100,000 times the work capacity of shallow sheets of runoff water." Raindrops falling vertically on unprotected gentle slopes will splash some of the soil particles uphill, but more particles will be moved in the downslope direction (Ellison, 1950, p. 245). Ekern (1953, p. 25) gives a general equation which states that the percent of downslope movement is equal to 50 plus the slope percent. For example, if the approximate mean slope of the Arroyo Ciervo basin is 0.34, then about 84 percent of the soil particles displaced by raindrop splash move in the downhill direction. The net movement of particles on any slope will be downhill, but on very steep slopes (mean slope greater than 0.50), all the particles should be splashed downhill.

The vegetation of the Arroyo Ciervo basin was mapped on the basis of vegetative density and the ability of the vegetation to retard erosion. The vegetation was subdivided visually into the five units shown on plate 4.

The areas of dune sand are the same as shown on the geologic map (pl. 3). Most of the dunes are active, and the vegetation on them consists of clumps of bushes and smaller plants such as verbena. Some dunes are not moving and support a denser vegetation that includes grass. In general, the surface of the dunes is exposed to raindrop-impact erosion, but the amount of erosion by runoff is probably minor because water tends to infiltrate the sand rapidly.

Many of the south- and west-facing slopes support only a meager growth of plants, and these slopes are classed as barren. Some barren areas have no vegetation; others have widely scattered bushes and grasses, but the amount of vegetation is so small that erosion is not impeded. An example of a barren area is shown in the left side of figure 6.

Areas of sparse grass cover about 30 percent of the drainage area. Sparse grass is thin, and patches of bedrock can be seen through the grass. The sparse grass probably retards erosion, but erosion is rapid enough to prevent the formation of a thick soil. In the lower part of the basin, a few widely scattered bushes grow in the areas of sparse grass, but bushes are rare in the grassy areas of the upper part of the basin.

About 25 percent of the area has a good grass cover. In these areas erosion is slow enough to allow a soil to form that will support a nearly continuous growth of grass. The grass helps to retard erosion by intercepting raindrops and decreasing the rate and amount of runoff. Most areas of good grass cover are in the higher parts of the basin which get more rain.

Areas of grass and bushes include about 18 percent of the basin. The bushes are not closely spaced, and grass grows in the areas between the bushes. Bushes are most common on the sandy soils, but a few areas have a good growth of bushes on soils derived from shale (fig. 6). In the lower parts of the basin the spaces between the bushes usually are filled with sparse grass, but they may be barren. In the higher parts of the basin a good grass cover may grow between the bushes.

The locations where representative samples of plant types were collected are shown by letters on plate 4. Twelve of the most common plants were identified, and the scientific and common names are listed in table 6. The plant numbers at the right side of the table indicate the common plants at the 10 collection sites shown on plate 4.

TABLE 6.—*Common plants and their distribution in the Arroyo Ciervo drainage basin*

[Identified by T. C. Fuller, California Dept. Agriculture]

| Common plants | | | Distribution | |
|---|---|---|---|---|
| Plant | Scientific name | Common name | Location (pl. 4) | Plants |
| 1 | *Atriplex canescens* | Shadscale. | A | 1, 2, 3, 6, 9, 10 |
| 2 | *Juniperus californicus* | California juniper. | B | 8, 9, 11, 12 |
| | | | C | 9 |
| 3 | *Ephedra californica* | California ephedra. | D | 1, 3, 6, 9, 10 |
| | | | E | 1, 3, 5, 6, 7, 9, 10 |
| 4 | *Eriogonum fasciculatum* var. *foliolosum*. | California buckwheat brush. | F | 1, 5, 6, 9, 10 |
| | | | G | 9, 10, 12 |
| 5 | *Marrubium vulgare* | Common hoarhound. | H | 3, 5, 6, 9, 10 |
| | | | I | 3, 4, 6, 9, 10, 11 |
| 6 | *Guttierezia sarothrae* | Matchweed | J | 1, 5, 9, 11 |
| 7 | *Aplopappus linearifolius*. | | | |
| 8 | *Poa scabrella* | Pine bluegrass. | | |
| 9 | *Bromus madritensis* | Downy chess. | | |
| 10 | *Schismus arabicus* | | | |
| 11 | *Erodium cicutarium* | Red-stem filaree. | | |
| 12 | *Lepidium nitidum* | Pepper grass. | | |

Shadscale (*Atriplex canescens*) is the most common bush throughout the basin. Some of the grasses such as *Erodium cicutarium* and *Lepidium nitidum* are very short, and two of the taller grasses are downy chess (*Bromus madritensis*) and *Schismus arabicus* (not a native grass).

The visual classification was supplemented with density tests which provided a quantitative way of comparing the vegetative density of different areas. A wire hoop was thrown into an area that appeared to be transitional between two visual-classification types, and the grasses within the 2 square feet were plucked and air dried. Density tests were made at various altitudes during the late spring and summer after a winter which had only two-thirds the normal rainfall. However, some of the plants that were picked were grasses which had grown the winter before when rainfall had been 1½ times normal.

The air-dry weight of the vegetation is expressed in pounds per acre. Some slopes have no vegetation within a given acre. The average of the hoop tests places the density break between barren and sparse grass at about 190 pounds per acre and the break between sparse and good grass at about 430 pounds per acre. Vegetative densities were not made in areas of grass and bushes or in areas of good grass cover.

The middensities within the classification limits can be used to estimate the average density: barren areas have an approximate vegetative density of 95 lbs per acre; areas of sparse grass and dunes, about 310 pounds per acre; areas of good grass cover, about 500 pounds per acre; and areas of grass and bushes, about 600 pounds per acre. The weighted mean of these types gives an average vegetative density of about 350 pounds per acre for the Arroyo Ciervo watershed. The area of each type is listed in table 7.

TABLE 7.—*Vegetative density of the Arroyo Ciervo drainage basin*

| Type of area or cover | Area (sq mi) | Percent of total area | Approximate vegetative density (lbs per acre) |
|---|---|---|---|
| Sand dunes | 0.20 | 2.5 | 310 |
| Barren | 1.96 | 24.5 | 95 |
| Sparse grass | 2.38 | 29.8 | 310 |
| Good grass cover | 2.00 | 25.0 | 500 |
| Grass and bushes | 1.46 | 18.2 | 600 |
| Total or average | 8.00 | 100.0 | 350± |

Fourteen cross-valley profiles of the Arroyo Ciervo basin were drawn using a vertical-profile plotter attached to a multiplex plotter (fig. 7.). The position of the profiles is indicated by the letters *A—A′* through *N—N′* on plate 3. The area is so rugged that vertical exaggeration is unnecessary.

The 1957–58 rainy season, when rainfall was about 1½ times normal, provided an example of the amount and type of deposition that the Arroyo Ciervo basin can produce. Panoche Junction, 2½ miles northwest of the mouth of Arroyo Ciervo, had a seasonal rainfall of 11 inches; and New Idria, 6 miles southwest from the headwaters of Arroyo Ciervo, had 26 inches of rain. The Arroyo Ciervo basin probably received rainfall ranging between the amounts at the two weather stations. Deposition on the Arroyo Ciervo fan consisted principally of mudflows that were deposited between the middle of December 1957 and April 1958. In 3½ months, 62 acre-feet of material was eroded from 5.5 square miles of shale and 2.5 square miles of other types of rock in the Arroyo Ciervo basin, which has a relief ratio

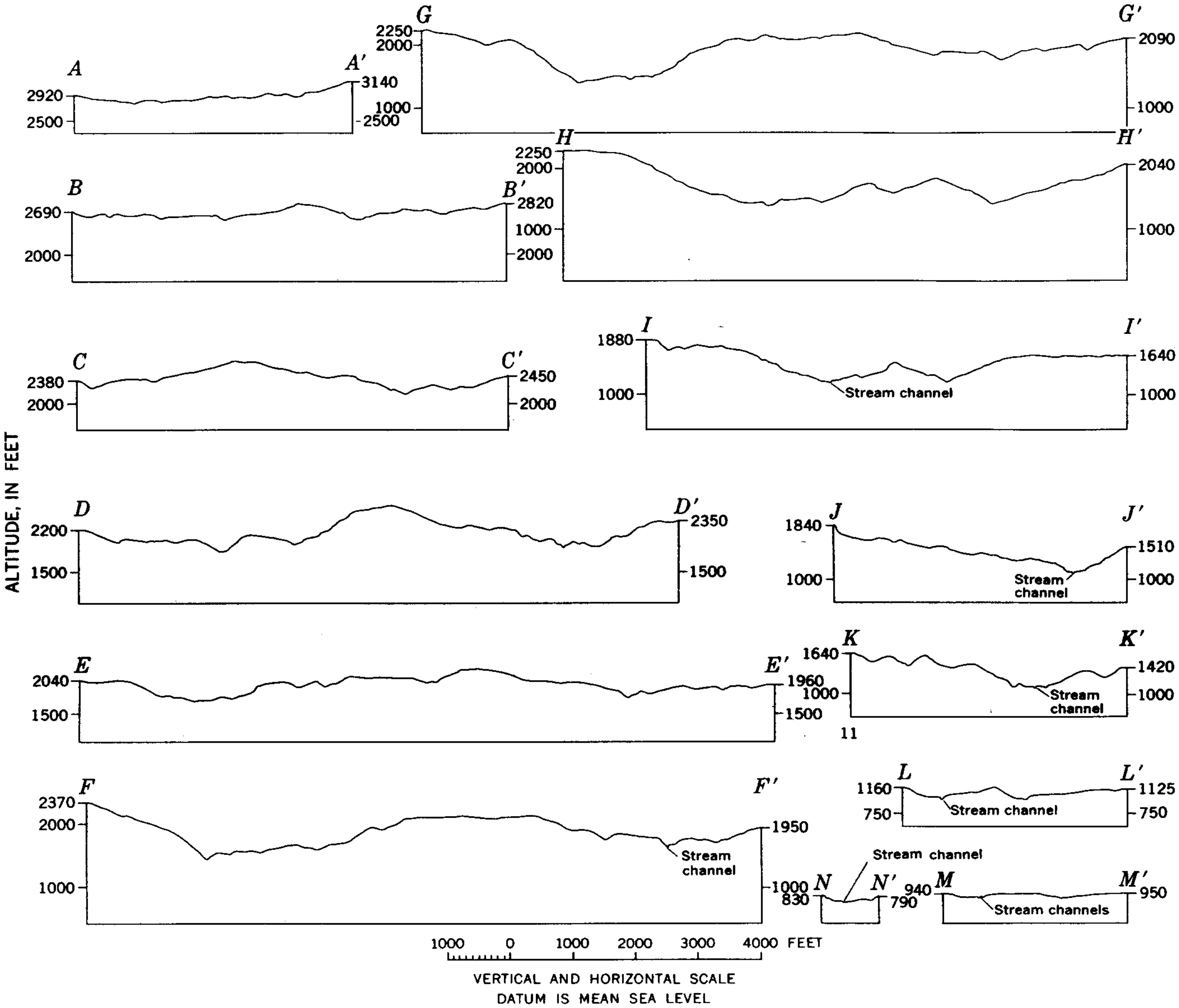



FIGURE 7.—Cross-valley profiles of the Arroyo Ciervo drainage basin.

of 0.077, an approximate mean slope of 0.34, and an estimated average vegetative density of 350 lbs per acre. The amount of material eroded represented a removal of an average of about 0.01 foot from the surface of the basin.

### SUMMARY OF THE GEOLOGY OF THE DRAINAGE BASINS

The use of selected numerical geomorphic parameters is partly successful in defining the differences between the drainage basins upstream from subsiding and nonsubsiding fans. The relief ratio and mean slope seem to be significantly larger for subsiding fans than for nonsubsiding fans. Parameters such as area, relief, and area-altitude integral do not show distinct differences between the basins of subsiding and nonsubsiding fans, but they are valuable for describing the drainage basins.

All the drainage basins studied except that of Little Panoche Creek are underlain mainly by marine sedimentary rocks. Soft clay-rich rocks predominate in drainage basins of subsiding fans; there, they underlie an average estimated 67 percent of the area as compared to an average estimated 38 percent for the drainage basins of nonsubsiding fans. Mass wasting in the form of earthflows and landslides is a striking feature on steep slopes underlain by shale.

Shaly soil usually supports less vegetation than sandy soil. Raindrop impact erosion is pronounced on slopes with little vegetative cover, and the lack of vegetation allows more runoff to reach channels at a more rapid rate than on densely vegetated slopes. In general, the basins of subsiding fans have a sparse vegetative cover, and the basins of nonsubsiding fans have a nearly continuous vegetative cover.

### GEOMORPHOLOGY OF THE ALLUVIAL FANS

Study of the geomorphology of the alluvial fans shows that the subsiding fans are thicker and almost twice as large as nonsubsiding fans derived from source areas of comparable size. However, because the geomorphology study did not reveal many criteria that could be used in appraisal of subsidence, the information is presented elsewhere (Bull, 1964a). The geomorphic characteristics of the fans are summarized in this section.

The shapes, areas, slopes, and histories of deposition of the individual fans in western Fresno County reflect a tendency toward a state of equilibrium, or balance, among a complex set of controlling factors, which include the area, lithology, mean slope, and vegetative cover of the drainage basin; slope of the stream channel; climatic and tectonic environment; and the geometry of the adjacent fans and the depositional basin itself. Changes in one or more of these factors will tend to cause a readjustment of the fan morphology.

The fans are derived from drainage basins that are generally similar with respect to topography, climate, and tectonic environment but that vary in size and lithology. Subsiding fans are associated with drainage basins that have abundant clay-rich rocks. Fans derived from mudstone- or shale-rich basins are generally 35–75 percent steeper than fans of similar area derived from sandstone-rich basins and roughly twice as large as fans derived from sandstone basins of comparable size. These facts indicate that the volume of fan deposits derived from the two rock types differs; presumably the difference can be attributed mainly to the greater erodibility of the mudstone and shale.

The equations expressing these relations between fan area, $A_f$, drainage-basin area, $A_d$, and fan slope, $S_f$, are as follows:

Drainage basins underlain by 48–86 percent mudstone and shale

$$A_f=2.4A_d^{0.98}$$
$$S_f=0.023A_d^{-0.16}$$
$$S_f=0.034A_f^{-0.28}$$

Drainage basins underlain by 58–68 percent sandstone

$$A_f=1.3A_d^{0.98}$$
$$S_f=0.022A_d^{-0.32}$$
$$S_f=0.025A_f^{-0.34}$$

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

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

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

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

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

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

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

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

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

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

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

## ALLUVIAL-FAN DEPOSITS

Near-surface subsidence is caused by the compaction of certain alluvial-fan deposits. This section provides a basic classification and description of alluvial-fan deposits in western Fresno County, with emphasis on the features that partly control the amount and rate of subsidence. Some of the controlling features are type and rate of deposition, clay content, textural and structural voids, and postdepositional changes. The effect of these features on the causes and mechanics of subsidence is discussed in the next section.

### CAUSES OF DEPOSITION

Deposition on alluvial fans generally is believed to be caused by a pronounced decrease in the slope of a stream channel downstream from the point where the stream leaves an area of higher relief. Longwell, Knopf, and Flint (1948, p. 87–88) state that the abrupt change in gradient may cause a stream to deposit most of its load. Blissenbach (1954, p. 178) believes that the decrease in stream gradient on the alluvial fan is one cause of deposition.

However, a study of topographic maps in western Fresno County shows that the gradient of the valley above the apex of a fan is about the same as the gradient of the upper fan segment. Profiles of fans and the valleys upstream from their apexes are shown in U.S. Geological Survey Professional Paper 352–E. (Bull, 1964a).

If there is no abrupt change in the stream gradient above and below the apex of a fan, deposition must be related to other hydraulic factors. In any stream channel, the discharge per unit of time, $Q$, is equal to the product of the width, $w$, the mean depth, $d$, and the mean velocity of flow, $v$. This basic equation, $Q=wdv$, is one of several equations applied to streamflow problems by Leopold and Maddock (1953), and it is used here to help explain why deposition occurs on alluvial fans. For example, when a flow reaches the end of a channel, it may spread out to many times the channel width as it continues to move downslope. If $Q$ is assumed to be constant, then an increase in $w$ must be accompanied by a decrease in $d$ or $v$, or both, to balance the equation. Therefore on alluvial fans, an increase in the width of a flow accompanied by a decrease in both velocity and depth causes part of the sediment to be deposited.

Actually, the quantity of flow may not remain constant as a flow moves along the channel and onto the fan. Water may be absorbed by the soil, and on dry fans the amount of absorption generally increases markedly as the wetted area increases. In the equation $Q=wdv$, a decrease in $Q$ while $w$ is increasing requires an additional decrease in $d$ and $v$; this also will promote deposition. The infiltration of water into the beds of ephemeral streams is discussed by McGee (1897, p. 99), Babcock and Cushing (1942), Leopold and Miller (1956, p. 13–15), and Schumm and Hadley (1957, p. 170). Blissenbach (1954, p. 178) suggests that deposition on alluvial fans is due partly to a continuous decrease in the volume of water.

### CLASSIFICATION AND DESCRIPTION

Flow in the stream channels in western Fresno County varies from clear water to viscous mud, and a usable classification must include deposits of mudflows, streamflows, and the intermediate gradations; also, it should be applicable to both surface and subsurface deposits.

Blissenbach (1954, p. 178) classifies the agents of alluvial-fan deposition into three types: sheetfloods, streamfloods, and streams. McGee (1897), Ives (1936), Davis (1938), and McKee (1957, p. 1726–1732) also have used the terms "sheetflood" and "streamflood." Blissenbach says that a sheetflood spreads out in the form of a sheet covering part of an alluvial fan, whereas a streamflood is confined to definite channels on the fan. Streams require a steady supply of water and thus are not common in arid or semiarid regions. The amount of debris is less in streams than in streamfloods or sheetfloods. The sheetflood-streamflood-stream classification is dependent on the shape of the resulting deposits as well as on the flow characteristics. For example, according to Blissenbach, a mudflow would be a sheetflood deposit if it were laid down in the form of a broad sheet, but would be a streamflood deposit if it were laid down in a stream channel.

It is difficult to infer the shape of a deposit and the place of deposition from subsurface samples, particularly if the samples are from a core hole. This is the main reason why the sheetflood-streamflood-stream classification of alluvial-fan deposits was not used for the deposits discussed in this paper.

A sharp classification line cannot be made between mud and sediment-laden water, and mudflow deposits and water-laid sediments are separated by types whose properties are intermediate between the two. This third group is not given a new name but is simply referred to as deposits that are intermediate between mudflow deposits and water-laid sediments.

This general three-part classification has flexible defining boundaries. The mudflow, intermediate, and water-laid classification is independent of the overall shape of the deposit and the place of deposition, and the scheme can be used to classify subsurface samples because parameters from grain-size analyses can be used to help describe each type.

The three types of deposits occur in all the fans studied in western Fresno County. Intermediate and mudflow deposits are commonest in subsiding fans, and water-laid sediments are commonest in nonsubsiding fans.

The deposits were also classified according to their grain-size distribution (fig. 8). The National Research Council (1947) grain-size definitions are used in this report, and the basic classification diagram used is triangular and is based on sand-silt-clay ratios (Shepard, 1954).

*National Research Council grain-size definitions*

| *Material* | *Grain size (mm)* |
|---|---|
| Gravel | 64–2 |
| Sand | 2–0.0625 |
| Silt | 0.0625–0.004 |
| Clay | <0.004 |

Shepard's diagram is shown in figure 8*A*. In this percentage classification the entire sample is taken into account, and equal weight is given to sand, silt, and clay. It is a simple diagram that consists of three basic lines within a reference triangle. The central triangle provides an area for deposits having approximately equal amounts of sand, silt, and clay and eliminates the necessity of forcing a characteristic name of sand, silt, or clay on a deposit in which no size predominates.

One disadvantage of Shepard's diagram is that a second diagram is necessary for classifying samples containing gravel, unless the gravel is included with the sand. As gravel content of 1 percent or more occurred in 68 of the 102 samples analyzed by the author, the gravel fraction was added to the sand fraction and the sample was named according to Shepard's classification only if the sample contained less than 20 percent gravel. A modification of Shepard's diagram, shown in figure 8*C*, was used when a sample contained 20 percent or more gravel. In the modified diagram, silt has been included with the clay so that gravel can occupy one of the corners, and the terminology has been changed to include the terms "gravel" or "gravelly." The cross-hatched area below the 20-percent-gravel line is never used, because any sample in this area would be classified according to Shepard's diagram (fig. 8*A*).

Figure 8*B* shows the distribution of sand and gravel, silt, and clay for 87 samples from alluvial fans in western Fresno County. Fifty-three of these samples had an average gravel content of 7 percent. Most of the samples contained more than 50 percent sand and had more clay than silt, but the pattern shows a variety of size distribution for the alluvial-fan deposits that were analyzed. Most of the samples were eroded from deposits of drainage basins in the foothill belt which supplied predominantly quartz, feldspar, and shale fragments. The small amounts of silt available for erosion in most drainage basins may explain why many samples contained more clay than silt. Also, the particles abraded from the shale chips during transport may have been clay-size instead of silt-size. Maximum

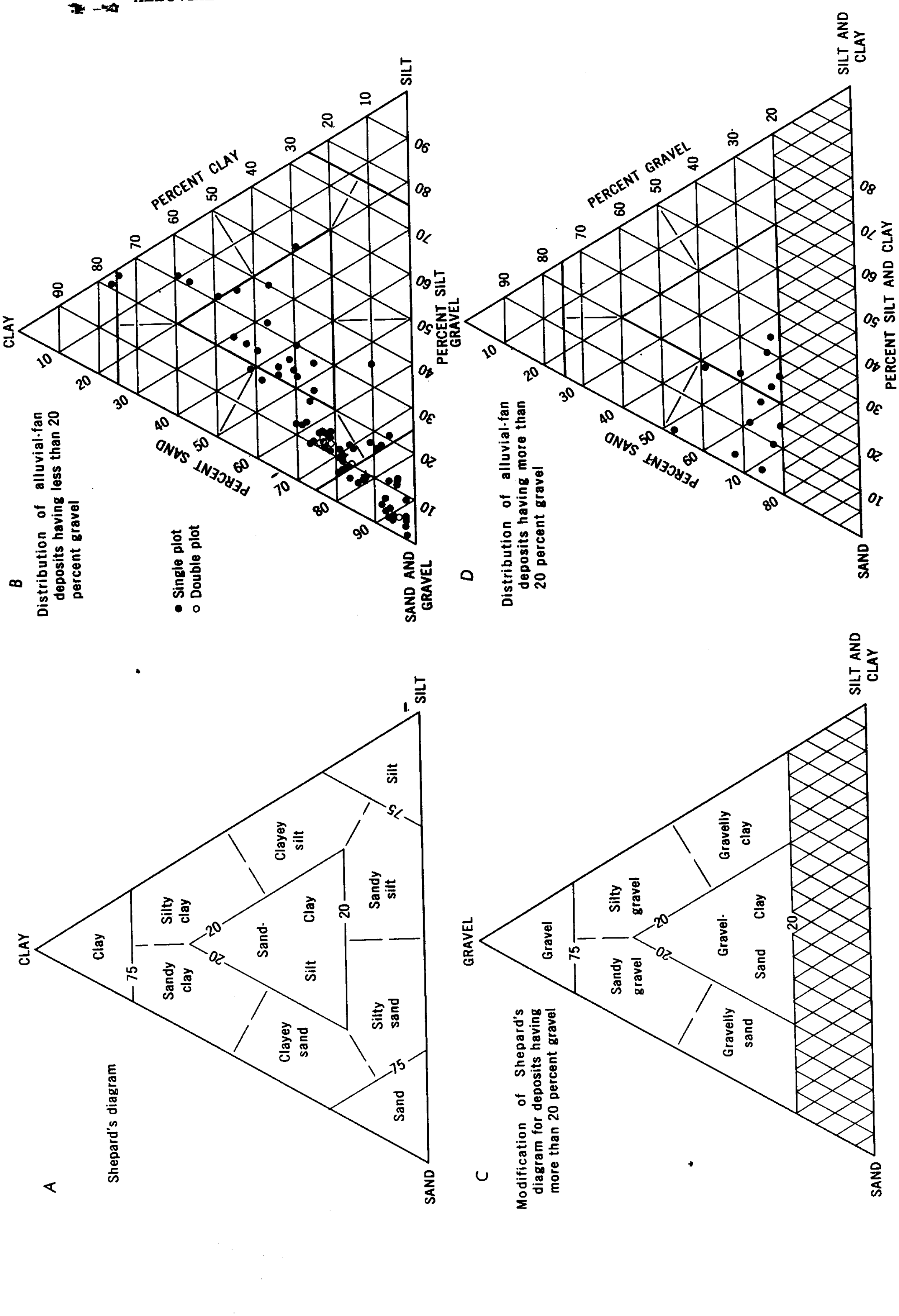



FIGURE 8.—Nomenclature and grain-size distribution of alluvial-fan deposits. *A*, Shepard's diagram; *B*, distribution of alluvial-fan deposits having less than 20 percent gravel; *C*, modification of Shepard's diagram for deposits having more than 20 percent gravel; *D*, distribution of alluvial-fan deposits having more than 20 percent gravel.

abrasion can occur in mudflows because of the larger amount of grain contact.

Figure 8*D* shows the size distribution for 15 samples that consisted of 20 percent or more gravel. The average gravel content was 31 percent, and the median was 25 percent. Most of the gravelly samples contained more than 10 percent clay and silt.

The nomenclature in figure 8 is geologic, and engineers may prefer an engineering nomenclature in which clay content is stressed. The Corps of Engineers Mississippi Valley Commission diagram (Casagrande, 1948) can be used to apply engineering terminology to the samples (fig. 9).

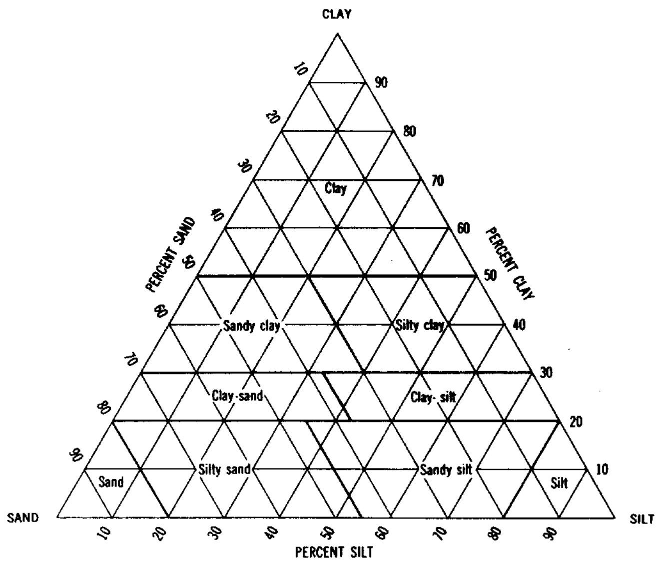



FIGURE 9.—Corps of Engineers Mississippi Valley Commission nomenclature diagram.

The collection-site location of all the samples analyzed by the author is listed in table 17 along with the percent gravel, sand, silt, and clay, and other properties.

The grain-size distribution and sorting of the 102 samples listed in table 17 are shown in figure 10. The grain diameter of the larger quartile is plotted against the grain diameter of the smaller quartile for each sample. The diagonal lines represent lines of equal sorting, based on the Trask sorting coefficient (1930, p. 594). If the larger and smaller quartiles of a sample had the same diameter, the sorting coefficient would be 1.0 and would indicate perfect sorting between the quartiles.

The spread of the points in figure 10 shows that the alluvial-fan deposits range from very well sorted sands to very poorly sorted mixtures of clay and sand. The trend of the points roughly parallels the smaller quartile axis. Where the smaller quartile is larger than 32 microns, the sample may be well sorted; but where it is smaller than 32 microns, the sample is usually poorly sorted. The contrast in sorting may indicate that the material carried in suspension is not sorted as well as the material that is moved predominantly as bed load.

Logarithmic plots of the coarsest 1-percentile grain size (C), and the median grain size (M) of deposits may make patterns characteristic of distinct sedimentary environments, according to Passega (1957). These parameters were selected because the coarse fraction of a sediment seems to be more representative of the agent of deposition than the fine fraction (Passega, p. 1957). "C" indicates the upper limit of competence of a depositional agent for the samples analyzed and assumes that a full range of sizes was available for transport. "C" usually is approximate because the slope of the cumulative curve in that part of most grain-size graphs is gentle. Passega obtained patterns for deposits of tractive currents, quiet water, beaches, and turbidity currents.

Textural patterns of surface samples of alluvial-fan deposits in western Fresno County are shown in figure 11, and values of C and M for each sample are listed in table 17. In figure 11 the sorting of a sample between the 50th and coarsest percentile is indicated. A sample on the line C=M would be perfectly sorted in its coarser half.

Two CM patterns are shown in figure 11. A tractive-current pattern is represented by the letters *PQRS*, which are the letters used by Passega to describe the segments of the pattern. The *RS* segment apparently

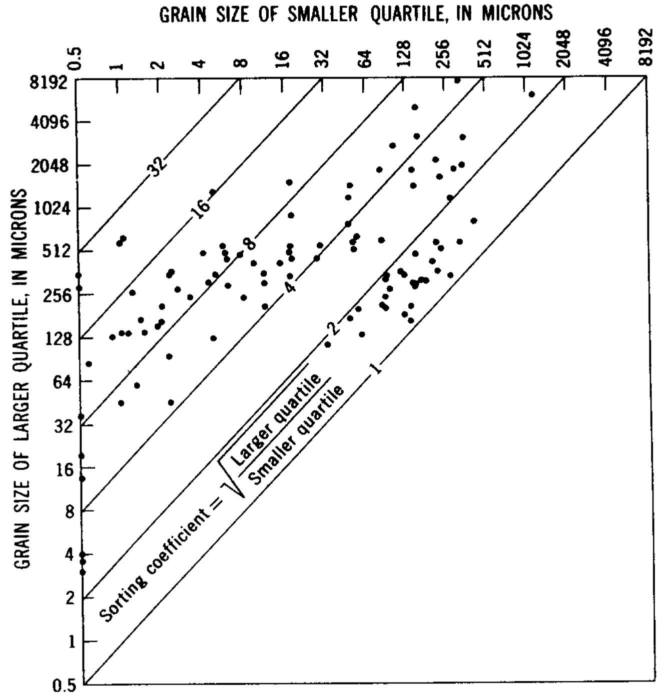



FIGURE 10.—Grain-size distribution and sorting of alluvial-fan deposits.

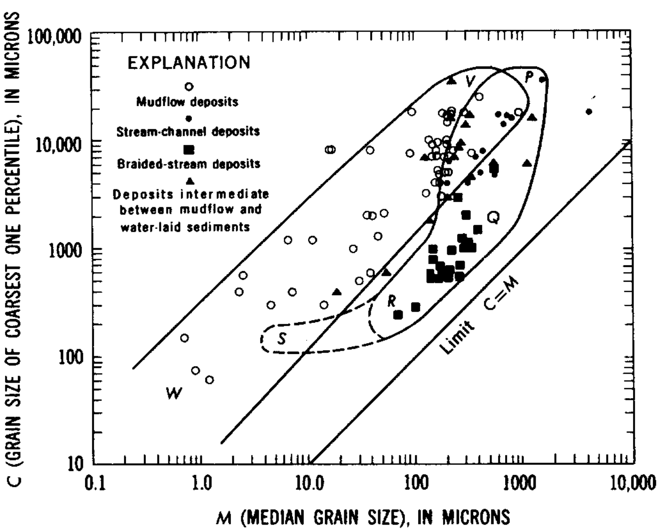



**Figure 11.**—Textural (CM) patterns of the coarsest one percentile and median grain size of alluvial-fan deposits in western Fresno County.

does not exist for alluvial-fan sediments and is shown by a dashed line so that the reader can compare a complete tractive-current pattern with Passega's type example (p. 1954) for the Mississsippi River, which was based on data from the U.S. Waterways Experiment Station at Vicksburg, Miss. In Passega's type example the segments of the CM pattern correspond with three divisions of the channel. The plot of samples from the main section of the channel were in the segment between *P* and *Q*, and the segment between *Q* and *R* represented samples from a submerged bank or bar. Samples from a deep, protected part of the channel were represented between *R* and *S*.

The pattern for tractive-current deposits derived by Passega (1957) consists of three variations of one type of deposition. In Passega's Mississippi River plot, *PQ* represents the coarsest bed material, whose lower limit of 600 microns for C indicated to Passega that particles larger than 600 microns were moved predominantly by traction. *QR* was parallel to the limit C=M between 350 and 600 microns. Deposits of this segment probably were in suspension part of the time, and sedimentation from the coarser grain sizes produced well-sorted sediments. Passega concluded that the *RS* segment is controlled by bed samples from a deep protected section of the Mississippi River channel. The upper limit of this segment is about at the line C=200 microns, which indicated to Passega that the Mississippi River is always turbulent enough to carry particles of that size in suspension. Not all tractive-current deposits show the three segments of the Mississippi River pattern, and Passega's tractive-current patterns from other rivers, bays, and tidal flats commonly have only two of the three segments.

The tractive-current pattern of alluvial fans (fig. 11) shows two of the three segments identified by Passega in the Mississippi River deposits. The stream-channel deposits plot in the *PQ* segment, and the lower limit of 1,500 microns for C in this segment may indicate that particles larger than 1,500 microns are transported predominantly by traction. The points included within the *QR* segment represent samples from deposits of shallow braided streams or sheets of water and from sandbars adjacent to the main part of a larger stream channel. This segment is roughly parallel to the limit C=M; therefore, C is roughly proportional to M.

The long rectilinear pattern *VW* in figure 11, like the middle segment of the *PQRS* pattern, is nearly parallel to the limit C=M; but the axis of the pattern is at a greater distance from the limiting line. The sample points within this pattern represent poorly sorted mudflow deposits. Most of the particles are carried in suspension, and a decrease in velocity and depth tends to cause precipitation of some of the coarser material along with some matrix. The low values of C and M probably represent deposition at a lower velocity than the velocity at which the coarser material is deposited.

The CM pattern for the mudflow deposits is the same type that Passega showed for turbidity currents and may indicate that mudflows are comparable to dense turbidity currents in their mechanics of deposition. The chief difference between mudflows and the low-density turbidity currents studied by Passega seems to be the density of the currents and, consequently, the sorting of the deposits. Passega mentioned that C for points along the axes of turbidity current patterns is 2.3–4.2 times M. C for points along the axis of the mudflow pattern ranges from about 40 to 80 times M. This indicates that mudflows are less well sorted and probably denser than the turbidity currents studied by Passega (Bull, 1962).

The upper ends of both patterns indicate the approximate maximum competence of the transporting agents for the samples collected. The source areas of most fans supply little material larger than fine gravel, although some deposits contain a few cobbles and boulders.

Deposits of mudflows and tractive currents provide two patterns that illustrate the strong contrast in the types of alluvial-fan deposition. The points representing deposits intermediate between mudflows and water-laid sediments plot within the two patterns and in the area between the mudflow and tractive-current patterns.

### MUDFLOW DEPOSITS

McGee (1897, p. 108) was one of the first to use the term "mudflow." Blackwelder (1928, p. 466) defined a mudflow as a type of landslide intermediate between a landslide and a waterflood, and it is generally recognized that mudflows follow definite stream channels. Mudflows may be caused by rainfall, volcanic action, snowmelt, or fluid landslides that follow stream channels. The mudflows in western Fresno County usually form during periods of intense rainfall.

The conditions favoring the formation of mudflows are summarized by Rickmers (1913, p. 195), Blackwelder (1928, p. 478–479), and Sharpe (1938, p. 56). These conditions include:

1. Unconsolidated material that contains enough clay to make it slippery when wet.
2. Slopes that are steep enough to induce rapid erosion or sloughing of material.
3. Short periods of abundant water.
4. Insufficient vegetative protection.

All these conditions are present at certain times in the foothill belt of western Fresno County. Clay-rich Cenozoic formations are characteristically poorly indurated and friable. Upper Cretaceous rocks are more indurated than the Cenozoic rocks but are more readily eroded than the older rocks of the Franciscan formation. The mean slope of many basins in the foothill belt is steep. The mudflows may be caused by periods of widespread intense rainfall or by rainfall from local cloudbursts. Vegetative cover on many slopes is insufficient to prevent rapid erosion, as was shown by the study of the vegetative density of Arroyo Ciervo basin.

Mudflows are common in western Fresno County. They were deposited on some of the alluvial fans in every year between 1955 and 1960, and aerial photographs taken before 1955 show mudflows so recent that vegetation had not grown over the deposits. This frequency of deposition contrasts with descriptions from other parts of the Western United States which suggest that the time interval between large mudflows is decades or centuries (McGee, 1897, p. 108; Davis, 1938, p. 1344).

Many ranchers and sheepherders say that mudflows are most common when heavy rain falls on dry hills early in the winter, whereas rain late in the winter is more likely to cause water flooding. This apparent seasonal distribution of mudflows may be caused by changes in the amount of debris in the stream channels and by changes in the vegetative density. Much of the runoff flowing down dry slopes and stream channels is absorbed by the soil, causing a concentration of sediment in the flow reaching an alluvial fan. Once the soils are wetted, a larger volume of water reaches the alluvial fan for any given storm, and the sediment concentration may be less. However, the type of runoff and the amount of material available for a flow to pick up vary. At the end of the rainy season the new growth of grasses and annual plants reduces raindrop-impact erosion and the velocity of flow down the slopes. Thus, runoff is not as rapid and does not contain as much sediment as that earlier in the season. The amount of debris in the channels is larger at the beginning of the rainy season than later on. Debris from slumps, landslides, and rodent activity accumulates in the stream channels for about 6 months of the year. Parts of stream channels in Arroyo Ciervo had 1 to 6 feet of slump debris in them 4 months after the winter rains had stopped in 1958. The amount of slumping is greater in wet years than in dry.

The most viscous mudflow in the 1957–58 season was during heavy rains in December. Mudflows can occur late in the rainy season, but a greater than usual intensity of precipitation may be necessary. The only deposition in the 1956–57 season was a mudflow in March when a new growth of annual plants was on the slopes.

Sediment concentration of a flow in an ephemeral stream is influenced partly by the length of the stream channel. The length partly controls the amount of surface area into which water can infiltrate, and if a stream channel is long, more bank material is available to slough into the channel. For example, the straight-line distance from the major fork in Arroyo Ciervo to the edge of the San Joaquin Valley is 6.1 miles, but the distance between the same points along the meandering stream channel is 12.3 miles. The long meandering channel provides a larger surface area into which water can infiltrate, and more bank material is exposed to supply debris than if the channel were relatively straight. Greater length also provides more time for water to infiltrate into the channel bed. These factors cause a large sediment concentration in a flow that reaches a fan.

Many authors have noted that mudflows move in surges down a stream channel (Conway, 1893, p. 292; Pack, 1923, p. 352; Blackwelder, 1928; Jahns, 1949, p. 12; Sharp and Nobles, 1953; and Kesseli and Beaty, 1959, p. 38, 54). Some surges are so viscous that they come to a halt in the stream channel, and some are ripples which catch up with the front of a flow. The surges result from temporary damming of a mudflow by obstructions or constrictions in the channel, or they may be caused by the peak flow from tributaries entering the main channel at different times. Mudflows usually plaster the sides of the channel with mud, and the height of the mud cake along the channel is one indication of how much damming has taken place. The author has found only two places where mudflows appear to have been temporarily dammed by material other than slump debris. One "dam" was a large boulder in a narrow channel, and the other was a constriction in a channel made by a sandstone ledge.

Although most of the mudflows occur in the ephemeral streams, they also occur in the intermittent streams. Lyle Christie (oral commun., July 1957) observed mudflows moving down Cantua Creek in 1934 and 1948; both flowed 3 miles into the San Joaquin Valley. The roar of the approaching mud could be heard half a mile away, and the front of the May 1948 mudflow was estimated to be 4 feet high. At least one of the mudflows was caused by a local cloudburst. Both mudflows originated in the canyons of the foothill belt.

When a mudflow approaches the lower end of the channel, it may overtop the banks, producing lobate tongues of mud that are most common on the outside of the bends in the stream channel. Farther downstream the mudflow overtops both banks and spreads out as a sheetlike deposit.

The thickness of a mudflow decreases uniformly downslope from the point where it starts to spread out on the alluvial fan. A sequence of mudflows deposited during the 1958 season on the Arroyo Ciervo fan decreases in thickness from 1.6 feet to 0.3 foot in 0.7 mile.

Some idea of the viscosity of a mudflow can be obtained from the orientation and position of the gravel-size material. A fluid mudflow shows graded bedding and horizontal orientation of the flat gravel fragments; but a viscous mudflow commonly has no graded bedding, and the larger rock fragments are oriented in vertical planes as well as in other positions. Most of the mudflows studied were of the fluid type.

Changes in graded bedding and particle orientation of a given mudflow may indicate that the mudflow was deposited in several surges. An increase in the viscosity would be reflected by a decrease in horizontal preferred orientation and graded bedding. Samples from near the edge of a mudflow on the Arroyo Ciervo fan showed the following changes, progressively, in the downslope direction: (1) Vertical, or no preferred orientation or graded bedding; (2) some horizontal orientation of shale fragments and poorly graded bedding; (3) good horizontal orientation of shale fragments and excellently graded bedding; and (4) some horizontal orientation of shale fragments but no graded bedding. The samples described were collected at intervals of 0.1 mile. The above sequence suggests that as the mudflow moved downslope it became less viscous and then more viscous. This sequence could be caused by a viscous surge of mud followed by waves of more watery mud. Eventually, these more fluid surges would become more viscous downslope as water drained from the flow.

The shape of some alluvial-fan deposits that were laid down in the 1957 and 1958 seasons is shown in figure 12. *A* and *B* are composite deposits; and *C*, *D*, and *E* are principally mudflow deposits. In places the shape has been distorted by flow along roads or ditches which parallel section lines. Thin streamers extend downslope from *C* and *E* and indicate places where the flow has followed old distributary channels. Lobate tongues are a diagnostic feature of mudflows; some have dimensions of only a few feet, and others are as large as tongues 1 and 2 in *B*, which are 200–500 feet long.

One of the better criteria for identifying mudflows is

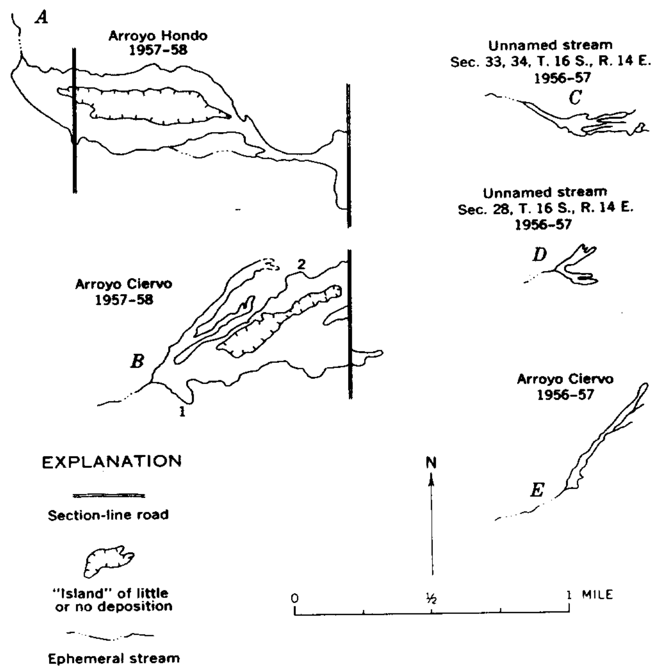



FIGURE 12.—Shape of alluvial-fan deposits. *A*, Arroyo Hondo, 1957–58. *B*, Arroyo Ciervo, 1957–58; 1 and 2 are examples of large lobate tongues. *C*, Unnamed stream in sec. 33, 34, T. 16 S., R. 14 E., 1956–57. *D*. Unnamed stream in sec. 28, T. 16 S., R. 14 E., 1956–57. *E*, Arroyo Ciervo, 1956–57.

abrupt, well-defined margins along the sides and downslope edges of the deposit. Some authors have described frontal scarps several feet high at the downslope end of viscous mudflows. Most of the mudflows studied in western Fresno County were from ⅛ to 1 inch thick at their edges, but the thickness usually increased to 2–3 inches within a few feet of the margin. There was no evidence that water had flowed away from the edge of the mudflows.

Most mudflows have been described as having much fine material mixed with coarse clasts. Mudflows in western Fresno County contain abundant clay derived from the mudstone and shale of the foothill belt. The clay occurs as a thick film around the sand and gravel grains or as a matrix that partly fills the intergranular voids. The mudflows studied are visibly poorly sorted and have a complete gradation of material from clay to gravel. Mudflows incorporate very light material such as fragments of vegetation and rabbit pellets that would be carried away by water floods.

Very few grain-size analyses of mudflows have been published. The author made grain-size analyses of 50 mudflow samples collected in western Fresno County, and the results of these analyses are summarized in table 17. Cumulative curves of some of these mudflows are shown in figure 13. The slope of the curves is gentle for all the samples, which range from clay to predominantly gravel. Some of the curves are bimodal, and others are polymodal. The bimodal nature of the cumulative curves of mudflows is mentioned by Crawford and Thackwell (1931, p. 102, 103), Chawner (1935, p. 261), and Sharp and Nobles (1953, p. 555, 556).

Grain-size analyses supply quantitative information for some of the visual observations. For example, the clay content of the 50 samples analyzed ranged from 12 to 76 percent and averaged 31 percent. Samples with a clay content of more than 40 percent are from the clay-rich downslope margins of mudflows; therefore, a median clay content of about 26 percent is probably a more realistic measure of the clay content of the average mudflow than is the arithmetic average.

The grain-size distribution of the graded bedding of the more fluid mudflows also was analyzed. One fluid mudflow had a medial parting, and grain-size analyses were made of both the upper and lower parts of the deposit at the same location. The lower part of the polygonal block was much coarser grained than the upper part.

| *Sample* | *Location within flow* | *Grain size of coarsest one percentile (mm)* | *Median grain size (mm)* |
|---|---|---|---|
| 48 | Top | 8.0 | 0.017 |
| 49 | Bottom | 25.0 | .40 |

Degree of sorting is a parameter that can aid in the classification of samples of subsurface mudflow deposits recovered from core holes. The three sorting indices used were the Trask sorting coefficient, $S_o$; the quartile deviation, $QD_\phi$, and the phi standard deviation, $\sigma_\phi$. The equation for the Trask coefficient is

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

A good discussion of Krumbein's (1936) phi-notation system is given by Inman (1952). Phi $=-\log_2$ of the grain diameter in millimeters. The standard deviation, $\sigma_\phi$, considers two-thirds of the sample, whereas the quartile indices consider the central 50 percent of grain-size distribution. The formula for the phi standard deviaion (a graphical approximation of the standard deviation) is $\sigma_\phi=\frac{\phi16-\phi84}{2}$, and the formula for the quartile deviation is $QD_\phi=\frac{\phi25-\phi75}{2}$. The 16, 84, 25, and 75 percentiles refer to the percent of material finer than the grain diameter for the percentile on the cumulative curve.[1] The phi sorting indices are positive because values of phi increase with a decrease in grain diameter.

Classification is difficult if features such as lobate tongues and well-defined margins are covered by more recent deposits. The sorting indices that were used to define the classification types were determined from samples that had clear depositional characteristics. Only 12 of the 277 sorting indices are outside the limits set for the three depositional types. Some cumulative curves did not cross either the 16th or 25th percentile line, and the grain diameter could not be read from the graph; but the values were extrapolated for some samples by extending their curves. The lower limits of the sorting indices of the mudflow samples were picked on the basis of the depositional characteristics, which can be borderline themselves. These lower limits were set at 5.0 for $S_o$, 4.1 for $\sigma_\phi$, and 2.3 for $QD_\phi$.

The sorting of the mudflow deposits is summarized below. The phi standard deviation, $\sigma_\phi$, was obtained for only half the samples, and most of these had below average values for the quartile sorting indices. Thus, the average and median for $\sigma_\phi$ are lower than they would be if all the samples could be considered.

Sample 18 is the best sorted: $S_o=5.8$, $\sigma_\phi=4.4$, and $QD_\phi=2.5$ (fig. 13). Sample 48 is the most poorly sorted: $S_o=25$, and $QD_\phi=4.6$. Sorting indices could not be determined for sample 7.

| | $S_o$ | $\sigma_\phi$ | $QD_\phi$ |
|---|---|---|---|
| Range | 5.0–25 | 4.1–6.2 | 2.3–4.7 |
| Mean | 9.7 | 4.7 | 3.1 |
| Median | 8.6 | 4.6 | 3.1 |

Quantitative properties such as clay content and sorting may be different for mudflows from different source rocks. Most of the samples analyzed by the author contained shale fragments and a montmorillonite-type clay in addition to quartz, feldspar, and other rock and mineral fragments. Crawford and Thackwell (1931, p. 102–103) show a cumulative curve for a mudflow whose source was a sandy terrace of Lake Bonneville. The sorting coefficient, $S_o$, for this mudflow is 2.8. Sharp and Nobles (1953, p. 555, 556) show cumu-

[1] Inman (1952, p. 130) uses percentiles from a percent-coarser cumulative curve, and hence the percentile values shown are the reverse of his definition.

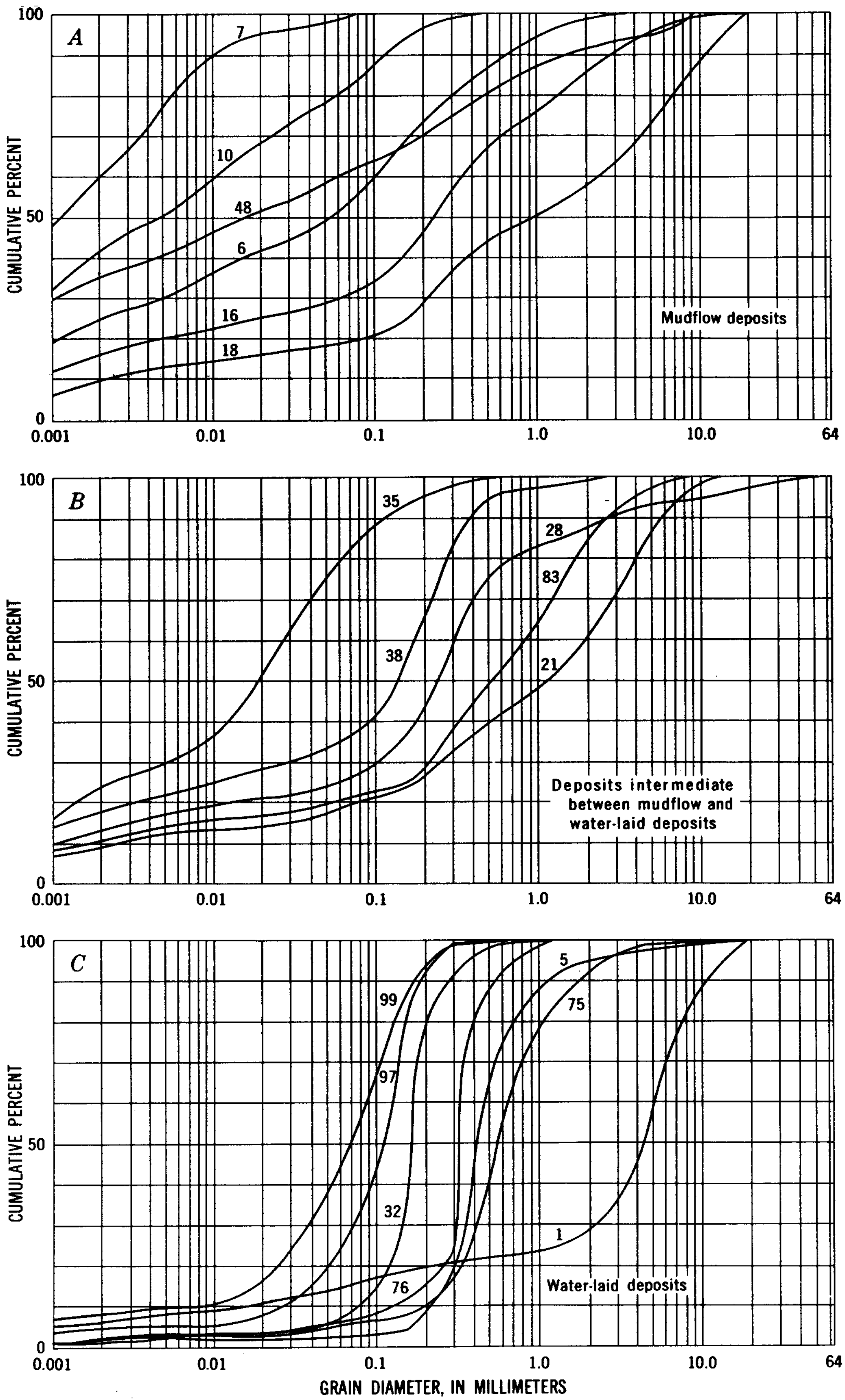



FIGURE 13.—Cumulative curves of alluvial-fan deposits. *A*, mudflow deposits; *B*, deposits intermediate between mudflow and water-laid deposits; *C*, water-laid deposits. Numbers adjacent to curves refer to samples in table 17.

lative curves for 10 mudflow samples collected along or near the channel of Sheep Creek on the north side of the San Gabriel Range, Calif., and the $S_o$ for these samples ranges from 2.7 to 5.0, averaging 3.9. The mudflows studied by Sharp and Nobles were caused by the rapid melting of deep winter snow, and the shattered and weathered Pelona schist of Precambrian age contributed nearly all the debris. The mudflows analyzed by Crawford and Thackwell and Sharp and Nobles had less than 5 percent clay.

A mudflow drops the larger stones when the velocity is not sufficient to keep them moving, and, because the velocity decreases to zero, the grain size should decrease progressively downslope. Grain-size analyses were made of 21 samples from the 1957–58 deposits on the Arroyo Ciervo fan. Seven samples were from the first mudflow of the season, which was more poorly sorted and appeared to be more viscous than the later mudflows. The grain size of the coarsest percentile, the median grain size, and the percent of clay for the seven samples are shown on the map of the season's deposits in figure 14*A*. In three-quarters of a mile, the grain size of the coarsest percentile decreases from 18 to 3 millimeters, and the median grain size decreases from 0.22 to 0.12 millimeter. The 10 samples of Sharp and Nobles (1953, p. 555) also show a decrease in median grain size with increase in distance from the source area. The amount of clay is almost the same for most of the Arroyo Ciervo samples and increases less than 20 percent in the two samples from farthest down the slope. These relations show that the mudflow represents mass flowage in which there is sorting of the coarsest fragments but no sorting of the finer-grained matrix.

Other parameters such as moisture content, dry bulk density, and sorting were examined in recent Fresno County mudflows to determine whether changes in the downslope direction were significant. If other conditions are about the same, the moisture content merely reflects the amount of clay and shale fragments in a sample. The dry density, which is controlled by the texture of a sample and the specific gravity of the grains, does not show a consistent change in the downslope direction.

Sorting within a single mudflow or between different mudflows may be distinctive. The seven samples from the first mudflow of the winter of 1957–58 (fig. 14*A*) have a range of $S_o$ from 8.2 to 17 and an average of 11. This range of sorting is distinctly different from that of a more fluid mudflow deposited later in the winter whose values of $S_o$ ranged from 5.1 to 9.4 and averaged 6. The overall sorting of some mudflows becomes poorer downslope, as is shown by increasing values for sorting indices. Most mudflows studied were sorted better in the central part of the sheet than near the edges, which probably indicates a decreasing viscosity and an increasing percentage of water in the successive surges of mud. In a given storm, the later waves of mud should not contain as high a percentage of debris as the first wave, which has to wet and clean out the channel. The sorting of the bottom part of some fluid mudflows is improved by the settling of the larger fragments.

### WATER-LAID SEDIMENTS

Water-laid sediments are most common on the nonsubsiding fans of the intermittent streams, but the deposits of some ephemeral streams also consist mainly of such materials. Deposition is from flows that contain much less debris than do mudflows, and there is sufficient water to winnow the finer material from the sand. The resulting deposits usually are composed of well-sorted sand and silt. Flows of water are more common toward the end of the winter season in streams that carry flows ranging from clear water to viscous mud. The new growth of grass late in the season causes more uniform and gradual runoff and decreases the amount of raindrop-impact erosion. Also, by the end of the season much of the debris may have been flushed out of the channels.

The amount of dissolved salts in a flow vary also. A sample of the first runoff of the 1959 season was collected from Arroyo Hondo, but, unfortunately, the author was not able to collect another sample later in the season. The analysis of the first runoff is shown below.

*Analysis of first runoff* [1]

| Constituent | Parts per million |
|---|---|
| Silica ($SiO_2$) | 1.0 |
| Calcium (Ca) | 446 |
| Magnesium (Mg) | 447 |
| Sodium (Na) | 3,030 |
| Potassium (K) | 59 |
| Carbonate ($CO_3$) | 0.0 |
| Bicarbonate ($HCO_3$) | 163 |
| Sulfate (SO ) | 8,090 |
| Chloride (Cl) | 619 |
| Fluoride (F) | 0.9 |
| Nitrate ($NO_3$) | 72 |
| Boron (B) | 2.0 |
| Sum | 12,847 |

[1] Analysis by the California Department of Water Resources.

The high concentration of ions caused the clay to flocculate when the water was allowed to stand, but it could not be determined whether the clay was transported in the flocculated state.

Two types of water-laid sediments occur on the alluvial fans. Most of the water-laid sediments consist

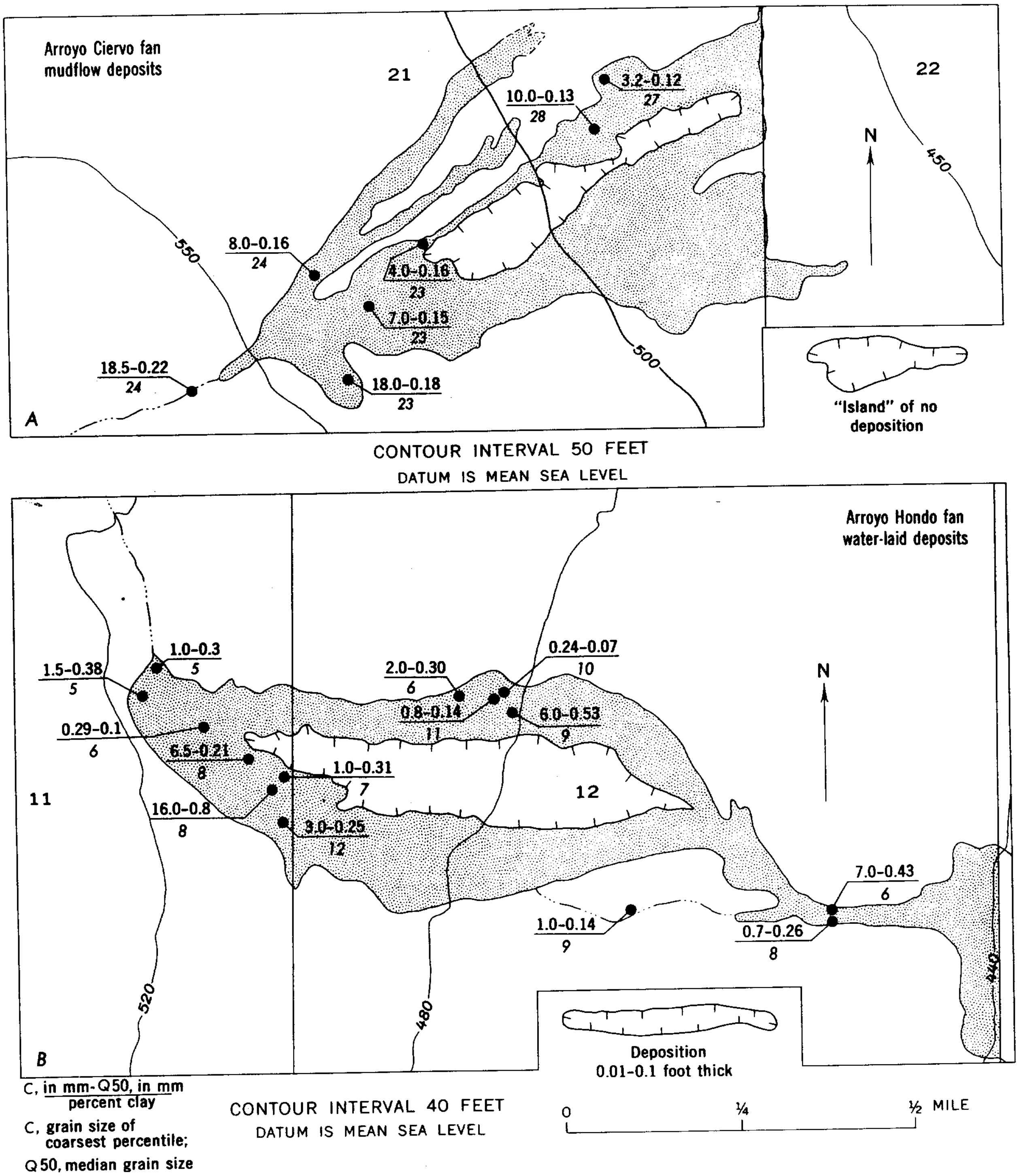



FIGURE 14.—Variation in the grain size and clay content in the downslope direction. *A*, Arroyo Ciervo fan mudflow deposits; *B*, Arroyo Hondo fan water-laid deposits.

of sheets of sand and silt deposited by a network of braided streams. The second type consists of sand and gravel deposited in the beds of the stream channels of the fanhead trenches and in the larger distributary channels farther downslope.

Ranchers and pipeline-maintenance men have described surges of water that spread in shallow bands or sheets over the fans. The maximum reported depth of the sheets of water was about 6 inches (William Deal, oral commun., August 1957), although the water probably was deeper in some of the distributary channels. The shallow distributary channels were described as continually filling with debris and then shifting a short distance to another location. Other authors have described surges in the flow of ephemeral streams (Jahns, 1949; Leopold and Miller, 1956, p. 4, 5).

Such a flow forms a sheetlike deposit of sand traversed by shallow channels that repeatedly divide and join. Most of these braided stream channels are less than a foot deep, and many are less than 4 inches deep. They are separated by low bars or islands. Such a sheet of sand has no distinct margins, and the silt or sand at the edges usually decreases in thickness until it is a thin film that merges with the underlying soil. The deposits are usually of clean sand or silt that contains little visible clay; in general, they are well sorted and may be crossbedded, laminated, or massive. Platy fragments, such as shale chips, have a definite preferred orientation or imbrication. Light debris, such as bits of vegetation and rabbit pellets, usually is carried away or piled against bushes or other obstructions.

The water-laid sediments in the beds of the main channel and larger distributary channels usually are coarser grained and more poorly sorted than the sheetlike water-laid sediments. In some places the sorting of these deposits is decreased because fine material fills the interstices. Sandbars near the sides of the main stream channels have characteristics similar to those of the braided-stream deposits on the surface of the fan. Samples 60 and 61 (table 17), from the bed of a channel and from an adjacent sandbar, respectively, show a marked contrast in both grain size and sorting.

| *Sample* | *Grain size of the coarsest percentile (mm)* | *Median grain size (mm)* | $S_o$ |
|---|---|---|---|
| 60 | 14 | 0.66 | 2.9 |
| 61 | .55 | .26 | 1.4 |

Figure 12*A* shows the shape of the Arroyo Hondo fan deposits for the 1958 season, the upper deposits of which are primarily water-laid sediments. The shape is distorted in places, particularly next to a manmade dike at the downslope edge of the deposits. The sediments are more than a quarter of a mile wide, including a central area of little deposition.

Samples represented by the cumulative curves shown in figure 13*C* range from silty sand to silty gravel. The central part of each curve has a steep slope, and on either side of the central part the curve flattens, indicating a coarse or fine "tail" of grain-size distribution. The S-shaped curves of the water-laid sediments are in marked contrast to the straight-line curves of the mudflow deposits. Some of the alluvial-fan sands, such as samples 32 and 76, are as well sorted as beach sands, and even the silty gravel (sample 1) shows remarkably good sorting in its coarsest two-thirds.

Grain-size analyses were made on 36 samples of water-laid sediments. Twenty-three of these samples were from sheetlike braided-stream deposits and from sandbars in the main stream channels, and 13 were from the beds of the main streams and larger distributary channels. The clay content of the water-laid sediments averaged 6 percent regardless of the place of deposition. In general, the upper limits of sorting for the water-laid-sediment classification were 3.0 for $S_o$, 2.3 for $\sigma_\phi$, and 1.6 $QD_\phi$. Six of the stream-channel deposits have higher sorting indices, but the poor sorting usually was caused by sand filling the interstices in gravel. For this reason, the maximum values of sorting in the tabular summary are higher than the general upper limits of sorting. The sorting of the braided-stream deposits and the stream-channel deposits, and of both groups combined, is summarized below.

| | $S_o$ | $\sigma_\phi$ | $QD_\phi$ |
|---|---|---|---|
| Braided-stream deposits: | | | |
| Range | 1.1–2.7 | 0.48–2.4 | 0.15–1.4 |
| Mean | 1.5 | 1.1 | .60 |
| Median | 1.5 | 1.0 | .56 |
| Stream-channel deposits: | | | |
| Range | 1.3–4.8 | 0.82–3.4 | 0.42–2.3 |
| Mean | 2.3 | 2.0 | 1.1 |
| Median | 2.1 | 2.0 | 1.1 |
| All water-laid sediments: | | | |
| Range | 1.1–4.8 | 0.48–3.4 | 0.15–2.3 |
| Mean | 1.8 | 1.4 | .79 |
| Median | 1.65 | 1.15 | .66 |

The grain size of the coarsest percentile, the median grain size, and the percent clay for some water-laid sediments are shown in figure 14*B*. All except two of the samples were deposited by shallow braided streams. Downslope trends are not evident for either the grain size or the clay content in the 1-mile reach sampled, and this indicates that these parameters are controlled partly by the velocity and depth of flow at the place of deposition. The depth, velocity, and amount of flow in the braided channels probably varied within one period of flow, and the situation is further complicated because the samples were deposited by runoff from several storms. Values for bulk density, moisture content, and sorting also are erratic and show no trends in the downslope direction.

#### DEPOSITS INTERMEDIATE BETWEEN MUDFLOWS AND WATER-LAID SEDIMENTS

Deposits of the intermediate group have characteristics between those of water-laid sediments and mudflows. For this reason, the defining limits of the group are fairly arbitrary.

Most of the intermediate deposits have the following depositional characteristics: The deposits have no sharply defined margins, and the clayey sediment thins outward until it appears to blend with the soil; the material has a visibly poor degree of sorting but not the extremely poor sorting of mudflows; clay occurs as films around the sand grains and as a partial filling in the intergranular voids; and most of the intermediate deposits have gravel-size fragments that are oriented horizontally and are concentrated in the bottom part, causing graded bedding.

Cumulative curves for some intermediate deposits are shown in figure 13*B*. The general slope of the curves is intermediate between those of the other classifications. Sorting indices are highest for sample 35 and lowest for sample 83.

The average clay content of 16 samples is 17 percent. Sorting indices used for the intermediate group are as follows: $S_o$, 3.0–5.0; $\sigma_\phi$, 2.9–4.1; and $QD_\phi$, 1.6–2.3. The average sorting of the intermediate deposits is summarized below.

| | $S_o$ | $\sigma_\phi$ | $QD_\phi$ |
|---|---|---|---|
| Range | 2.6–5.0 | 3.1–4.7 | 1.4–2.3 |
| Mean | 4.0 | 3.9 | 2.0 |
| Median | 4.2 | 3.95 | 2.05 |

Not enough samples of intermediate-type deposits were analyzed to evaluate changes of properties downslope. Analyses of seven samples from the Arroyo Ciervo fan are available, but they were collected during two seasons. These tests seem to indicate that the values of the grain size of the coarsest percentile and the median grain size, clay content, bulk density, moisture content, and sorting indices tend to be erratic and do not show a change downslope.

### BOULDERS AND ARMORED MUD BALLS

Boulders and armored mud balls are common on the fans of some ephemeral streams. Boulders are most abundant on fans bordering the Panoche Hills and rare south of Panoche Creek. Armored mud balls are spherical masses of clayey material studded with pebbles.

Both the boulders and the armored mud balls are deposited in clumps or trains. Trains usually consist of either boulders or mud balls, but occasionally the two are mixed. Within a single train, the size of the boulders or mud balls decreases slightly downslope, but most of them are roughly the same size. The average size of the boulders or mud balls within successive trains decreases in the downslope direction. The maximum size of the boulders is about 9 feet, and that of the mud balls is about 2 feet. Boulder trains occasionally occur as long narrow strips roughly parallel to the trend of the stream channel. One narrow train of boulders and cobbles is 10–15 feet wide and 840 feet long. The boulders and mud balls usually occur near, but not in, the stream channels.

The distribution of the boulder trains on a fan south of Little Panoche Creek is shown in figure 15. Boulder trains at this locality occur downslope from the outside of the bends in the fanhead trench, and the only train that does not seem related to the present-day channel is boulder train *F*. The boulders in this clump are more fractured than the boulders adjacent to the present-day channel, and they are pocked with depressions resembling those used by Indians to grind food. Boulder train *N* is a heterogeneous exception to the general rule of decrease in boulder size downslope, probably because it is at the end of the fanhead trench and was deposited by many storms.

Nearly all the boulders are sandstone concretions or pieces of concretions that have weathered from the Panoche Formation. Many of the boulders retain the spherical shape of the concretions from which they were derived. One of the concretions had a density of 138

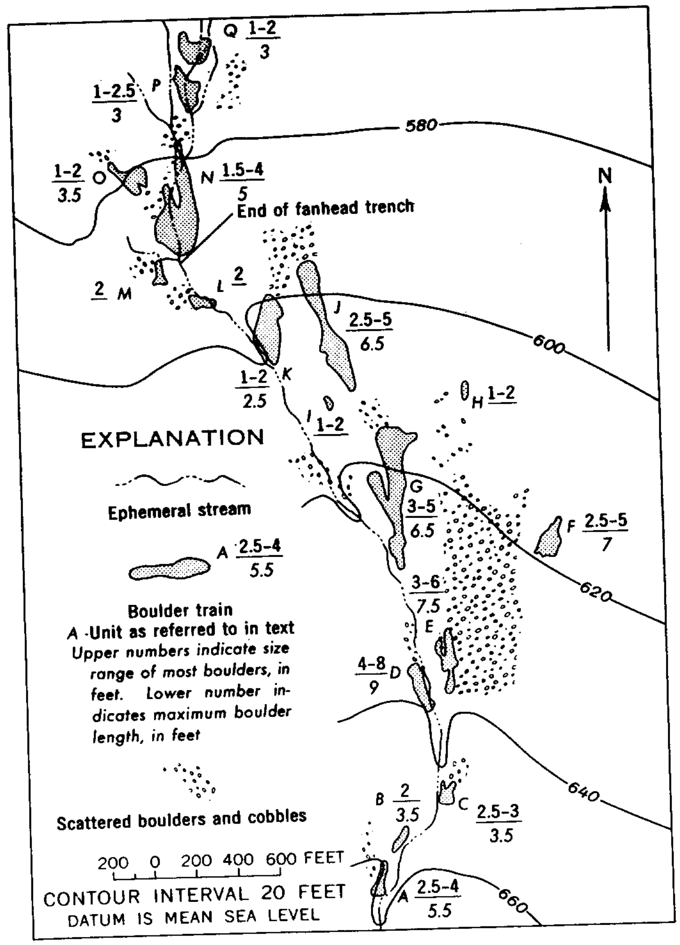



FIGURE 15.—Distribution of boulder trains on an alluvial fan in sec. 27, T. 13 S., R. 11 E.

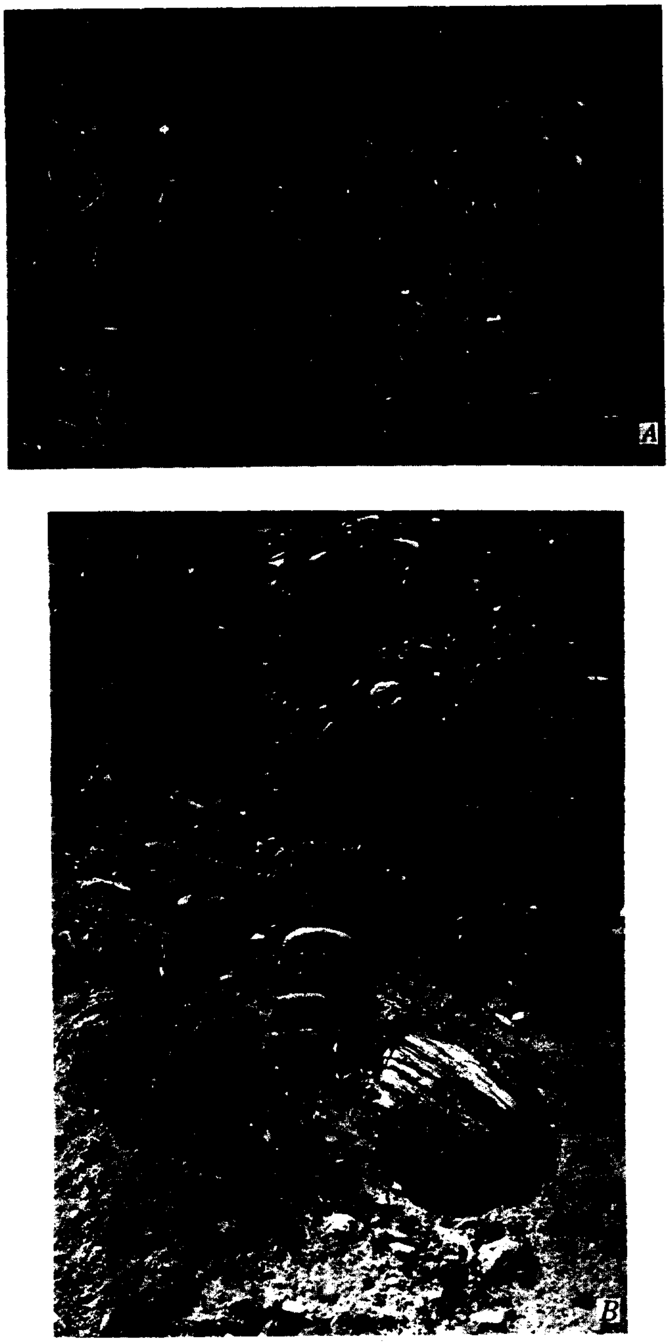


FIGURE 16.—Armored mud balls and desiccation cracks in armored mud balls and shale cobbles. *A*, Armored mud balls; *B*, desiccation cracks in armored mud balls and shale cobbles.

pounds per cubic foot; using this value, the weight of an 8-foot spherical concretion would be about 18 tons.

A large force is required to move these boulders. A 4-foot test pit dug among the boulders in train *E* showed that most of the material around the boulders was a poorly sorted clayey sand suggestive of mudflow-type deposition. Gravel is not abundant on the fan because there is no abundant source for it. The greater density of a mudflow provides more buoyant support for boulders than does water, and the higher viscosity might enable a mudflow to carry the large boulders down the channel. The stream channel probably has become deeper during a period of channel trenching in the last 100 years, so the boulders probably were moved out of a channel that was not as deep as the present-day channel. The channel may have been deep enough adjacent to boulder trains *A*, *B*, and *C* to contain boulders as large as those in trains *D* and *E*. Once the boulders were swept out of the channel they continued downslope in about a straight line. The depth of the mud probably became less as the flow spread out on the fan, and the boulders were deposited as the depth and velocity of flow decreased. The moderate decrease in boulder size downslope for any given boulder train may be the result of a continuing decrease in the depth and velocity of the depositing flow. It could not be determined whether most of the boulder trains shown in figure 15 were deposited by one flow or by a series of flows.

Not all boulders are deposited by mudflows. Residents of the area have watched boulders being washed out of fanhead trenches by water floods. This is plausible because many fanhead trenches are essentially slotlike flumes in which deep water can move at high velocities.

Armored mud balls, made during a period of flow, are found with mudflows or water-laid sediments but are most common in the intermediate-type deposits and water-laid sediments on the fans of ephemeral streams. The mud balls are made as pebbles are embedded in a core that is rolled along the stream channel. The core is composed of material that has fallen or slumped into the channel and may be mudstone, shale, sandstone, or a part of a polygonal block of a mudflow that was exposed in the wall of the fanhead trench. Most cores consist of material that becomes sticky when wet. Mud balls that have a sandstone core usually have a rim of clay into which the pebbles are pressed.

Bell (1940), who made a detailed study of the origin and properties of armored mud balls, says that most mud balls are molded and abraded from pieces of material from the sides of the channel. The mud ball grows by accretion until a heavy coat of pebbly armor stops further growth. The mud balls probably are formed and deposited before the interior of the core becomes wet. Bell also says that impact forces would destroy many mud balls if the core were wet during transport.

The diameter of the mud balls in western Fresno County ranges from less than 1 inch to about 2 feet. Two large mud balls in the bottom of Tumey Gulch are shown in figure 16*A*. Most of the clasts that make up the armor are shale fragments derived from the Tertiary marine rocks of the drainage area.

Both the clay-rich armored mud balls and the cobbles or boulders of shale are poorly preserved because they shrink while drying and break up. The outside dries first, and as it shrinks around the wetter core it cracks and spalls, as is illustrated in figure 16*B*. The ground around the mud balls is littered with pieces of rock armor. One of the shale cobbles broke into many small pieces, and another developed prominent cracks along the bedding planes. Bell (1940, p. 28) says that the core may shrink away from the shell if it has more clay than the shell.

#### TEXTURAL AND STRUCTURAL FEATURES OF ALLUVIAL-FAN DEPOSITS

The alluvial-fan deposits in western Fresno County have a variety of textural and structural features. Some of the features already mentioned are graded bedding, laminations, crossbedding, and the orientation or imbrication of the larger fragments. Textural and structural voids such as intergranular voids, bubble cavities, interlaminar voids, polygonal and smaller desiccation cracks, and voids left by buried vegetation will be discussed in this section. These are the principal voids that can be compacted to cause near-surface subsidence. Many voids may be gradational between two or more types.

Intergranular voids are the most common type of opening, and their size is controlled by the particle size, sorting, and the degree and type of packing. In some samples the voids constitute a "normal" porosity; in others the large intergranular voids result from poor packing of the sand grains. Large intergranular voids result when a mixture of sand, clay, and water settles into a low-density packing arrangement in which the grains are held in place by the clay bond after the deposit has dried.

The clay bond will preserve many of the intergranular openings that would be reduced in size if no clay were present, as continuing deposition adds to the overburden load. Large amounts of clay binder should preserve more intergranular voids than should small amounts of clay, but excessive amounts of clay may fill some of the voids. For example, under natural conditions more voids should be reduced in volume for a sample containing 6 percent clay than for a sample containing 12 percent clay, but a sample containing 35 percent clay will have intergranular voids partly filled with clay.

Bubble cavities are formed when air is trapped at the time of deposition, and they occur in all types of alluvial-fan deposits except water-laid gravelly sediments. Bubble cavities in mudflows and water-laid sediments are mentioned by Sharp and Nobles (1953, p. 554), and Crandell and Waldron (1956, p. 352, 361) describe cavities that may have been formed by air entrained in a volcanic mudflow.

Mudflows can pick up air in two ways. Air can be incorporated into mudflows as they move down tributary ravines and main stream channels, and this entrained air actually may decrease the viscosity of the mudflow. The other source of air is the deposits beneath the mudflow as it spreads out on the alluvial fan. Part of the air in the soil can move upward and be trapped by the mudflow to form bubble cavities. Air can be trapped by water-laid sediments in the same manner if they are deposited on soils that contain air which can move up into the freshly deposited sediments. Bubble cavities are much more common in the water-laid sediments of ephemeral streams than in those of intermittent streams. Probably more air is available for entrapment on the fans of ephemeral streams because the surface deposits dry out more completely between periods of flow. Intermittent streams may flow continuously for several months and keep the surface deposits saturated.

Bubble cavities are definitely more abundant in mudflow deposits than in water-laid sediments. The cavities in mudflows tend to be of irregular shape and smaller than a sixteenth of an inch across. Bubble cavities are scattered throughout most mudflow deposits, but they may be concentrated adjacent to shale fragments. If part of a mudflow is clay or silty clay, the cavities usually are larger and more spherical. An unusually large number of bubble cavities is shown in the clay in figure 17*A*. A clay-rich mudflow may trap many bubbles if the clay jells after the mudflow stops. Most of the clay apparently is montmorillonite, and more air can be trapped by montmorillonite because it has a greater tendency to jell than other clay minerals.

Bubble cavities in water-laid sediments may be spherical or irregular in shape. Most are $\frac{1}{16}$ to $\frac{1}{8}$ of an inch across, but some may be larger than half an inch. Spherical bubble cavities are abundant in the sandy silt shown in figure 17*B*, whereas cavities of irregular shape tend to be in coarser-grained sediments. The irregular-shaped bubble cavities in figure 17 are elongate; the largest is 1 inch long.

Many water-laid sediments are thinly laminated, and, in general, the laminations appear to represent fluctuations or repeated periods of deposition. Each lamina may be the result of a surge of water that eventually caught up with the main front of water spreading out over the fan. The surges may range in size from large

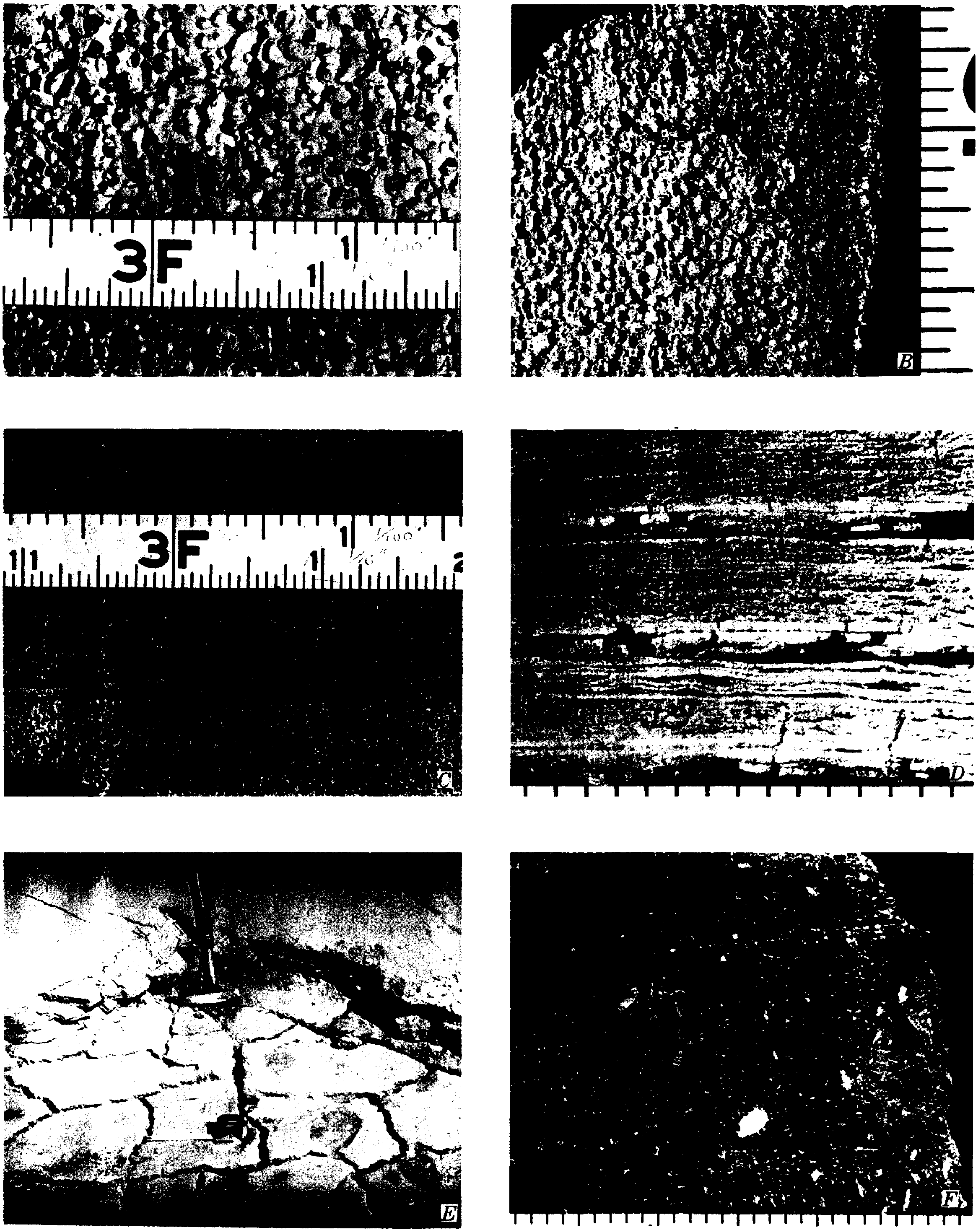



FIGURE 17.—Textural and structural features of alluvial-fan desopits. *A*, Bubble cavities in clay. *B*, Bubble cavities in silt; scale, 1/16-inch divisions. *C*, Irregular cavities in sand. *D*, Interlaminar cavities in silt; scale, 1/100-foot divisions. *E*, Buried, but unfilled, polygonal cracks. *F*, Section of a mudflow; scale 1/100-foot divisions.

bores to fast-moving ripples. If the laminations are inclined to the main bedding planes, as in the lower right part of figure 17*C*, the deposit is crossbedded.

Many laminated sediments have irregular disc-shaped openings between the laminations. Interlaminar openings in a sandy silt are shown in figure 17*D*, which shows three sections of the same sample cut at 1-inch intervals. Some of the interlaminar openings may be due to warping as the deposit dried. The warping probably was caused by an unequal distribution of clay, which caused differential shrinking. Bubble cavities and large intergranular voids may be alined between laminations, as in figure 17*C*.

Polygonal mud-crack patterns are found in most dry clay-rich deposits. Water-laid clay is not common on the alluvial fans in western Fresno County, but polygonal cracks are a characteristic feature of mudflow and some intermediate-type deposits. The spacing of the cracks increases with increasing thickness of a deposit, and the width of the cracks increases with an increase in the clay content.

Polygonal cracks were found in many test pits on the fans of ephemeral streams. Some of these cracks were filled with sand or silt, but many were open although buried by several feet of deposits. Buried, but unfilled, polygonal cracks are shown in figure 17*E*. The tape is on a mudflow that has well developed polygonal cracks. Several inches of water-laid sand on top of the mudflow were removed; the rock hammer is leaning against the sand that was not removed.

The buried, open cracks probably have been preserved by the following sequence of events. The mudflow was deposited first, and the sand was deposited before the mudflow dried. Then the whole deposit dried after the rainy season. The sand at the surface dried first, but conspicuous cracks did not develop because of the low clay content (about 10 percent). The mudflow dried next, and a pattern of shrinkage cracks developed as the clay (34 percent) dried. The sand did not fall into the open cracks because it had attained enough dry strength to bridge the gap between the polygonal blocks.

Binocular-microscope studies of 500 surface and subsurface samples show that small dessication cracks are common in clayey alluvial-fan deposits. The small cracks occur as horizontal partings, as vertical cracks, and as irregular cracks around sand grains. The cracks are only a small part of the void space in most samples, but their collapse may contribute to the reduction in volume that causes subsidence.

Some voids are made by vegetation that is picked up and incorporated into mudflows and some intermediate-type deposits and is buried and later dries or decomposes. Vegetation carried by water usually floats and is not incorporated into the sediments; growing vegetation may be buried by any type of deposition. The continuous seams of organic matter that are found in test pits may represent grasses that were buried in place.

A section of part of a polygonal block of a mudflow is shown in figure 17*F*. The mudflow does not have graded bedding, and the disc-shaped gravel fragments appear to be oriented in a near vertical position. Many of the small bubble cavities were filled with clay during the grinding process. The arrow marks the location of a void left by a piece of dried vegetation. Some parameters from the grain-size analysis of this mudflow are listed in table 17 (sample 95).

Thin sections were cut from samples of the alluvial-fan deposits. The clay films around some grains were as thin as 2 microns, but most of the clay films were thicker than 5 microns. Petrographic examination showed that the clay particles were oriented in some clay films, but most of the clay did not show particle orientation, especially in the mudflow deposits. Most of the laminated sediments do not show graded bedding for each lamina, as may be found in laminations made in other depositional environments. In general, more pertinent detail can be seen in three dimensions using a binocular microscope than in the two dimensions represented by thin section.

### OLDER DEPOSITS

Samples from deposits in the walls of the main stream channels and from core holes were studied and analyzed. In this paper these deposits are classified as older deposits to distinguish them from the sediments of 1955–60.

The post-depositional environment on the fans of ephemeral streams changes the character of the alluvial-fan deposits. Dry hot air during the summer months removes much of the moisture from the top 1 or 2 feet of the deposits, and clay-rich materials such as mudflows are baked until the polygonal blocks are like adobe bricks. Repeated wetting and drying causes the clay to slake and crumble on the exposed parts of the polygonal blocks. After the deposits are buried, water from later periods of flow may infiltrate a few feet into the ground, and the roots of the bushes and grasses then remove moisture during the long dry season. The plants however, never remove as much water from the soil as does exposure to the dry air; thus, most of the subsurface deposits have a moisture content that is roughly equivalent to the wilting coefficient. Roots of plants disturb the depositional textures, and some buried soil horizons have many irregular tubular cavities made by roots. Infiltrating water dissolves salts

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such as gypsum from the soil and deposits them as efflorescent salts lining the root cavities. Rodent burrows are common on some of the alluvial fans, and the tunnels of these animals may be several feet deep. The rodent population probably is larger now than it was before the area was settled, because many of the natural predators have been killed.

Nineteen core holes were driven to a depth of 18 feet into the fans of ephemeral streams. One-inch cores and loose material were obtained using Viehmeyer soil tubes.[2] Fifteen of the 19 core holes were in the Arroyo Ciervo fan, 2 were south of Cantua Creek, and 2 were in a fan south of Little Panoche Creek. The material from the core holes was dry or only slightly damp to the touch, except that from one hole in a field that had been irrigated. Features such as root cavities, efflorescent salts, bubble cavities, and large intergranular voids were common in many of the cores. Bubble cavities and large intergranular voids were not noted in the material from the core holes south of Cantua Creek, probably because the coring disturbed the material and because the sands that had little clay binder were reduced to loose sand.

The 15 core holes on the Arroyo Ciervo fan were along 3 lines radiating from the apex. The number of blows with a 30-pound hammer needed to drive the soil tube each foot in depth was recorded, and the samples were color coded using Munsell Soil Color Charts. A correlation of the Arroyo Ciervo alluvial-fan deposits was attempted on the basis of lithologic description, color-code number, blows per foot recorded, and the presence of buried incipient-soil profiles. There was no obvious correlation of deposits across the fan parallel to a given contour line, but two of the three sets of core holes along the radial lines show a possible correlation of deposits on the younger part of the fan. One correlation indicates that part of the upper 18 feet of the alluvial-fan deposits thins downslope at a rate of about 9 feet in 1½ miles. In general, the results of the attempted correlation between core holes are what would be expected on a fan where deposition occurs as tongues along radial lines and where the thickness of surface deposits is known to decrease downslope.

Twenty- to 30-foot sequences of alluvial-fan deposits are exposed in many stream channels. One pronounced feature is the thin-to-medium bedding of the deposits; usually three or four beds occur within an average foot of section. The downslope extent of a given bed is usually much greater than its lateral extent.

[2] The Viehmeyer soil tubes were loaned by the University of California at Davis.

Some comparisons can be made between the material deposited during the 1957 and 1958 seasons and the material obtained from core holes and exposed in stream channels. All the types of deposition and textural features studied in the surface deposits also were observed in cores and in the walls of the fanhead trenches. Evidence of viscous clay-rich mudflows is not as common in the subsurface deposits as in the surface deposits; and, on some fans, water-laid deposits seem to be more common in the older deposits. Armored mud balls rarely are exposed in the sides of the fanhead trenches. Bell (1941, p. 7) says that armored mud balls never are preserved unless they are buried completely at the time of deposition. Few rodent burrows are exposed by the fanhead trenching.

Samples were taken from five 30-foot core holes drilled by the California Department of Water Resources on the Arroyo Ciervo fan, and grain-size analyses were made on 40 samples. Parameters from these grain-size analyses are listed in table 18.

Grain-size analyses made by other agencies of the Inter-Agency Committee are not used in this paper because the methods of making grain-size analyses vary enough to make results noncomparable. Two methods of making grain-size analyses are discussed and a comparison of parameters from tests made by the author is shown in the section "Methods of making grain-size analyses and density tests."

The location of the Arroyo Ciervo fan-profile holes is shown in figure 18. FP–1 through FP–4 are about on a radial line, and FP–5 is offset onto an older side of the fan. The average grain size of the coarsest percentile, the median grain size, and the clay content for the samples from each core hole also are shown.

Some of the parameters from the grain-size analyses show a trend in the downslope direction, but others are erratic. The grain size of the coarsest percentile shows a definite decrease in the downslope direction. The median grain size is about the same for the samples from the two upper holes and then decreases slightly for the samples from the three holes farther downslope. The clay content is lowest for the samples from the older side of the fan (FP–5) and shows a fairly constant increase downslope for samples from holes FP–3 through FP–1. The averages for the grain diameter of the larger and small quartiles and for the sorting indices are erratic.

A comparison of the percent sand and gravel, silt, and clay in the surface and subsurface deposits of the Arroyo Ciervo fan is shown in figure 19. Samples with 20 percent or more gravel are not shown, and, in those

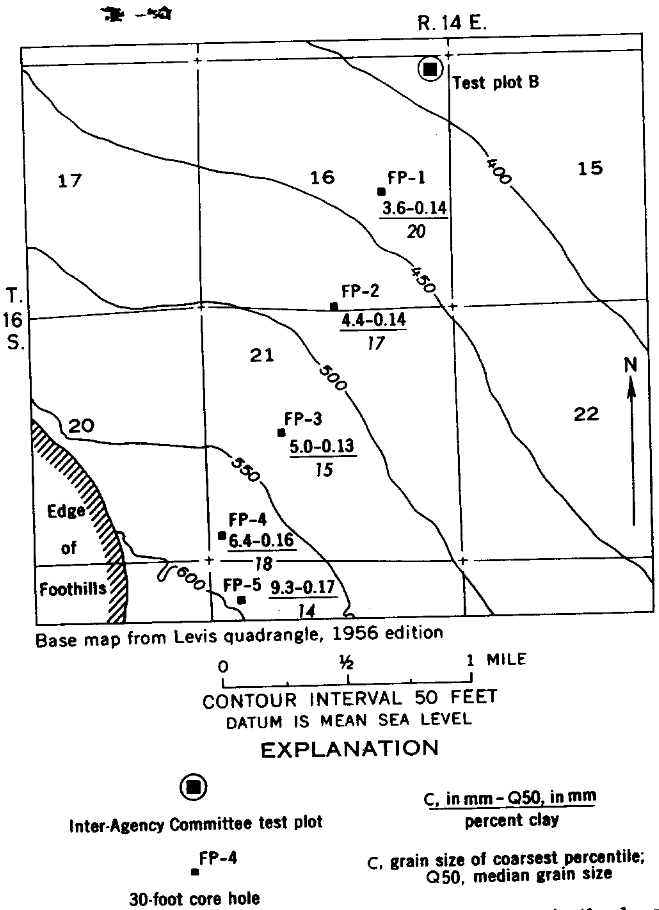



FIGURE 18.—Variation in the grain size and clay content in the downslope direction for samples from 30-foot core holes in the Arroyo Ciervo fan.

with less than 20 percent gravel, the gravel and sand are undifferentiated. Two subsurface and four surface samples had more than 20 percent gravel.

Most of the points for the surface samples (fig. 19*A*) are concentrated in one area, but one-third of the points are scattered. Nine mudflow and 2 intermediate samples were taken from the 1957 deposits; and 12 mudflow, 4 intermediate, and 4 water-laid samples were taken from the 1958 deposits. There are about twice as many samples of mudflows as there are samples of the two other types combined.

Points for the subsurface samples (fig. 19*B*), compared with points for the surface samples, are clustered in a larger area; but there is no scatter of points as was shown by the surface samples. The subsurface samples, which contain more silt and less clay than the surface samples, were classified according to their sorting, using sorting limits derived from known surface samples. Eight of the phi standard-deviation indices did not agree with the quartile indices. The samples were classified as follows: 9 mudflow, 19 intermediate, and 10 water-laid deposits.

As can be seen from the overall comparison of the 35 surface and 40 subsurface samples given below, the surface samples are coarser grained and have more clay and hence are more poorly sorted than the subsurface samples.

| | 35 surface samples (mean) | 40 subsurface sample (mean) |
|---|---|---|
| Grain diameter of coarsest percentile ..mm.. | 7.9 | 6.4 |
| Grain size of largest quartile........do.... | .67 | .51 |
| Median grain size.....................do.... | .21 | .15 |
| Grain size of smallest quartile.......do.... | .035 | .032 |
| Gravel...........................percent.. | 9 | 5 |
| Sand..................................do.... | 55 | 61 |
| Silt..................................do.... | 14 | 18 |
| Clay..................................do.... | 22 | 16 |
| $S_o$ | 6.8 | 4.7 |
| $\sigma_\phi$ | 4.0 | 3.3 |
| $QD_\phi$ | 2.5 | 2.1 |

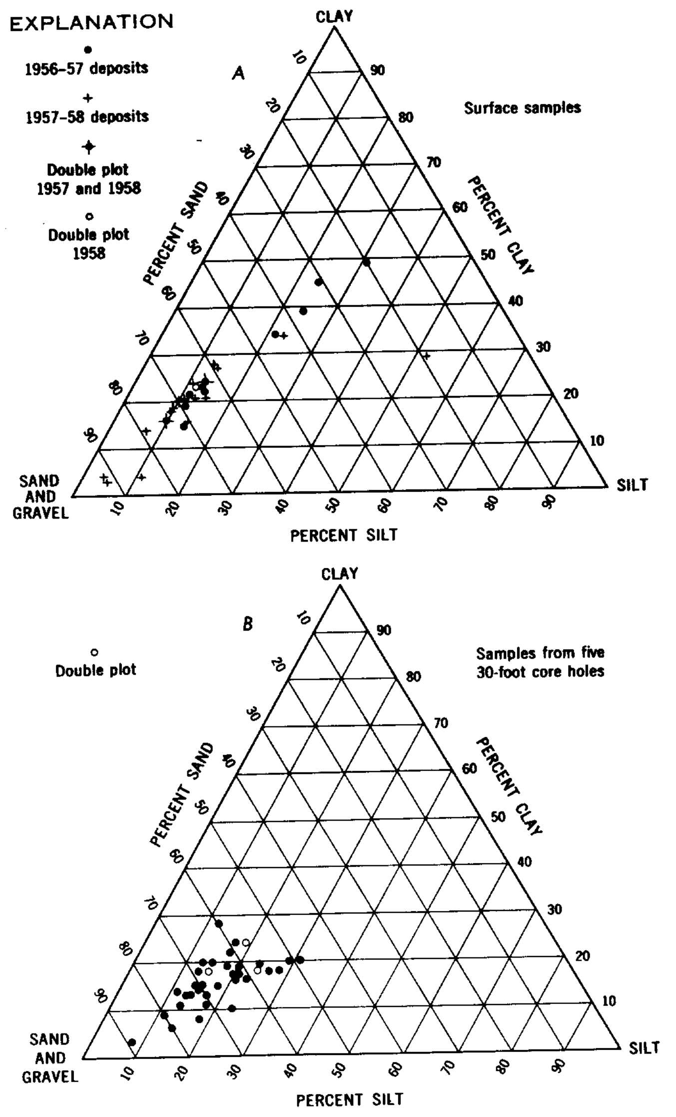



FIGURE 19.—Grain-size distribution of surface and core-hole samples from the Arroyo Ciervo fan. *A*, samples from materials deposited in the winters of 1956–57 and 1957–58; *B*, samples from five 30-foot core holes.

The surface deposits do not show the true nature of the older deposits if the 40 subsurface samples are representative of the upper 30 feet of the fan. The surface samples may have moderately different characteristics because (1) the samples were not collected to give average areal sampling, (2) deposits for only two seasons are represented, and (3) they were deposited under different hydrologic conditions than part or all of the subsurface samples.

The author collected samples on the basis of textural features, depositional types, and position within a deposit. Test results from such a subjective method of sampling made the pattern of points shown in figure 19*A*. The samples included clean sand and silty clay even though these types constitute but a small percentage of the surface deposits. The core-barrel type of sampling was more objective, hence there are fewer clean sands; no samples containing 30–50 percent clay are represented in figure 19*B*.

The surface samples represent the deposits of only 2 successive years, but the cores may represent deposition in as many as 40 separate years scattered through a much longer period of time, possibly several thousand years. The 1957 season had less than normal rainfall and only one period of runoff. The 1958 season had one of the largest amounts of rainfall on record, which caused repeated deposition on the alluvial fan. Fourteen samples were collected from the 1957 deposits, and 21 samples were collected from the 1958 deposits. The 1958 deposits might be coarser grained because the amount of flow was larger than usual. Also, the collection of samples was not representative of either the volume of the different types of deposits or the yearly volume; the deposits of the 1957 season constitute less than 3 percent of the total volume of material deposited in both years. This irregularity of distribution in time and space is probably also true of the core samples.

Sampling methods or climatic changes do not seem to explain all the differences between the surface and subsurface deposits. The method of sampling may explain the scatter of points in figure 19*A* and the apparent coarser nature of the surface deposits, but sampling methods do not explain why the surface deposits are predominantly mudflows whereas the subsurface deposits are mainly intermediate types of deposits. Selective sampling does not explain this difference because the proportion of surface-mudflow deposits is even larger than indicated by the number of samples for each type. An increase in the annual rainfall is not indicated by moisture-content and moisture-equivalent tests made on samples from the upper 130 feet of deposits beneath subsidence test plot B. The average amounts of daily rainfall from 1956 to 1960 do not seem much different from the average for the past 60 years, but evidence is not available to show whether there has been a change in the hourly amounts of precipitation. However, mudflows during this period were caused by 10-hour storms as well as by rain that lasted less than half an hour.

The difference in the proportion of mudflows in the surface and subsurface deposits is probably due chiefly to changes in the hydraulic characteristics of the stream channel. Part of the subsurface material was deposited when there was no fanhead trench, but all the surface deposits were deposited by flows that moved along a narrow confining channel. A greater number of the mudflows than formerly may reach the alluvial fan now because the mudflows now move along a narrow confining channel instead of a broad shallow channel in an alluviated valley. Figure 6 shows the narrow channel of Arroyo Ciervo incised into the valley floor 6 miles from the edge of the San Joaquin Valley. If a mudflow moved as a sheet down a broad stream channel it might not reach the alluvial fan because of its lower velocity and because it would lose more of its water to the material in the bed of the stream channel. Under present-day conditions the more fluid flows may pick up material that has slumped into the channel from the steep banks of the stream channel and fanhead trench and then be deposited on the fan as a mudflow. If the same type of flow moved down a channel that had no steep banks to furnish slump debris, the material deposited on the fan might be an intermediate type of deposit.

The fanhead trench influences deposition in another way. Normally, the coarsest material should be deposited on the fanhead, but fanhead trenching causes all material to be deposited farther out on the fan (Buwalda, 1951). Prehistoric fanhead trenching may be one reason why some of the grain-size parameters of the core-hole samples do not show a more consistent decrease farther out on the fan.

### AMOUNT AND RATE OF DEPOSITION

The rate of deposition partly determines how much a fan will subside. Rapid burial can preserve delicate textural features that would be destroyed if left near the surface. If the intervals between deposition are moderately long, exposed sandy material will gradually assume a closer packing. If deposits are not buried for a long time, part of the clay will be removed from the upper zones and concentrated in the lower zones as a soil profile is formed.

Alluvial-fan deposition has been rapid in western Fresno County. Electric-log studies by R. E. Miller (written commun., 1962) show that the Diablan fan deposits above the widespread lacustrine Corcoran clay

TABLE 8.—*Section of alluvial-fan deposits exposed in Arroyo Hondo, NE¼SE¼ sec 3, T. 17 S., R. 14 E.*—Continued

| Lithology | Thickness (feet) | Depth interval (feet) |
|---|---|---|
| Silt-clay, sandy | 0.2 | 11.1 –11.3 |
| Sand, clay films around grains | .2 | 11.3 –11.5 |
| Sand, poorly sorted | .1 | 11.5 –11.6 |
| Sand, clayey | .1 | 11.6 –11.7 |
| Sand-clay | .2 | 11.7 –11.9 |
| Sand, clayey | .55 | 11.9 –12.45 |
| Clay | .15 | 12.45–12.6 |
| Sand, clayey, some pebbles, root cavities | .9 | 12.6 –13.5 |
| Gravel, clayey | .6 | 13.5 –14.1 |
| Sand, silty, coarser-grained toward the top. Root cavities near the top | 1.2 | 14.1 –15.3 |
| Gravel, silty | .15 | 15.3 –15.45 |
| Sand, moderately well sorted, some silt Root cavities near top | .45 | 15.45–15.9 |
| Sand, pebbly, clay films around grains | .3 | 15.9 –16.2 |
| Gravel, silty, sandy | .1 | 16.2 –16.3 |
| Sand, pebbly, silty | .2 | 16.3 –16.5 |
| Sand, poorly sorted | .5 | 16.5 –17.0 |
| Gravel-clay | .5 | 17.0 –17.5 |
| Concealed | | |
| Total thickness | 17.5 | |

The previous season's deposits on the Arroyo Ciervo fan were mapped during the summers of 1957, 1958, and 1959, and spot measurements were made to estimate the amount of material deposited during the 1956 and 1960–63 seasons. The amounts of erosion and deposition at Arroyo Ciervo and the seasonal rainfall at nearby stations are listed in table 9. The erosion, in tons per square miles, was based in part on the mean dry (110°C) bulk weight of 34 samples of the deposits (78 pounds per cubic foot). The acre-feet of rock eroded is not equivalent to the acre-feet of deposits because of the increase in volume that occurs during the conversion of rock to sediment. If the fan deposits are assumed to have an intergranular porosity of 30 percent and a bulk density of about 80 pounds per cubic foot, then the bulk density of the average source rock would be about 110 pounds per cubic foot. Actual bulk densities of source rocks tested ranged from 56 pounds per cubic foot for diatomite to 138 pounds per cubic foot for calcareous sandstone. Two samples of diatomaceous shale had an intermediate density of about 85 pounds per cubic foot. An average density of about 110 pounds per cubic foot is reasonable for a basin that is underlain by 69 percent diatomaceous shale.

The amount of deposition during the 1956 and 1958 seasons was large, but aerial photographs taken in other years show that earlier seasonal deposits covered about the same area. The average seasonal sediment yield for the 8-year period was 3,200 tons per square mile, which is two to three times the average sediment yield given by Langbein and Schumm (1958) for stations in areas of similar effective precipitation.

The amount and rate of erosion may be greater during periods of channel trenching. Periods of channel trenching, such as occurred between 1875–95 and 1935–45 (Bull, 1964b), represent times of accelerated erosion throughout the drainage basins. However, channel trenching or filling was negligible between 1957 and 1963 in the vicinity of 15 channel markers on Arroyo Ciervo and Arroyo Hondo.

Drainage-basin denudation rates are discussed in detail by Schumm (1963). Approximately, rates of denudation representative of sedimentary rocks in a semiarid climate average 0.25 foot per 1,000 years and reach a maximum of 3 feet per 1,000 years for drainage basins of about 1,500 square miles (Schumm, 1963, p. H12).

The period of record for the data in table 9 is short, but if it is assumed to be representative, a denudation

TABLE 9.—*Sediment yield of the Arroyo Ciervo drainage basin, and rainfall data from nearby stations*

| Season | 1955–56 | 1956–57 | 1957–58 | 1958–59 | 1959–60 | 1960–61 | 1961–62 | 1962–63 |
|---|---|---|---|---|---|---|---|---|
| Deposition (acre-feet) | [1] 45 | [2] 1.7 | [2] 62 | [2] 0.2 | [3] 0 | [3] 2 | [3] 4 | [3] 7 |
| Erosion per square mile of drainage basin: | | | | | | | | |
| Tons | 9,500 | 360 | 13,000 | 40 | 0 | 400 | 800 | 1,500 |
| Acre-feet | 3.9 | .14 | 5.4 | .02 | 0 | .2 | .3 | .6 |
| Seasonal rainfall (inches):[4] | | | | | | | | |
| New Idria [5] | 16.39 | 10.47 | 26.29 | 12.93 | 8.02 | 10.69 | 18.73 | 14.61 |
| Panoche Junction [6] | 7.90 | 5.04 | 10.55 | 4.31 | | 4.76 | 6.50 | |
| Halfway Pumping Station [7] | | 4.13 | 9.68 | 4.14 | 2.48 | 5.32 | 6.44 | 6.67 |

[1] Estimated from field studies in July 1957.
[2] Mapped.
[3] Estimated from spot measurements.
[4] Includes rainfall in the period July 1–June 30.
[5] The New Idria Station, at an altitude of 2,650 feet, is about 6 miles southwest of the headwaters of Arroyo Ciervo.
[6] Panoche Junction is half a mile from the foothills and 2½ miles north of the mouth of Arroyo Ciervo. Complete record not available for the 1960 and 1963 seasons.
[7] Halfway Pumping Station is 1½ miles from the foothills and 5 miles southeast of the mouth of Arroyo Ciervo.

rate of 2.1 feet per 1,000 years is obtained for the Arroyo Ciervo basin. The overall denudation of large basins requires more time than for small basins, because sediment may be deposited in the valleys several times before it reaches the basin mouth. Based on Brune's (1948, fig. 3) relation between source area and sediment yield, the denudation rate for Arroyo Ciervo would decrease from 2.1 to 1.0 feet per 1,000 years as the size of the source area is increased from 8 square miles to Schumm's unit basin size of 1,500 square miles. A value of 1.0 foot per 1,000 years is four times the average and one-third of the maximum rate of denudation based on Schumm's summary—a rate that seems reasonable for a 1,500-square-mile basin with the characteristics of the Arroyo Ciervo basin.

### SUMMARY OF ALLUVIAL-FAN DEPOSITS

Deposition on alluvial fans is caused mainly by the decrease in depth and velocity of flow that results from the increase in width as a flow spreads out on the fan. If water from the flow infiltrates into the ground, the decrease in volume of flow also causes deposition.

The classification as mudflow, intermediate, or water-laid deposit was adopted because it is independent of the overall shape of the deposit and place of deposition, which is a definite advantage when materials from core holes are classified. The general properties of each type of deposit, as sampled at the land surface, are as follows:

| Type of deposit | Depositional characteristics | Average parameters from grain-size analyses |
|---|---|---|
| Water-laid sediments | No discernible margins; usually clean sand or silt; crossbedded, laminated or massive. | Clay content, 6 percent; $S_o$, 1.8; $QD_\phi$, 0.8; $\sigma_\phi$, 1.4 |
| Intermediate deposits | No sharply defined margins; clay films around sand grains and lining voids; graded bedding and oriented fragments. | Clay content, 17 percent; $S_o$, 4.0; $QD_\phi$, 2.0; $\sigma_\phi$, 3.9. |
| Mudflow deposits | Abrupt well-defined margins, lobate tongues; clay may partly fill intergranular voids. May not have graded bedding or particle orientation. | Clay content, 31 percent; $S_o$, 9.7; $QD_\phi$, 3.1; $\sigma_\phi$, 4.7. |

The three types of deposits occur in all the fans studied; but the clay-rich intermediate and mudflow deposits are most common in subsiding fans, and water-laid sediments are most common in nonsubsiding fans. Clay in the mudflow and intermediate deposits is distributed throughout the sediments and causes an overall high "dry" strength. The clay in water-laid deposits occurs chiefly in clay-rich seams and causes an overall low "dry" strength.

Boulders or armored mud balls usually are deposited in trains, and within a given train most of the boulders or mud balls are within a narrow size range. The average size of boulders or mud balls for each train decreases downslope. Most large boulders are deposited by mudflows, but some are moved down the fan-head trenches by water floods. Armored mud balls and shale cobbles are rarely preserved unless they are buried at the time of deposition.

Voids, which may be compacted to cause subsidence, are commonly found in alluvial-fan deposits. They include 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. The polygonal cracks occur chiefly in mudflow and intermediate deposits, and the interlaminar openings occur mainly in water-laid sediments. The other voids are found in all types of alluvial-fan deposits. Voids are usually more common, and may be preserved longer, in clayey deposits.

All the types of deposits and textural features can also be found in the walls of the main stream channels and in cores. Grain-size analyses of 40 samples from 5 core holes on the Arroyo Ciervo fan show that the grain size for the coarsest percentile decreases downslope, and that the clay content increases downslope. Mudflows may be more common in the surface deposits than in the subsurface deposits because stream entrenchment has made a narrow confining channel that enables mudflows to reach the alluvial fan and because the steep banks provide additional debris for any type of flow.

The rate of deposition on the fans seems large. For example, the average rate of deposition on the Arroyo Ciervo fan for the eight-season period 1956–63 is 25,500 tons per season, which is equivalent to a sediment yield of about 3,200 tons per square mile of drainage basin. If this rate of erosion is representative of that of the Arroyo Ciervo basin, the basin is being eroded at a rate of about 2 feet per 1,000 years.

Rapid burial may preserve open-packing arrangements and textural features that would be destroyed by long exposure to the surface elements. Preservation of these features provides more voids that may be compacted after burial to cause subsidence.

## NEAR-SURFACE SUBSIDENCE

### INTER-AGENCY COMMITTEE ON LAND SUBSIDENCE TEST PLOT PROGRAM

In 1954 the Inter-Agency Committee on Land Subsidence in the San Joaquin Valley was formed, with J. F. Poland of the U.S. Geological Survey as its chairman. 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 of the committee were to estimate future subsidence and to suggest ways of decreasing or alleviating damage caused by subsidence.

Nine agencies and universities are represented on the committee. The Federal agencies are the Bureau of Reclamation, the Geological Survey, the Coast and Geodetic Survey, the U.S. Army Corps of Engineers, and the Soil Conservation Service. The State agencies are the California Department of Water Resources and the California Division of Highways. The University of California at Davis and Stanford University also are represented on the Inter-Agency Committee.

The most significant near-surface-subsidence project undertaken by the Inter-Agency Committee included the establishment of irrigation test plots and the laboratory testing of cores taken from the plots. The purpose of the test plots was to measure the amount and rate of subsidence and to compare the amounts and rates of subsidence with the engineering properties of the cores taken from the plots. Inter-Agency test plots B, C, and D were constructed on the unirrigated parts of the alluvial fans of Arroyo Ciervo, Arroyo Hondo, and Moreno Gulch (pl. 2). Cores were taken from test site E on the Panoche Creek fan, but a plot was not constructed at that site (pl. 2).

The test plots were about 100 feet square, and surface and subsurface bench marks were used to measure the subsidence. After a plot was leveled, 3-foot levees were built with a bulldozer that scraped up dirt outside the plot, starting about 80 feet away from the levees. Each plot had five surface bench marks that consisted of staff gages bolted to angle irons anchored in concrete. Three to six subsurface bench marks were used to determine the amount of compaction within certain depth intervals. They consisted of an outer 1½-inch casing and an inner half-inch pipe that was anchored in a concrete plug at a predetermined depth. The half-inch pipe did not move downward until the percolating-water front had advanced past the concrete plug. Figure 20 shows the location of the bench marks and the assembly used for the subsurface bench marks that were set beneath test plot B. Figure 21*A* is a view of test plot B after

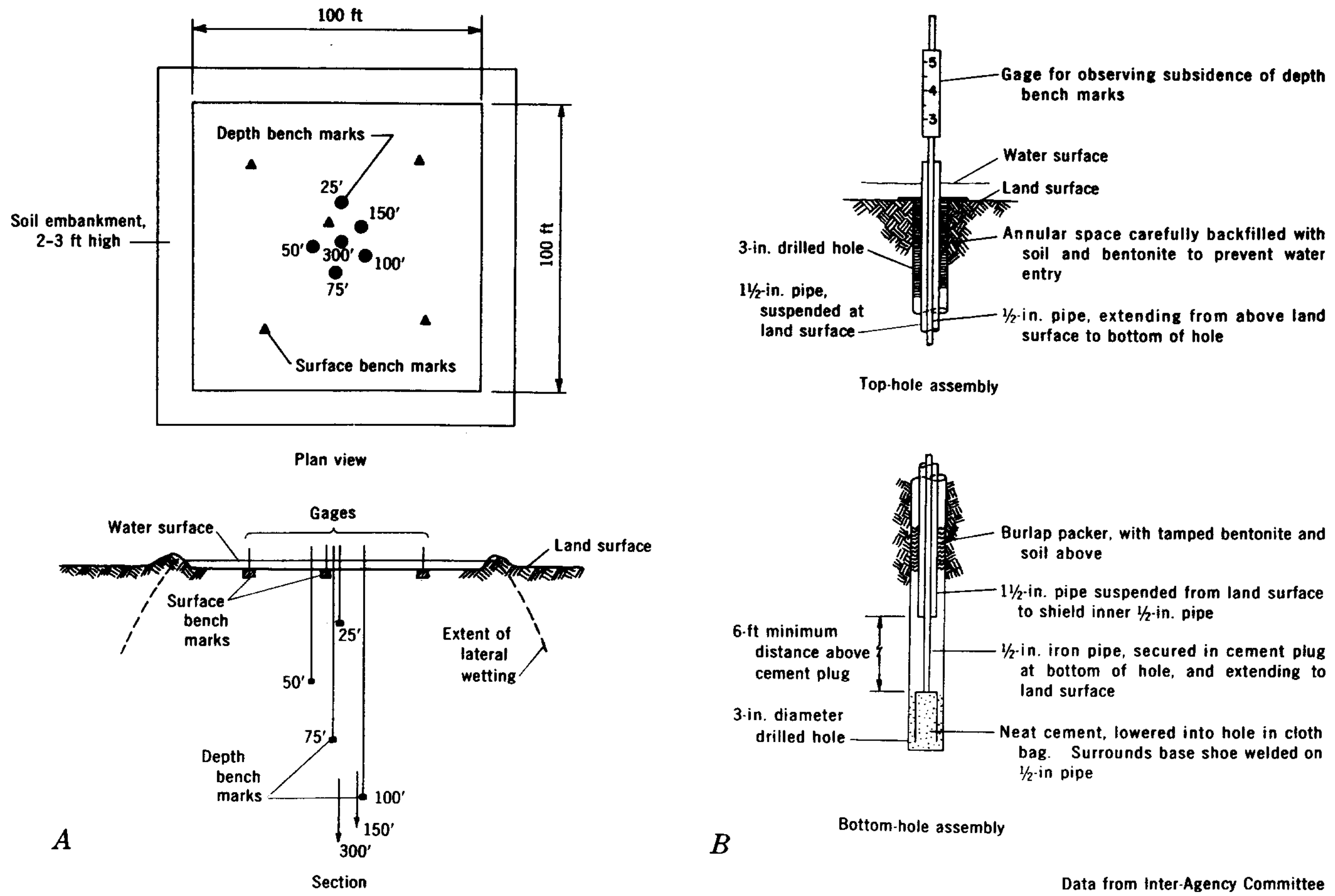



FIGURE 20.—Location and design of bench marks used for test plot B. *A*, Plan and section of test plot B; *B*, top-hole and bottom-hole assembly used for the depth bench marks in test plot B.

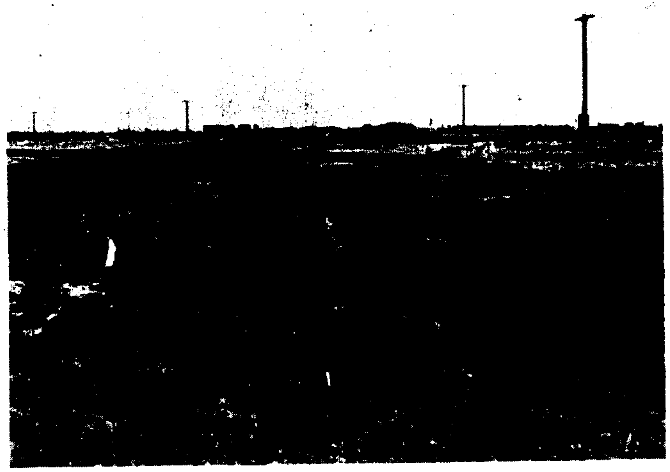


FIGURE 21.—Views of subsidence test plot. *A*, View of test plot B after 14 months of operation; *B*, view of concentric subsidence cracks along one side of a test plot. Mendota Test Site of the California Department of Water Resources, SW¼ sec. 16, T. 16 S., R. 14 E.

14 months of operation. The floor of the plot had dropped 9 feet below the unirrigated land, and the plot was encircled by subsidence cracks.

### DESCRIPTION OF NEAR-SURFACE SUBSIDENCE

Near-surface subsidence is identified by two diagnostic characteristics. One is the actual settlement of the land surface, and the other is the formation of subsidence cracks between the wetted area that is subsiding and the area that remains stable. Settlement of the land surface is characteristic of all types of subsidence; but in the San Joaquin Valley, open cracks in the soil are peculiar to near-surface subsidence.

The amount of settlement varies from one area to another and with respect to distance from the mountain front. Plate 2 shows the areas of near-surface subsidence in western Fresno County. About 82 square miles has subsided; about 42 square miles probably would subside if irrigated; and about 13 square miles possibly would subside if irrigated. The subsidence area is bounded on the southwest by deformed Cenozoic rocks; but its other boundaries, as shown in plate 2, are where subsiding fans coalesce with nonsubsiding fans or in the lower parts of subsiding fans where subsidence is not apparent. The amount of subsidence generally decreases from the middle parts to the lower parts of the fans.

Areas of probable subsidence are upslope from subsiding irrigated areas, but small test plots on the areas of probable subsidence indicate about the same magnitude of potential subsidence as on the middle part of the fans.

Areas of possible subsidence consist of fans that have the same general characteristics as the subsiding fans but have not been irrigated. The California Division of Highways established a small test plot in the area of possible subsidence between Panoche Creek and Inter-Agency test plot D (SW cor. sec. 21, T. 14 S., R. 12 E.), and the plot subsided about a foot.

The fans of Little Panoche Creek, Panoche Creek, and Cantua Creek are considered nonsubsiding, and subsidence is lacking or not apparent on the fans within the area studied north of Little Panoche Creek and south of Cantua Creek.

The amount of subsidence is a function of how deeply irrigation waters have penetrated, and areas of more than about 6 feet of subsidence are usually along ditches and canals where infiltration is nearly continuous for much of the year. Three to 5 feet of subsidence is common, and more than 10 feet of subsidence has been reported in several localities. Inter-Agency plot B has subsided 10½ feet.

The rate of subsidence depends partly on the rate at which water enters the soil and the rate at which the percolating front advances. The Inter-Agency test plots had a maximum subsidence rate of about one-quarter of a foot per day shortly after they were first flooded, but the rate decreased to a few hundredths of a foot per day after several months. At plot B the decrease in the rate of subsidence was due to two factors. First, the initial water infiltration rate decreased from about 1 foot per day to 0.25 foot per day after 3 months of flooding. Secondly, the seepage front expanded laterally, as well as moving downward, because of the capillary properties of the deposits. Thus, the seepage front enlarged in area while the intake area at the surface remained the same. Even if the infiltration rate had remained the same, the subsidence rate would have decreased because the downward movement of the expanding seepage front would have decreased progressively.

The infiltration rate, and hence the rate of subsidence, is slower on farmed land than on the test plots because crops are irrigated intermittently. In general, furrow irrigation will put more water into the soil than sprinkler irrigation. The advance of the water front under

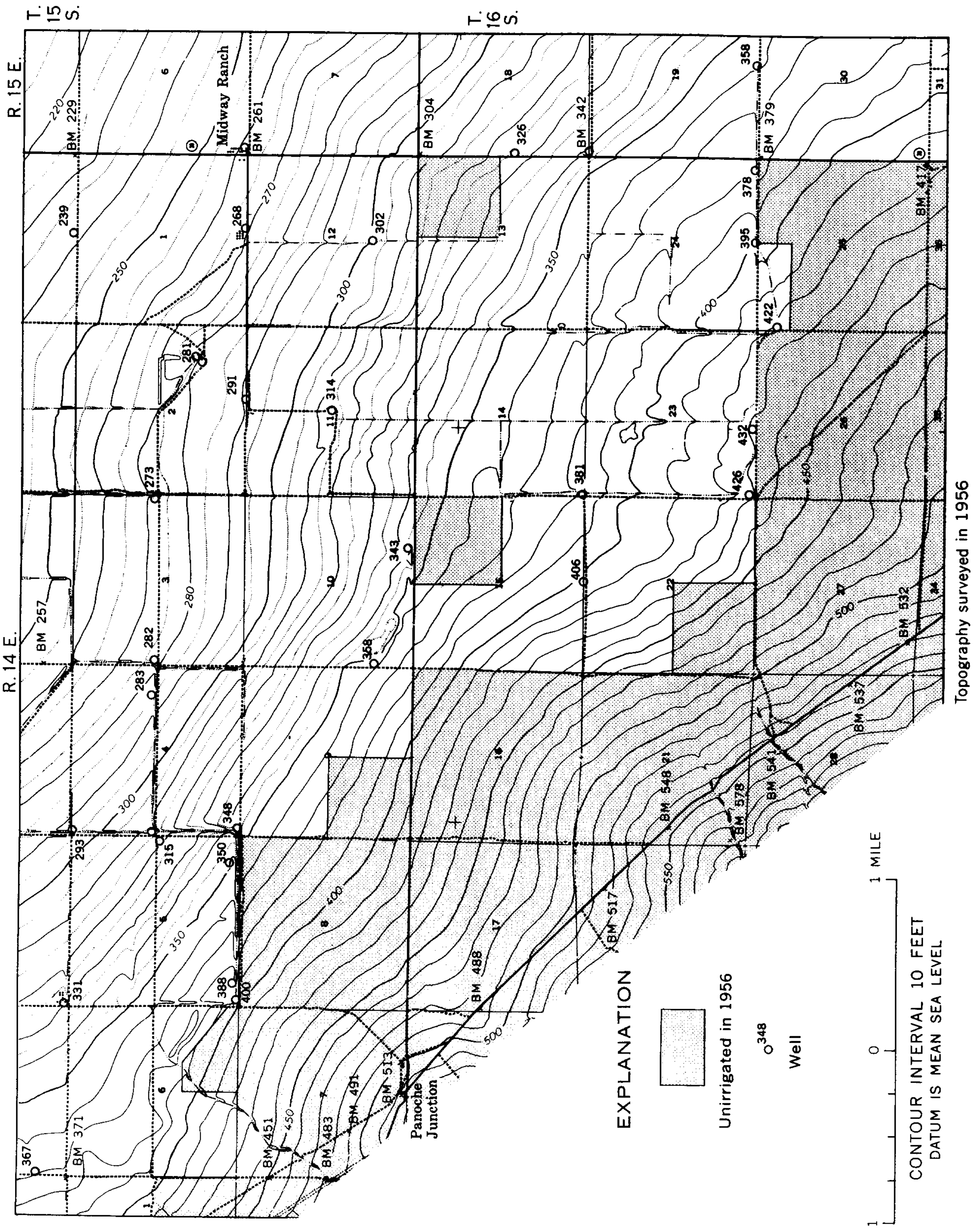



FIGURE 22.—Subsidence features in part of the Levis quadrangle, Fresno County, Calif.

sprinkler irrigation may be only a few feet per year. Some land near the Hammond Ranch is reported to be still subsiding after 20 years of furrow and sprinkler irrigation. The infiltration rate is probably highest in unlined ditches, because the flowing water tends to prevent the sealing of the soil, and because the ditches contain water much of the time. Furthermore, compared to a field, a ditch is essentially a line source of infiltration from which the seepage bulb can expand laterally in two directions. Thus, the area of the seepage front beneath a ditch may be several times as great as the infiltration area.

On subsiding fans the contours of the unirrigated land are smooth, whereas the contours of the irrigated areas are irregular despite repeated land-leveling operations. Features shown in figure 22 such as the hummock in sec. 6, T. 16 S., R. 14 E., and the hollows in secs. 10 and 23 are common in areas of near-surface subsidence. The land was once flood irrigated, but the farmers now use sprinklers. The location of former ditches along section and half-section lines is readily seen on the topographic map. Most of the ditches were temporary and, in general, were about 3 feet deep and less than 10 feet wide. Now their alinement is represented by broad swales that may be 200–300 feet wide. Broadening of the subsidence areas along the ditches was probably related to lateral movement of water away from the ditch. The fields subsided also, and, in general, the contour map shows how much more the ditches have subsided than the fields. The ditch between secs. 5 and 8 is now more than 10 feet deep; but, as this area has not been releveled, part of this depth is the original depth of the ditch.

The other diagnostic characteristic of near-surface subsidence is the pattern of discontinuous subsidence cracks that forms between the wetted subsiding area and the area that has remained stable. These cracks are most pronounced adjacent to areas of severe subsidence, such as ditches and sumps, and commonly show a vertical displacement of several inches, with the downthrown side of the crack nearest the area of subsidence. The cracks may be open, and if so, the maximum width is usually less than a foot; most are 1–6 inches wide. Cracks adjacent to large wetted areas appear to be vertical or to dip slightly toward the wetted area. Some cracks adjacent to small (8-foot diameter) test plots appear to dip slightly away from the wetted area.

Displacement along individual cracks around test plot B was as much as 18 inches after 21 months of flooding and 10 feet of subsidence. At this locality, a series of exploratory holes drilled by the California Department of Water Resources showed that water

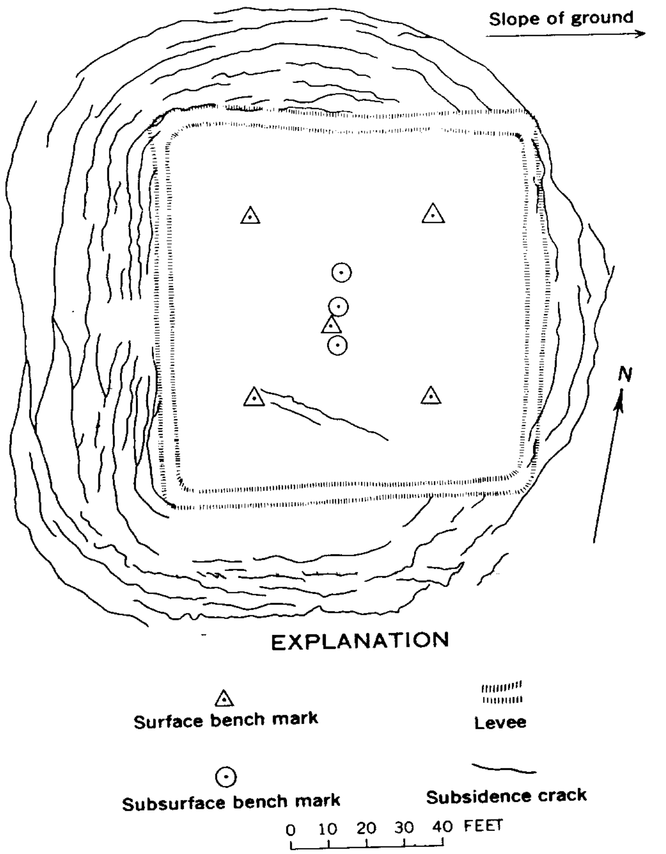



FIGURE 23.—Pattern of subsidence cracks after 42 days of flooding, test plot D.

had moved laterally more than 200 feet in the 39 months after water was introduced into the plot.

The pattern of subsidence cracks around Inter-Agency plot D after 42 days of flooding is shown in figure 23. Cracks started to open on the uphill side 2 days after the plot was filled with water. The first cracks opened in the levees, and successive cracks opened farther away from the plot. The older cracks closed as new cracks opened farther away from the plot; and after several months, cracks opened at a distance of more than 60 feet from the edge of the water. Cracks were wider and more closely spaced on the uphill side than on the downhill side of the plot, and the two sides parallel to the slope showed an intermediate and about equal development of cracks. During the first few weeks, the cracks roughly paralleled the borders of the plot; then the pattern of outermost cracks became arcuate, and eventually the pattern of cracks became circular. The maximum vertical displacement of single cracks was only three-eighths of an inch after 1½ feet of subsidence had occurred in the test plot.

The view of concentric cracks in figure 21*B* shows several features that are typical of subsidence cracks. The man is standing on the edge of the area that was ponded. The surfaces of the blocks between the cracks slope toward the wetted area. The cracks near the wetted area have less vertical displacement than they did in an earlier stage in the history of the plot and have partly closed.

The formation of the cracks is related to the decrease in the volume of deposits as the water front moves downward and outward in the fine-grained deposits. Any process that explains the formation of subsidence cracks must conform to the following facts:

1. The cracks are essentially open fissures and are nearly vertical to depths as great as 10–20 feet.
2. Vertcial displacement of the surface on opposite sides of a crack is not always evident but may be as much as 18 inches.
3. The surface of the blocks between the cracks usually slopes toward the wetted area at less than 10°. Tilting of the blocks is illustrated by telephone poles that lean toward adjacent irrigated areas.
4. As a new crack farther from the wetted area opens, the cracks closer to the wetted area close.

A possible process for the formation of subsidence cracks is shown in figure 24. The process is different from the "circular arc" type of slope failure because vertical instead of lateral support is being removed. In figure 24*A*, crack *a* has already opened and closed, crack *b* has opened, and crack *c* has started to open. The material above the wetted zone between *b* and *c* is acting as a block. The wetted front has penetrated past the lower part of crack *b* and has been accompanied by a reduction in volume of the wetted materials represented by the dotted area. The left side of the block between *b* and *c* is not fully supported by the underlying deposits. In figure 24*B* a gravity induced rotation has closed crack *b*, opened crack *c*, and has left the surface of the block sloping toward the wetted area. If there is vertical displacement, it indicates that the block nearer the wetted area has subsided more than the block farther from the wetted area. After the blocks have formed, other types of failure may occur as material slumps into open cracks. The process discussed above conforms with observations of ditches, fields, and test plots.

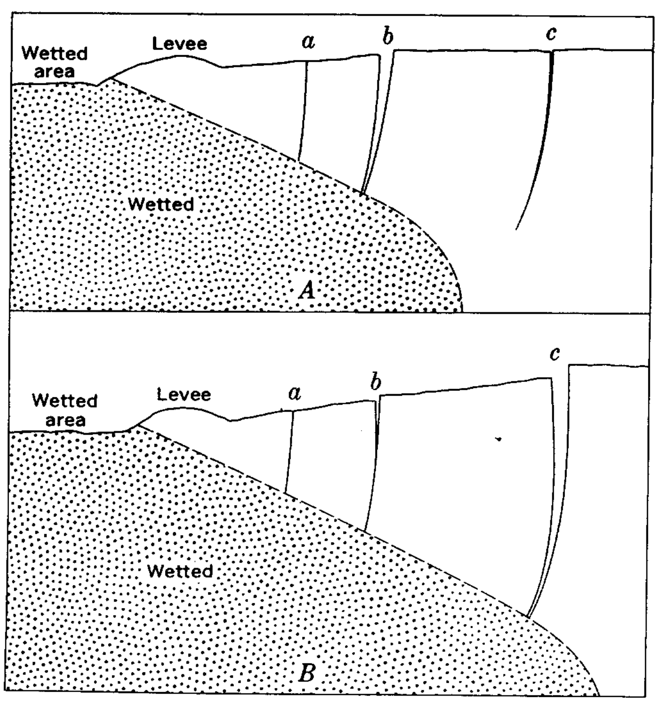



FIGURE 24.—Diagrammatic sections showing a possible explanation of subsidence cracks: a, b, and c are progressively younger cracks. *A*, before the wetted front has moved as far as crack c; *B*, after the wetted front has moved past crack c.

### HISTORY OF NEAR-SURFACE SUBSIDENCE

The first man-made structure in western Fresno County to be affected by near-surface subsidence probably was a large unlined ditch that crossed a small subsidence area in the valley of Panoche Creek. The ditch was constructed in 1887 and 1888 by the Panoche Development Co. and was used to carry water away from a dam across Panoche Creek in sec. 16, T. 15 S., R. 12 E. The small subsidence area in sec. 15 (pl. 2) is on an alluvial fan that extends into the valley of Panoche Creek. This fan has as least one 3-foot subsidence hollow accompanied by the usual subsidence cracks. Although subsidence cracks could not be found along the ditch, the ditch is visibly wider where it crosses the subsidence area.

Between 1887 and 1912 many people obtained land under the Desert Land Act. To obtain the land they had to divert water from one of the streams to the land they wished to acquire. Water was diverted from the smaller streams as well as from larger streams such as Panoche Creek. Dams and ditches to divert and carry the water were built on the fans of Arroyo Hondo, Arroyo Ciervo, and Moreno Gulch, which are now known to subside, and some of these old waterworks probably were affected by subsidence. Eventually, all the stream diversion works were abandoned as floods ripped out the dams on the larger creeks and as dryer years reduced the amount of flow in the ephemeral streams.

Chaney Pump Station in the S½ sec. 26, T. 15 S., R. 13 E., (pl. 1) was one of the first buildings to be affected by subsidence. The subsidence was caused by the ponding of flood waters, the irrigation of lawns, and the disposal of sewage. Sneddon (1951) summarizes the damage that has occurred since the pump station was built in 1915. The buildings were tilted, and cracks as much as 2 inches wide formed in the floors. A 65-foot smokestack was tilted out of plumb about a foot and had to be replaced. The casing of a water well broke at a depth of 40 feet, and the rear ends of some of the boilers subsided 5 inches lower than the front ends. Sections of the oil pipelines had to be removed at various times to relieve the stress caused by the subsiding building. The pump station underwent extensive repairs in 1935; and at that time, rainwater from the eaves and sewage were carried to a safe distance before they were allowed to enter the ground. A series of ditches was built to keep flood waters away from the pump station, and the irrigation of lawns was discontinued shortly after construction of the pump station.

After World War II there was a vigorous expansion of farming into areas that had not been irrigated before (Davis and Poland, 1957, p. 412), and the upper slopes and fans susceptible to near-surface subsidence were brought under cultivation. By 1961 most of the valley land was under irrigation except a strip 2–3 miles wide east of the edge of the foothills (pl. 2). Most of this unirrigated belt is upslope from areas of known subsidence and probably will subside if it is farmed. Additional expansion of farming into this unirrigated strip probably will occur if water is imported into the area.

### EFFECT OF SUBSIDENCE ON AGRICULTURAL OPERATIONS

The farmer is one person who must continually repair the damage caused by subsidence. Most of his subsidence problems center about the distribution of water in canals, ditches, pipelines, and across fields (fig. 25). As shown in figure 22, irrigated farmlands tend to have hummocks and hollows caused by differential subsidence, and the cost of releveling these fields can be as much as $10 per acre.

A farmer using a furrow type of irrigation practice may find that some parts of a field subside at a faster rate than others. Water flowing down a furrow will collect in a hollow that has been formed and supply even more water for subsidence. The crops in the hollow are flooded out, but farther downslope the crops die because of a lack of water.

A field on the Azhderian Bros. Ranch had an initial slope to the east-northeast of 95 feet per mile and was originally furrow irrigated from the west. The owners found that by the time water reached the east side of the field the furrows on the west side had been wetted for many hours, and because more water was delivered to the west side of the field, it subsided more than the east side. Although the field had been leveled many times, eventually it became necessary to irrigate from south to north (Mat Gabe, Azhderian Bros. Ranch, oral communication, July 1957).

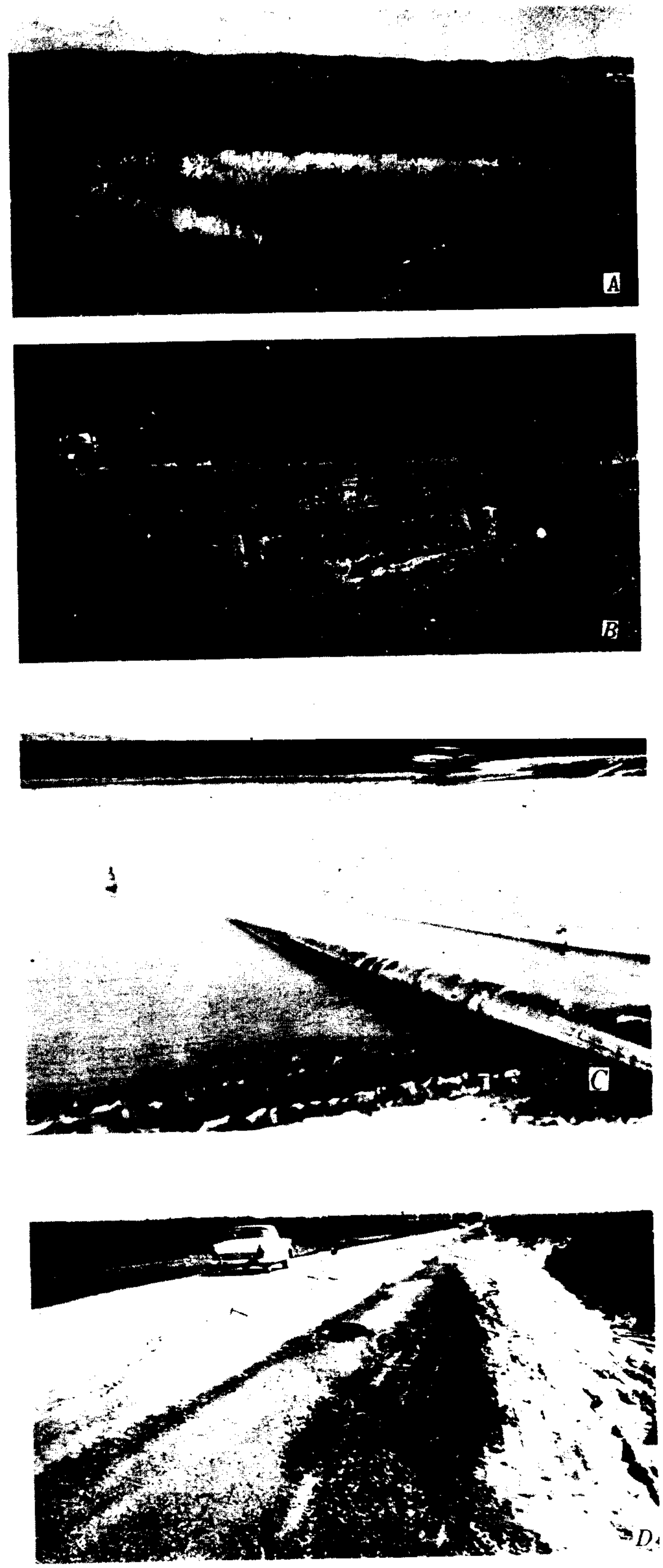



FIGURE 25.—Examples of damage caused by subsidence. *A*, Subsidence hollow in a cotton field; *B*, sprinkler pipeline parted by subsidence; *C*, subsidence hollow caused by water from leaky pipelines; *D*, subsidence cracks in a paved road.

A second principal agricultural problem is the effect of subsidence on ditches. Water is delivered to the furrows by a system of unlined ditches, some segments of which may drop rapidly while other segments remain fairly stable. Water concentrated in the subsiding sections of a ditch may accelerate the subsidence until the water flows over the levees. If a ditch subsides uniformly throughout its length, the farmer is faced with the problem of pumping the water out of the sunken ditch to the level of his fields.

An unlined ditch was used to carry water to the vicinity of test plot D. The first 1,200 feet of the ditch crossed a barley field that had been irrigated for 2 years, and the subsidence along this section was negligible. The last 300 feet of the ditch crossed land that had never been irrigated, and several feet of subsidence occurred. Water ponded in the 300-foot section of the ditch although initially it had a gradient twice that of the section across the barley field. During the first 2 weeks of operation, the subsiding section of ditch had to be rebuilt twice, raising its banks 2–4 feet above their original level in several places.

Most of the farmers in the areas of subsidence have stopped irrigating by ditches and furrows and have changed to sprinkler irrigation. By this method water flows under high pressure through pipelines and is sprayed over the crops through nozzles. The main advantage of this method is that the fields do not need to be leveled as carefully as under a furrow type of irrigation. The land surface may be undulating and sprinklers can still be used. Another advantage of the sprinkler system is that a subsidence hollow cannot keep water from reaching the lower end of a field.

Subsidence hollows are common in some sprinkler-irrigated fields. Figure 25*A* shows a subsidence hollow in a cotton field that is being irrigated by sprinklers; the pond is more than 3 feet deep at its center. Hollows such as this may persist for several years. Water will continue to percolate downward, causing subsidence, and the material used to fill the hollow probably will be compacted somewhat once irrigation is resumed. Thus, even though the area has been releveled, the hollow may remain a potential low area in which water can collect.

Hummocks usually are formed when part of the field does not subside as rapidly as the rest. Once hummocks are formed in sprinkler-irrigated fields, they persist because water flows away from these high areas.

Sprinkler pipelines can be damaged by subsidence, as is shown in figure 25*B*. A leak in the coupling allowed water to enter the ground and start a subsidence hollow. The pipeline was then set up on blocks, but water in the ground continued to move downward, causing more subsidence, and the leak opened again. The pipeline parted at the coupling after about 3 feet of subsidence and was abandoned because of this and two other subsidence hollows. A large hollow caused by water from leaky sprinker pipelines is shown in figure 25*C*.

### EFFECT OF SUBSIDENCE ON ENGINEERING OPERATIONS

Subsidence affects a variety of engineering structures such as buildings, canals, highways, power-transmission lines, and oil and gas pipelines and makes the irrigation of crops difficult. Subsidence causes the most damage to man-made structures when one part of a structure subsides more than the remainder.

The Panoche lift system is a large unlined canal that was designed to carry water upslope from the Delta-Mendota Canal. The lift system has subsided more than 3 feet over much of its route where it crosses the subsiding fan of Moreno Gulch. The last half mile of the lift system subsided even more and eventually had to be abandoned.

Subsidence of part of the Azhderian lift system, shown in figure 26*A*, was started by water seeping through expansion joints or other cracks in the concrete. The resulting subsidence enlarged the cracks and allowed large volumes of water to enter the ground, causing a basin of subsidence. The ditch was originally 7 to 8 feet wide and 3 feet deep; but where the lift system has subsided, the average width is about 18 feet, and locally 21 feet. Subsidence is continuing despite the fact that all visible cracks were coated with a plastic sealer during the winter months when the lift system was drained. The deepest part of this canal is now 18 feet deep (Mat Gabe, oral commun., August 1959), representing subsidence of about 15 feet, and two other places along the lift system have dropped more than 12 feet. As the basin of subsidence extends away from the canal, the embankments may drop below the water surface in the ditch. If the system is to operate, the sides of the canal lining must be built up during the winter repair period; no repairs to the canal lining can be made during the summer because water must keep flowing to the crops. Although the lift system is only 1.65 miles long, the cost of sand and cement alone has been as much as $5,000 per year.

The Azhderian lift system has been kept in operation for 7 years, but other canals have not lasted as long. A concrete-lined ditch on the William Deal ranch near test plot B was reduced to broken concrete slabs in a few months and had to be abandoned before the end of a single summer's growing season.

Several pipelines that carry oil and gas to the San Francisco Bay area pass through areas of near-surface subsidence. Locally, where they pass through irrigated land, the pipelines are downwarped where the soil around them has settled, and in several locations they have been ruptured. Figure 26*B* shows two oil pipelines that have been downwarped by subsidence caused by water ponding in a hollow near a field. Railroad ties were placed under the pipelines after they were uncovered. The pipeline on the right side of figure 26*B* is bowed, due probably to stretching of the pipeline as the supporting ground subsided.

Poles and towers that carry electric power lines are tilted by subsidence. Poles along the side of a road adjacent to a subsiding field commonly lean toward the field, and some of the poles have had to be reset or supported by guy wires. Three Pacific Gas and Electric Co. steel transmission towers south of Panoche Creek have been tilted more than 5°, and severe tilting such as this may buckle or break some of the steel parts of the towers; one of the three towers had to be replaced (Mr. Burnette, Pacific Gas and Electric Co., oral commun., August 1959).

Buildings are damaged by subsidence when water seeps into the ground near them. The water may come from cesspools, concentration of rainfall running off of roofs, or the watering of lawns and shrubs. Occasionally, flood waters from ephemeral streams will pond around buildings and cause subsidence. If the building is small, the whole structure may be tilted toward the local area of maximum subsidence. In larger buildings, the foundations may be broken by subsidence or cracks may appear in the floors and walls.

Both dirt and paved roads are broken by subsidence cracks as water seeps under the roadbed. Dirt roads can be repaired without much difficulty, but the repair of paved roads is more expensive. Where irrigation ditches parallel both sides of a road, the level of the road may subside as much as 5 feet below the general level of the fields on either side. If there are no ditches adjacent to the road, however, the roadbed is usually higher than the nearby subsiding fields.

Subsidence cracks in the pavement of Shields Avenue where it crosses the fan of Moreno Gulch are shown in figure 25*C*. The subsidence was caused by water that ponded in a sump for waste irrigation water and then moved laterally underneath the road. A large crack is indicated by the alinement of holes in the pavement, and another crack is marked by a series of small breaks. Vertical displacement along the small breaks is as much as 2 inches. Where Shields Avenue crosses unirrigated areas west of the Moreno Gulch fan, the level of the roadbed is about a foot below the general land surface. According to the farmers living in the area, Shields Avenue used to be about a foot below the land surface

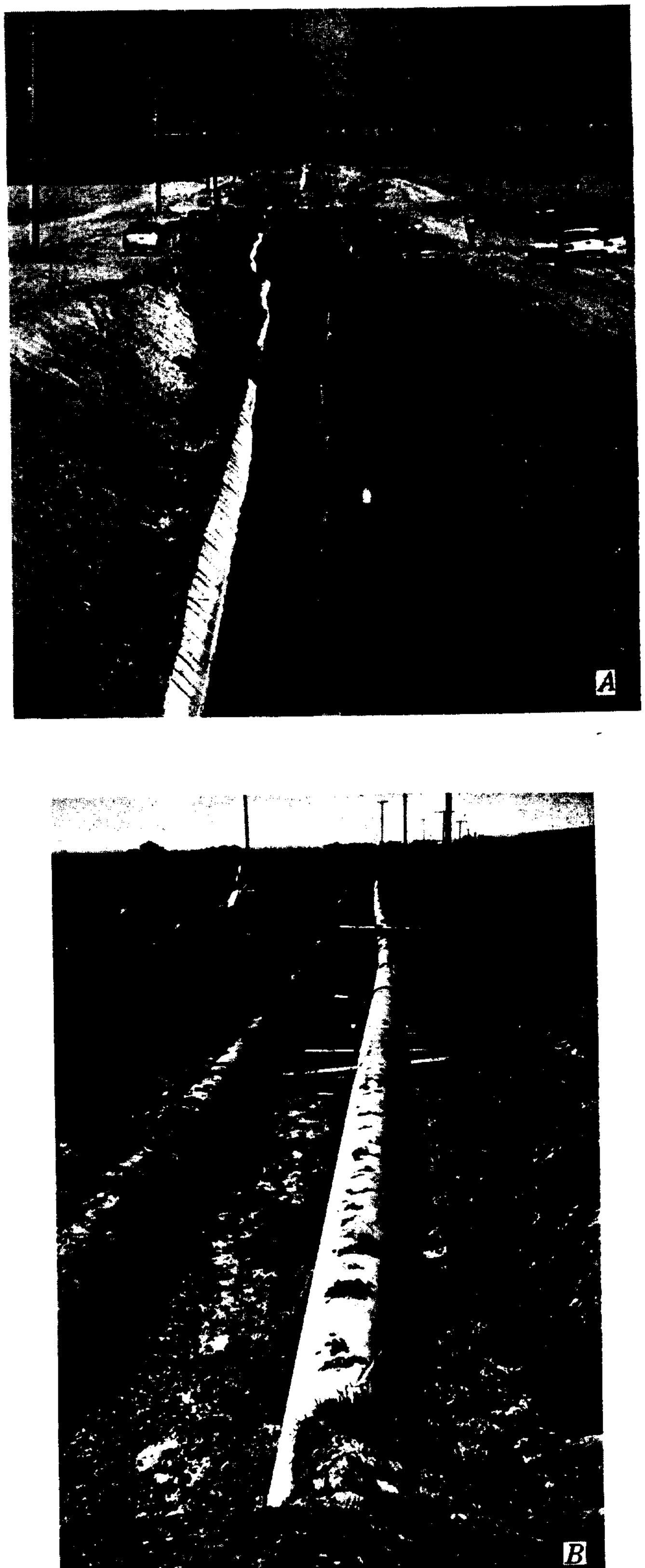



FIGURE 26.—Damage to a lined canal and oil pipelines caused by subsidence. *A*, Subsidence of part of a concrete-lined irrigation ditch; *B*, oil pipelines downwarped by subsidence.

in the subsiding areas also, but now the roadbed is about 1½ feet above the general level of the irrigated fields to either side. Subsidence has left the road as a broad gentle ridge.

The proposed routes of major canals cross areas of near-surface subsidence in Fresno and Kern Counties. These canals are part of an aqueduct system that will cost billions of dollars, and it may be difficult to keep a canal and its distributary works operating at peak efficiency because of subsidence problems. At the present time, one of the favored solutions is to preconsolidate the deposits along the canal alinement, but this will require large volumes of water and considerable time.

Part of one of the planned major highways in California, the Westside Freeway, will cross the upper parts of some of the subsiding fans. Measures will have to be taken to keep storm and irrigation waters from ponding near this highway, because subsidence has already damaged every paved road within the area of near-surface subsidence.

### CAUSES AND MECHANICS OF NEAR-SURFACE SUBSIDENCE

Subsidence results chiefly from the compaction of deposits by an overburden load as the clay bond supporting the deposits is weakened by water percolating through them for the first time. The amount the deposits of a subsiding fan will compact depends mainly on the overburden load, moisture conditions, and type and amount of clay. The geologic term "compaction," as used in this paper, refers to the decrease in the volume of deposits caused by increase in overburden load or initial wetting under load; the engineering term "consolidation" is used in reference to the laboratory tests on compactable sediments. For example, consolidation tests were made to measure the amount of compaction.

#### OVERBURDEN LOAD

The amount of compaction increases with an increase in the overburden load, as is illustrated by subsidence of the Inter-Agency test plots. Initially, the surfaces of the three test plots rose slightly after the water was applied because the surface deposits swelled. The amount of swelling could not be measured until after the areas had been wetted for 6–12 hours. As the water reached greater depths, however, the volume of the deposits was reduced, causing compaction and subsidence. This volume reduction increased with depth, and subsurface bench marks set beneath test plot B at depths of 25, 50, 75, 100, 150, and 300 feet (fig. 20) afforded a means of measuring the amount of compaction that occurred within each depth interval. The compaction after 42 months of operation of test plot B is shown in figure 27. Each point in figure 27 represents 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 with increasing depth, the percentage doubling between the points at 12½ feet and 87½ feet. In the 100–150-foot depth interval, however, the percentage decreases; the reason for this anomaly is discussed on page A53. The plot is a striking illustration of the effect of the amount of overburden load on compaction. The nearly straight-line increase in the percentage of compaction to a depth of 100 feet is due directly to the amount of overburden, which under natural conditions increases nearly directly with depth.

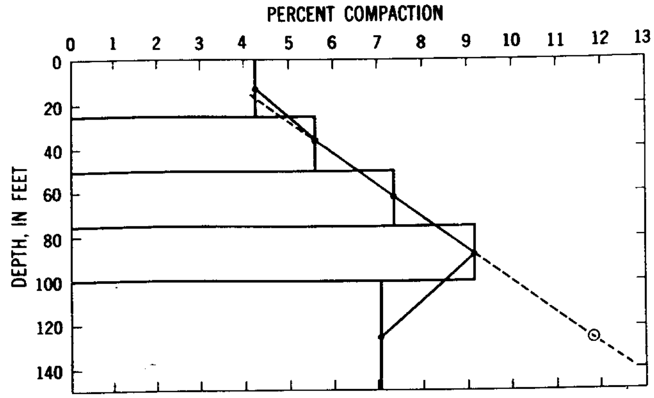



FIGURE 27.—Effect of overburden load on compaction, Inter-Agency test plot B after 42 months of operation.

Pairs of samples carved from homogeneous polygonal blocks were tested in a consolidometer at loads that simulated 50 and 100 feet of overburden. The results of these tests indicate that more compaction occurs at 100 feet than at 50 feet. Sample 95 (table 17) was divided into two samples; one swelled when water percolated through it under a load equal to 50 feet of overburden, but the other compacted when wetted under a load equal to 100 feet of overburden.

#### MOISTURE CONDITIONS

The moisture condition of the deposits not only determines whether a fan will subside but also partly controls the amount of subsidence. The effect of the moisture conditions on the amount of subsidence is discussed in the section "Strength of clay."

The seasonal moisture cycle on the fans of ephemeral streams consists of a 3- to 5-month rainy period when flows of short duration may spread out on the fans, followed by a 7–9-month period of little or no rain when evapotranspiration removes most of the moisture from the surface deposits. This pattern varies considerably from year to year—from no flows in some dry years to repeated flooding of the fans in some wet years. Bushes and grass in the areas of present-day deposition may continue to grow vigorously during a dry year following a wet year, and this indicates that it may take several years to reduce the moisture content of the soil to the wilting coefficient.

The moisture cycle is different for the intermittent streams. The streams may flow for several months during wet years, and water may penetrate below the root zone. The clean sands of these fans probably allow a greater depth of water penetration than do the clay-rich deposits of some of the fans of ephemeral streams. Thus, the moisture content of parts of the deposits of intermittent streams should approach field capacity.

The moisture content of samples from beneath Inter-Agency test plots B and C is shown in figure 28. Many of the fluctuations are due to variations in the amount of clay and shale fragments. The amplitude of the fluctuations was smoothed by plotting three-point moving averages of the moisture content, and these are shown to the right of the plots of actual moisture content. The moisture content beneath plot B ranges from 5 to 19 percent in the upper 125 feet; there is a general increase in the moisture content from 12 to 25 percent between approximately 125 feet and 210 feet; and from about 210 feet to 290 feet the moisture content increases steadily from 23 to 33 percent. The plot C test results show an erratic but increasing moisture content with increasing depth, particularly below 110 feet.

One way of appraising the moisture condition of deposits is the moisture-equivalent test, which is used by agronomists to obtain an approximate value of field capacity. The closeness of the approximation varies with the lithology and the depth of sampling. For example, the natural moisture content of a compacted sediment at a depth of 100 feet may be at field capacity, but a sample of loose disturbed material from that depth tested for moisture-equivalent may be able to hold more, or rarely less, water than in its compacted field condition. Nevertheless, if the moisture content of a deposit is about the same as the moisture-equivalent value for a centrifuged sample of the deposit, the moisture condition is reasonably close to field capacity, and more water should cause little or no additional compaction of the deposits. If the moisture content is much less than the moisture equivalent, however, the moisture condition may indicate wilting coefficient or even hygroscopic (air-dry) conditions.

This relationship can be conveniently described by the term relative moisture, which, as used in this paper, is the moisture content expressed as percent of moisture equivalent.

Moisture-equivalent and moisture-content tests were made by the University of California at Davis and by other agencies. Both tests were made on each sample except for the samples from test plots B, C, and D, and test site E. The average relative moisture percentages for these four were derived by averaging the results of moisture-content and moisture-equivalent tests made on separate samples.

The average relative moisture of samples from 17 alluvial fans in Fresno and Kern Counties is shown in table 10. The relative moisture data of some fans are from several sources: for example, the Arroyo Ciervo fan data are from Inter-Agency plot B, State plot 1, and from core holes on other parts of the fan.

TABLE 10.—*Relative moisture of alluvial-fan deposits in Fresno and Kern Counties*

[Cores obtained by the California Department of Water Resources and the U.S. Bur. Reclamation. Moisture-equivalent tests made by the Univ. California at Davis. Kern County subsidence data from the California Department of Water Resources]

| Alluvial fan | Relative moisture | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Subsiding | | | | Nonsubsiding | | | |
| | Irrigated | | Unirrigated | | Irrigated | | Unirrigated | |
| | Percent | Number of samples | Percent | Number of samples | Percent | Number of samples | Percent | Number of samples |
| **Fresno County** | | | | | | | | |
| Moreno Gulch | 74 | 5 | 44 | 3 | | | | |
| Test plot D | 83 | | 36 | | | | | |
| Panoche Creek | | | | | 77 | 1 | | |
| Test site E | | | | | | | 73 | 10 |
| Tumey Gulch | 97 | 3 | | | | | | |
| Arroyo Ciervo | 81 | 4 | 47 | 23 | | | | |
| Test plot B: | | | | | | | | |
| 0–150 ft | | | 45 | | | | | |
| 150–300 ft | | | 73 | | | | | |
| To wetted front at about 130 ft | 96 | | | | | | | |
| State plot 1 | | | 49 | 12 | | | | |
| Arroyo Hondo | 82 | 12 | 51 | 5 | | | | |
| Test plot C: | | | | | | | | |
| 0–150 ft | | | 51 | | | | | |
| 150–300 ft | | | 66 | | | | | |
| To wetted front about 80 ft | 105 | | | | | | | |
| Cantua Creek | | | | | 82 | 3 | 49 | 536 |
| Martinez Creek | | | | | 89 | 4 | | |
| Los Gatos Creek: | | | | | | | | |
| State plot 2 | | | | | | | 41 | 5 |
| **Kern County** | | | | | | | | |
| Bitterwater Creek (North) and adjacent fans: | | | | | | | | |
| State plot 3 | | | | | | | 82 | 5 |
| State plot 4 | | | | | | | 72 | 6 |
| Santos Creek: | | | | | | | | |
| State plot 5 | | | | | | | 53 | 5 |
| Temblor Creek: | | | | | | | | |
| State plot 6 | | | 61 | 6 | | | 71 | 4 |
| Sandy Creek | | | | | | | | |
| Little Signal Hills | 114 | 2 | 55 | 6 | | | | |
| Bitterwater Creek (south) [1] | | | 71<br>42 | 4<br>2 | | | | |
| State plot 7 | | | 53 | 5 | | | | |
| Bitter Creek | | | 41 | 21 | | | | |
| Santiago Creek | | | 25 | 7 | | | 102 | 8 |
| San Emigdio Creek | | | | | | | | |
| Average | 92 | | [2] 45 | | 83 | | 68 | |

[1] Results from 2 core holes. Oilfield waste sumps common in area.
[2] Excluding samples below 150-foot depth in test plots B and C, the samples from State plot 6 on Temblor Creek fan, and the high figure for Bitterwater Creek (south).

The moisture condition of the irrigated and unirrigated parts of the subsiding fans show a marked contrast. The relative moisture of groups of samples from irrigated areas ranged from 74 to 114 percent and averaged 92 percent, indicating that the moisture condition of these deposits was close to field capacity. The relative moisture of groups of samples from unirrigated areas[3] ranged from 36 to 55 percent and averaged 45 percent, indicating a moisture condition approximating the wilting coefficient. The average relative moisture of seven samples from the Santiago Creek fan was only

[3] Excluding samples below 150-foot depth in test plots B and C, the samples from State plot 6 on Temblor Creek fan, and the high figure for Bitterwater Creek (south).

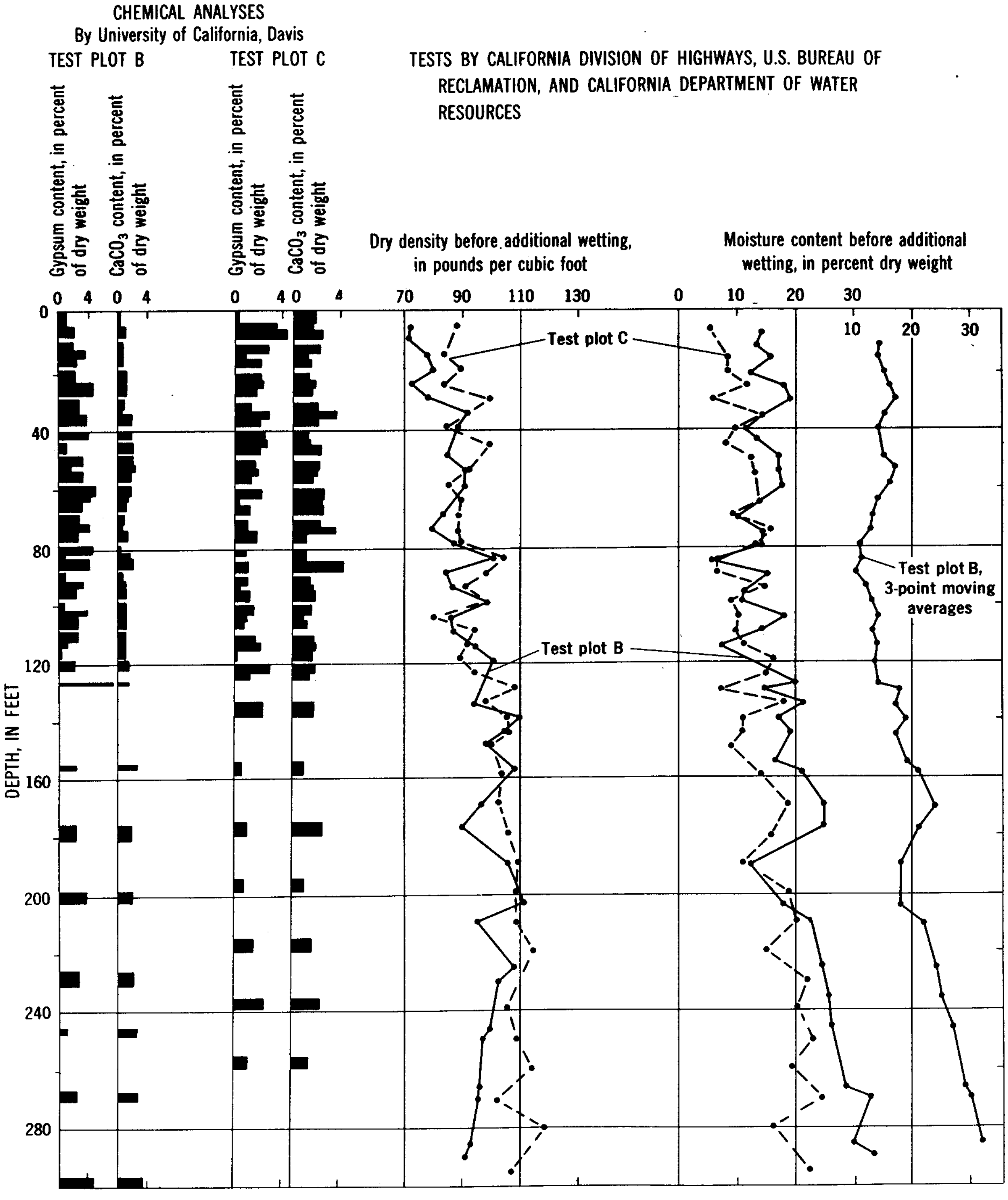



FIGURE 28.—Chemical analyses, dry density, and moisture content for samples from test plot B (Arroyo Ciervo fan) and test plot C (Arroyo Hondo fan).

25 percent, indicating that the moisture condition of these deposits may have been between the wilting coefficient and the hygroscopic coefficient. Samples from State plot 6 on the Temblor Creek fan had an average relative moisture of 61 percent. The test plot showed 0.5 percent compaction between 25 and 50 feet, but no compaction due to wetting occurred above 25 feet or below 50 feet.

The deposits of most nonsubsiding fans have relative moistures suggestive of field capacity. Most of the unirrigated deposits have average relative moistures ranging from 72 to 102 percent, and these fans should show little or no subsidence upon addition of more water.

Samples from the Martinez Creek fan, Los Gatos Creek fan, and Santos Creek fan have moisture contents near the wilting coefficient; but test plots on the Los Gatos Creek fan and Santos Creek fan did not subside, and there is no surface indication of subsidence on the Martinez Creek fan. The reasons for the apparent lack of subsidence on fans such as that of Martinez Creek are discussed in the section "significance of clay."

Nearly all the fans have relative moistures of either more than 70 or less than 55, which indicates that the overall moisture condition for deposits of a given fan either approaches field capacity or the wilting coefficient. The deposits in the 150–300-foot depth intervals of the Arroyo Ciervo and Arroyo Hondo fans and from the Temblor Creek fan may represent gradational or interlayered moisture conditions.

Moisture-equivalent tests were made by the author on 36 samples from the Martinez Creek fan; the depth and relative moisture for each sample are listed in table 11. Relative moisture ranged from 27 to 76 percent, and averaged 49, which implies that some deposits did not have much water removed by plants, and that other deposits are practically air dry. The overall moisture condition approximates the wilting coefficient. The amount of moisture removed by plants may have varied during the history of the fan. If the group of samples is divided roughly into thirds, the bottom and top thirds have relative moisture of 44 and 43 percent, respectively, but the middle third has a relative moisture of 57 percent. The zone of higher relative moisture may represent a wetter climate during that period of deposition.

### SIGNIFICANCE OF CLAY

The amount, type, and moisture condition of the clay in the alluvial-fan deposits directly affect the amount of subsidence. The moisture condition of the deposits was discussed in the preceding section, and the amount and type of clay are described in following paragraphs. How the strength of the deposits is controlled by these three variables is discussed in a third section.

TABLE 11.—*Relative moisture of core-hole samples from Martinez Creek fan, NE¼SE¼ sec. 8, T. 18 S., R. 15 E.*

[Samples obtained by the California Dept. Water Resources. Tests made at the Univ. California at Davis]

| *Depth (feet)* | *Relative moisture (percent)* | *Depth (feet)* | *Relative moisture (percent)* |
|---|---|---|---|
| 20.9 | 48 | 46.5 | 51 |
| 21.6 | 41 | 51.9 | 64 |
| 21.7 | 43 | 52.1 | 64 |
| 26.0 | 35 | 52.3 | 68 |
| 26.2 | 52 | 52.7 | 76 |
| 26.3 | 38 | 55.4 | 56 |
| 26.5 | 48 | Average relative moisture, 32.5–55.4 ft | 57 |
| 26.7 | 50 | 55.5 | 51 |
| 26.9 | 47 | 55.7 | 48 |
| 32.4 | 34 | 56.0 | 42 |
| 32.5 | 41 | 60.5 | 34 |
| Average relative moisture to 32.5 ft | 43 | 60.7 | 49 |
| 32.7 | 52 | 60.9 | 49 |
| 33.2 | 57 | 61.0 | 50 |
| 40.6 | 58 | 61.2 | 45 |
| 41.2 | 59 | 71.0 | 41 |
| 45.8 | 48 | 71.2 | 44 |
| 46.0 | 58 | 71.3 | 27 |
| 46.1 | 37 | Average relative moisture, 55.5–71.3 ft | 44 |
| 46.3 | 56 | | |
| Average of all samples | | | 49 |

### AMOUNT OF CLAY

The clay content of subsiding fans usually is higher than that of nonsubsiding fans. The average clay content for the Arroyo Ciervo fan is 22 percent for 35 surface samples and 16 percent for 40 subsurface samples. Subsurface samples to depths of 30 feet from the three downslope holes spaced at half-mile intervals (fig. 18) show an increase in the average clay content downslope from 15 to 17 to 20 percent. Test plot B is a half mile farther downslope on the same radial line and has a clay content of about 22 percent in the upper 30 feet of deposits.

The clay content of the subsurface deposits of other subsiding fans had to be estimated because the method of grain-size analysis used by other agencies was different from the method used by the author. A comparison of the two methods is made in the section "Methods of making grain-size analyses and density tests." The average clay content of 22 samples from the surface deposits laid down in the 1956–57 and 1957–58 seasons on the Arroyo Hondo fan is 16 percent; and the upper 100 feet of deposits beneath test plot C, which is 3½ miles from the apex of the fan, have an estimated average clay content of about 18 percent. The estimated average clay content of the upper 65 feet of deposits beneath test plot D on the Moreno Gulch fan is about 20 percent.

At test site E on the nonsubsiding Panoche Creek fan, the upper 90 feet of deposits has an estimated clay content of about 10 percent. Test site E is near the apex of the fan, and deposits 10–20 miles farther out on the fan are presumed to have considerably more clay. The same situation probably exists in the Little Panoche Creek fan and the Cantua Creek fan.

The grain-size distribution of 10 samples from a 70-foot core hole in the Martinez Creek fan is shown in figure 29. Only one sample has more than 4 percent gravel. The pattern of points is in marked contrast with the patterns of the Arroyo Ciervo fan shown in figure 19. Every sample except one has less than 10 percent clay, including the sample with 63 percent silt; the average clay content is only 6 percent.

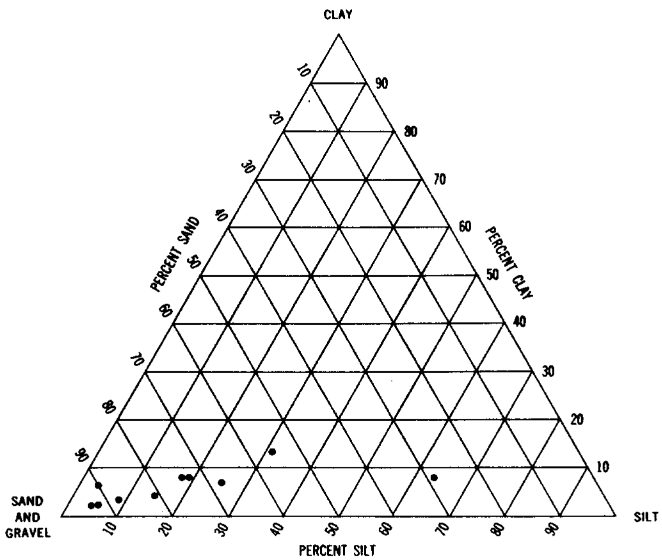



**Figure 29.**—Grain-size distribution of sediments from a 70-foot core hole on the Martinez Creek fan.

Distribution of clay in the alluvial-fan deposits depends partly on the type of deposition. Clay in most mudflows is distributed throughout the deposit but may be concentrated toward the top of the more fluid mudflows and in some intermediate deposits. The water-laid sediments have little clay, although a few consist principally of clay. The overall sequence of water-laid sediments consists of fairly clean sands and silts with seams of clay or clayey silt.

### TYPE OF CLAY

The predominant clay mineral in most fans is montmorillonite. Table 12 shows the amounts of montmorillonite, illite, chlorite, and kaolinite in surface and subsurface samples from fans whose streams head in the foothill belt. All values are based on X-ray tests. The clay minerals in samples from Panoche and Cantua Creek (table 13) are also predominantly montmorillonite, but the content of chlorite and kaolinite is higher than in the samples from fans listed in table 12. Montmorillonite content is much lower in the samples from Little Panoche Creek, indicating that the Franciscan formation may be the source of much of the illite, chlorite, and kaolinite. The Franciscan underlies about 41 percent of the basin, and most of the Tertiary continental rocks consist partly of Franciscan debris.

**Table 12.**—*Clay mineralogy of fans whose streams head in the foothill belt*

[R. H. Meade, analyst, U.S. Geol. Survey, Ground Water Branch. Samples 2, 4, and 6 collected by the California Div. Highways; sample 8 collected by the California Dept. Water Resources; samples 1, 3, 5, and 7 collected by the author]

| Fan | Depth (feet) | Clay minerals (estimated parts in ten) | | | |
|---|---|---|---|---|---|
| | | Montmorillonite | Mixed-layer montmorillonite-illite | Illite | Chlorite and kaolinite |
| Moreno Gulch | 0–0.3 | 7 | Trace | 1 | 2 |
| Moreno Gulch | 55 | 4 | Trace | 3 | 3 |
| First fan south of Capita Canyon fan | 0–1.1 | 8 | Trace | Trace | 1 |
| First fan south of Capita Canyon fan | 24 | 9 | 0 | Trace | Trace |
| Arroyo Ciervo | 0–0.3 | 8 | 0 | Trace | 1 |
| Arroyo Ciervo | 33 | 8 | 0 | 1 | 1 |
| Martinez Creek | 0–1.0 | 7 | 0 | 2 | 1 |
| Martinez Creek | 71 | 8 | 0 | 1 | 1 |

**Table 13.**—*Clay minerals in samples from streams that head in the main part of the Diablo Range*

[Samples collected and analyzed by R. H. Meade, U.S. Geol. Survey, Ground Water Branch]

| Creek | Material sampled | Clay minerals (estimated parts in ten) | | | |
|---|---|---|---|---|---|
| | | Montmorillonite | Mixed-layer Montmorillonite-illite | Illite | Chlorite and kaolinite |
| Little Panoche | Suspended sediment | Trace | 3 | 6 | 1 |
| Little Panoche | Creek bed | 2 | 2 | 4 | 1 |
| Panoche | Suspended sediment | 7 | 0 | 1 | 2 |
| Panoche | Flood plain | 7 | 0 | 1 | 2 |
| Cantua | Suspended sediment | 7 | 0 | 1 | 2 |
| Cantua | Flood plain | 7 | 0 | 1 | 2 |

### STRENGTH OF CLAY

The amount of strength due to clay in a deposit is dependent on the moisture content of the clay, the type of clay, and the amount of clay. These three variables are significant because they control the amount of compaction under a given overburden load.

All clay has strength, but dry clay has more strength than wet clay. Even wet clay around sand grains can be regarded as a binder, although it is weak compared to dry clay. But what do the terms "wet" and "dry" mean? Some clays contain more water than the "dry" weight of the clay and therefore have moisture contents of more than 100 percent. Conversely, clay that has been heated to 110°C continues to lose moisture if subjected to higher temperatures. In this paper the term "dry" refers to material that has been dried in an oven at 110°C for 12 hours or more. Wet deposits are those which have moisture conditions indicating field capacity or wetter conditions.

The strength of clay varies considerably with moisture content. Subsidence is chiefly the result of compaction caused by increasing the moisture content of deposits that have moisture contents less than field capacity. This general relation is shown by the following diagrammatic sketch (fig. 30).

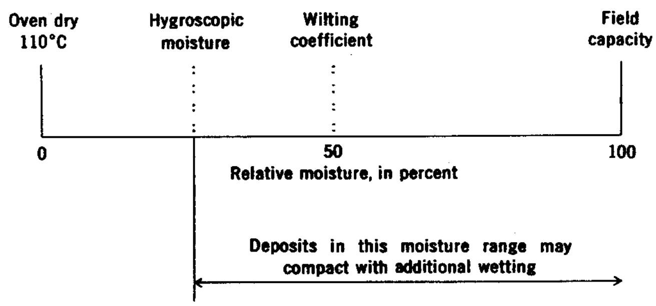



FIGURE 30.—Relation of compaction to moisture content.

For a given clayey sample under a certain overburden load, the amount of compaction due to wetting will be more if the moisture condition is near hygroscopic moisture than if moisture condition is near field capacity. The deposits of unirrigated parts of subsiding fans were shown to have an average relative moisture of 50 or a little less.

A good example of the significance of the moisture condition is provided by the compaction record of the upper 150 feet of deposits under test plot B. The lithology does not appear to change with depth, and there is no trend in the moisture equivalents within the upper 150 feet; yet the percentage of compaction in figure 27 shows a marked change in trend for the point representing the percentage of compaction in the 100–150-foot zone. The amount of compaction in this zone is only 7 percent, but the circle on the dashed line indicates that the amount of compaction for that overburden load should be about 12 percent. The reason for the decrease in the compaction due to wetting is apparent in figure 28, which shows a pronounced increase in moisture content starting at a depth of about 125 feet. These higher natural-moisture contents increase the natural compaction. Thus the higher relative moistures below 125 feet should cause a smaller amount of compaction due to wetting than if the relative moisture had remained the same as at shallower depths. Therefore, the lower part of the percent-compaction graph in figure 27 probably deviates from the trend because of an increase in the natural relative moisture of the deposits.

Water was allowed to percolate through samples during consolidation tests to simulate irrigation. The increase in relative moisture caused compaction due to wetting, and the samples finally approached equilibrium for the new moisture condition. For a few samples, the consolidometer unit was flooded to simulate a rising water table. This saturation of the samples did not produce additional compaction.

Near-surface subsidence illustrates the significance of water in the natural compaction of sediments. Most alluvial sediments are compacted in the presence of excess water as the overburden load is increased. But on the fans susceptible to subsidence, only part of the normal compaction occurs as the overburden load is gradually increased, because the deposits are moisture deficient. The application of additional water by irrigation allows the compaction to increase suddenly to the normal amount for a given overburden load, causing surface subsidence.

The strength of clay at a given moisture content depends partly on the types of clay minerals present. All clays tend to absorb water, and the surface area per unit volume of clay is the determining control for adsorption. The water farther away from the clay particles is not held so tightly as the water next to the clay particles. The predominant clay mineral in the alluvial-fan deposits in western Fresno County is montmorillonite. Because montmorillonite is very finely divided, it has much more surface area per unit volume than clay minerals such as kaolinite or illite. Thus, water is held more tightly by montmorillonite, giving it more strength at a given moisture content than other clay minerals. Furthermore, in the presence of unlimited water, montmorillonite can absorb more water than the other clays; and because of this, it has distinctive swelling properties. The affinity for water also makes montmorillonite one of the weakest clay minerals in the presence of unlimited water.

Examples of these concepts have been described by several authors. Trask and Close (1958), in their studies of synthetic mixtures, note that montmorillonite is much stronger than any other clay mineral at a given moisture content. Montmorillonite can have a higher water content than other clay minerals and still be stronger. Trask and Close (p. 834) state that "* * * a sample of Wyoming bentonite with 500 percent water has essentially the same shear strength as a kaolin clay with 70 percent water." Langston and others (1958, p. 234) in their studies of the strength of natural sediments also note that montmorillonite-rich samples can contain more water than other samples and have the same shear strength. Evidently small amounts of montmorillonite can noticeably increase the strength of a deposit. Langston and others (p. 217) found that "* * * the samples richer in montmorillonite—those containing 10 to 20 percent montmorillonite—tended to be relatively strong for a given water content." The moisture content of their samples ranged from 18 to 93 percent.

The concepts discussed above help explain why the clay in the alluvial-fan deposits of western Fresno County is strong enough to help support large overburden loads at a moisture content near the wilting coefficient, and why this clay becomes weaker in the presence of additional water. The change in the strength of the deposits causes near-surface subsidence.

The amount of clay in a deposit directly influences the strength. In general, the strength decreases with decreasing clay content at a given moisture content. Trask has noted this, and most of the features from a graph by him (1959, fig. 3) are reproduced in figure 31 to illustrate the relation of clay content to shear strength and water content. The montmorillonite (bentonite) was mixed with various amounts of silt that had a median grain size of 16 microns. The shear strength of all the mixtures decreased with increasing water

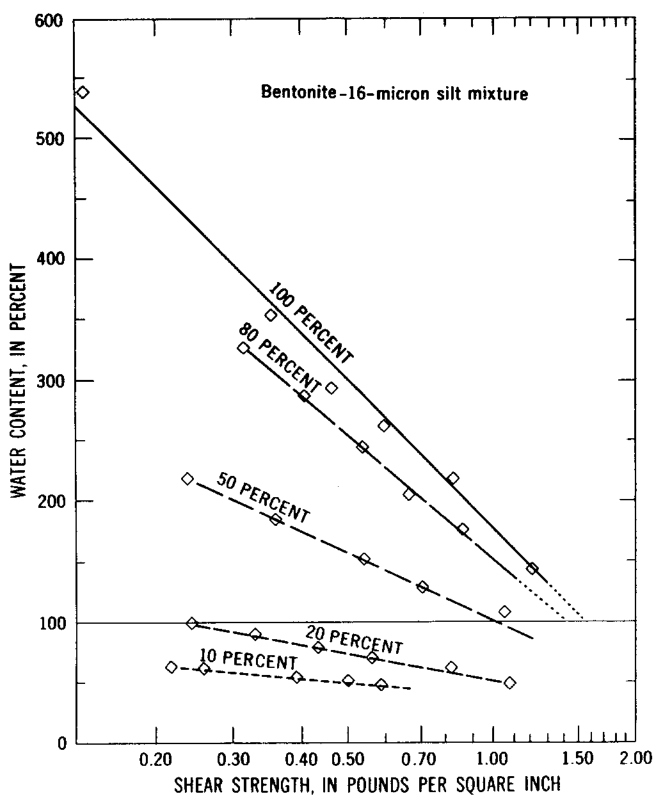



FIGURE 31.—Relation of bentonite concentration to shear strength and water content.

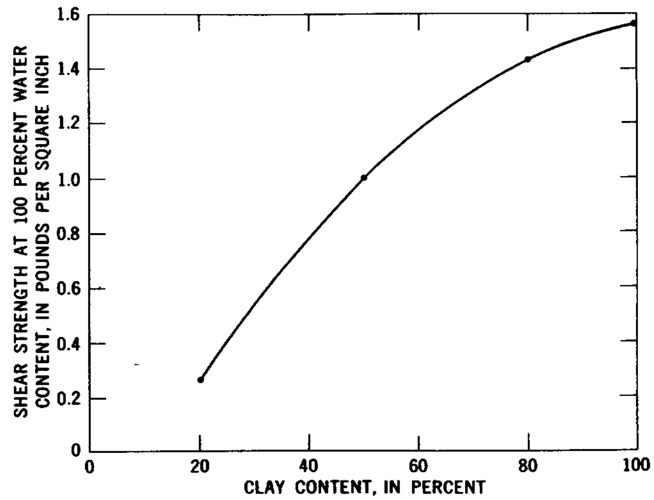



FIGURE 32.—Change in shear strength with variation in clay content (montmorillonite-silt mixture).

content, but the shear strength also decreased with decreasing clay content for any given water content. For example, consider the changes in the shear strength at a water content of 100 percent. The dots represent short extensions of Trask's 80- and 100-percent clay-content lines so that an estimated shear strength can be read on the 100-percent water-content line. The shear strength of the 50-percent-clay mixture is 30 percent less than that of the 80-percent-clay mixture, and the strength of the 20-percent-clay mixture is about 77 percent less than that of the 50-percent-clay mixture.

A graphical presentation of these changes in shear strength with variation in the clay content is shown in figure 32. The data were taken from figure 31. The curve shows that for a given change in the clay content a greater change in shear strength will occur at a low clay content than at a high clay content.

The moisture contents of the alluvial-fan deposits are much lower than those of the synthetic samples with which Trask and Close were working, but the same basic concepts probably apply to deposits in western Fresno County. For example, samples 92 and 95 from the Arroyo Hondo fan had bubble cavities of about equal size, and water was allowed to percolate through both samples at a simulated 50-foot overburden load. The load and the moisture conditions were the same, but the cavities collapsed in sample 92 and did not collapse in sample 95. The respective clay contents were 11 and 34 percent. The sample with 34 percent clay was stronger because it had more binder to give it strength—namely, the wet clay. The same concepts should be true for any other moisture condition—for example, the wilting coefficient.

Variations in the strength of deposits sampled under hygroscopic moisture conditions were also measured.

The results of consolidation tests illustrating the effect of clay content on compaction due to wetting are shown in figures 33 and 34. The consolidation tests were made on samples collected from surface deposits; and, therefore, all overburden loads were simulated. The main advantage of the method is that some of the variables can be controlled—for instance, the overburden load can be made the same for all the samples. If core-hole samples are used, they should not be tested under loads less than their natural state. Another advantage is that the moisture condition is about the same for all the surface samples because they were collected during the summer and sealed in wax at hygroscopic moisture conditions. The clay in the samples consists mainly of montmorillonite, and although textural and lithologic features of the samples vary, the textural features are largely a factor of the clay content. The two points marked with an *S* in figure 33 represent samples that consist of more than two-thirds shale fragments. Both points are anomalous: one shows too much compaction, and the other shows too little compaction. Most samples from mudflow and intermediate deposits have some shale fragments, but the water-laid samples tested contain few if any shale chips.

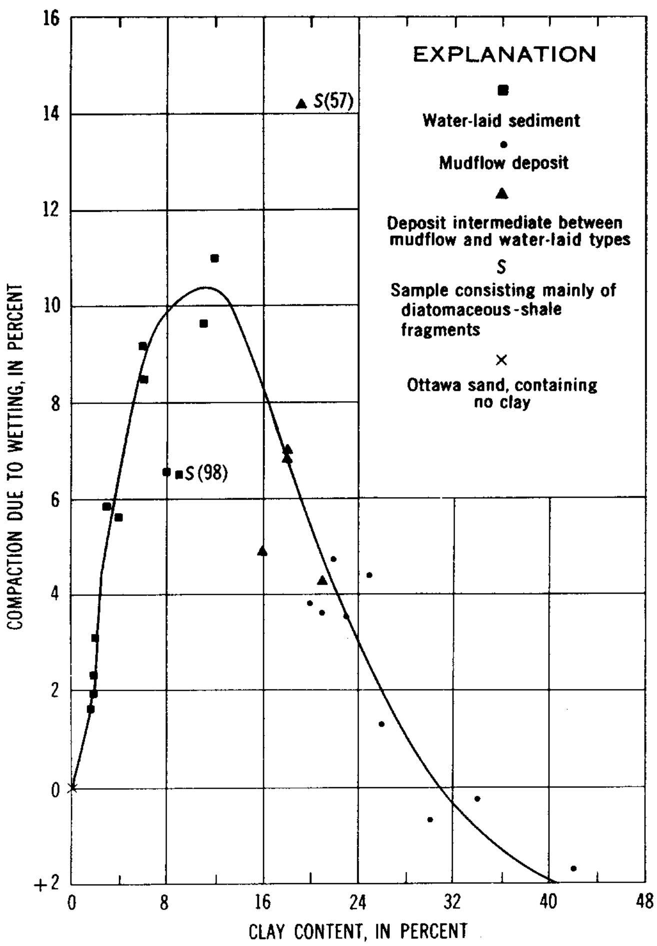



FIGURE 33.—The effect of clay content on compaction due to wetting under a simulated 50-foot overburden load.

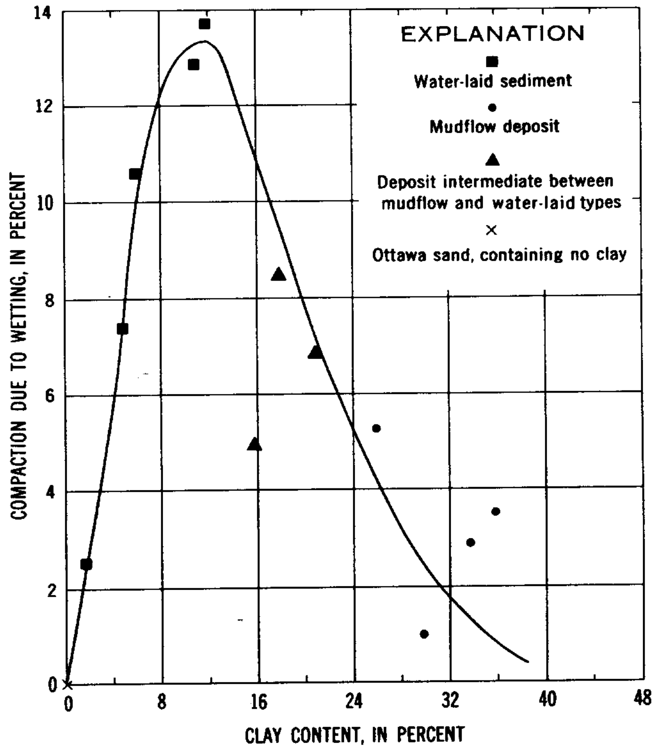



FIGURE 34.—The effect of clay content on compaction due to wetting under a simulated 100-foot overburden load.

The amount of clay is the chief variable. The curve in figure 33 shows compaction due to a change from a hygroscopic moisture content to a moisture content of more than field capacity. All the alluvial-fan deposits contain some clay. For purposes of comparison, ottawa sand, which contains no clay, was tested in the same way as the other samples but did not show any compaction due to wetting. The other extreme is shown by samples of mudflows containing more than about 30 percent clay. These clay-rich samples not only had enough strength to resist compaction when wetted but showed a net swell under the simulated overburden load. The maximum compaction due to wetting for the samples tested was at a clay content of about 12 percent. If less than this amount was present, the dry overburden load already had 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 of the sample to compaction when wetted also increases. In addition, the montmorillonite clay minerals swell. Both factors reduce the compaction progressively; and, for the samples tested, the net compaction decreased to zero at about 30 percent clay.

The effect of the clay content on compaction due to wetting under a simulated 100-foot overburden load is shown in figure 34. The general shape of the curve is the same as for the 50-foot overburden condition. None of the samples swelled enough to show a net expansion, and the maximum amount of compaction was about 14 percent instead of about 11 percent for the samples with a simulated overburden load of 50 feet of sediments. The part of the curve for samples with a clay content less than 5 percent is the same as that for the samples tested under a simulated 50-foot overburden load. All samples with clay contents of more than about 5 percent compacted more when tested under the simulated 50-foot overburden load. These results indicate that for air-dry samples with clay contents less than about 5 percent the effect of overburden load is negligible compared to the effect of clay content.

The curves shown in figures 33 and 34 are two of a family of curves relating compaction due to wetting, clay content, and overburden load for air-dry samples. The compaction due to wetting can be expected to decrease with decreasing overburden load for deposits that contain more than 5 percent clay. A net swell can be expected at overburden loads of about 5–15 feet, however, for deposits with a clay content of more than about 15–20 percent clay. This inference is based on measurements of bench marks in test plots that recorded a net swell during the first 1–3 days of flooding.

The amount of clay and the moisture conditions seem to be the main factors controlling the amount of subsidence, because the clay type is predominantly montmorillonite. The compaction would have been less if the clay binder had consisted principally of clay minerals other than montmorillonite.

Both the curve in figure 33 and the curve in figure 34 represent the air-dry end member of a family of curves relating compaction due to wetting, clay content, and moisture conditions, under the assumption that overburden load is constant and initial moisture content is varied. The other end member would be at a moisture condition of field capacity where 100 percent natural compaction had occurred. The moisture content of the deposits of most subsiding fans is at about half of field capacity—about the wilting coefficient. These deposits will compact less when wetted, at a given clay content and overburden load, than will air-dry samples. Also the peak of such a curve may be at a greater clay content than the peak of the curve for samples tested under air-dry conditions. The transition point of the curve, from net compaction to net swell, would be the same for any family of curves at a given overburden load.

Particle-size analyses of field samples show that the clay content generally increases downslope, and that on the lower parts of subsiding fans clay content is generally greater than that producing optimum compaction. This explains why subsidence is less on the lower part of a fan than on the upper part.

Deposits of the Martinez Creek fan have a moisture content approximating wilting coefficient conditions and a clay content of less than 10 percent (10 samples from a 70-foot core hole averaged 6 percent clay). Irrigation of several square miles of the Martinez Creek fan for several years has produced no surface evidence of subsidence. The deposits probably compacted naturally because the low clay content did not impart sufficient strength to withstand the natural overburden load.

These conditions of low clay content and native moisture at the wilting coefficient represent a borderline case. Water percolating through the deposits may cause additional compaction and subsidence that is not readily apparent in fields irrigated by sprinklers. It is quite possible that manmade compaction, if any, would be so small that it would be detected only by operating test plots.

The moisture condition of the deposits of the Arroyo Ciervo fan is also about at the wilting coefficient, but the clay content is 16–22 percent, in contrast to the average clay content of only 6 percent for samples from the Martinez Creek fan. Evidently this difference in the clay content of the two fans explains why a greater percentage of natural compaction has occurred in the deposits of the Martinez Creek fan than in those of the Arroyo Ciervo fan.

The evidence presented on preceding pages shows that the amount, type, and moisture conditions of the clay in alluvial-fan deposits affect the amount of compaction due to wetting and, therefore, the amount of near-surface subsidence. A logical question is, "Why is this type of subsidence not more common in the arid and semiarid areas of the western United States?" The annual rainfall of many of these areas is less than, or similar to, the range of 7–18 inches in most of western Fresno County; consequently, the moisture condition of many alluvial fans is about at the wilting coefficient. Possible explanations for the apparent lack of near-surface subsidence in most other irrigated semiarid areas might be that the alluvial-fan deposits do not contain much clay or that the clay may not be chiefly montmorillonite. Many mountains in the Basin and Range province are composed chiefly of metamorphic, intrusive, and volcanic rocks, which do not furnish large amounts of clay under a semiarid environment. Limestone also is common, but it would tend to furnish a cement for the alluvial-fan deposits. When fans in other semiarid areas are irrigated, some may subside, but the amount of subsidence may be small.

## DENSITY OF SUBSIDING AND NONSUBSIDING FANS

The dry bulk density of a deposit is dependent on the grain densities and texture of the material. In general, the density of the alluvial-fan deposits increases with an increase of quartz and feldspar and decreases with an increase of diatomaceous shale fragments. An increase in the volume of voids will decrease the bulk density of any deposit.

Three types of standard density tests were made on deposits of subsiding and nonsubsiding fans. Ninety chunks from the deposits of the 1956–57 and 1957-58 seasons were tested by the immersion method, and the deposits within the upper 2 feet of the fans were tested by the sand-pit method (U.S. Bureau of Reclamation, 1960, p. 582–591). The third type of test consisted of weighing cores of a known volume. Moisture contents were determined for all samples in order to compute dry density.

Many core-hole samples were obtained by the Inter-Agency Committee from unirrigated deposits upslope from areas of known subsidence. The average densities of core-hole samples from the irrigated and unirrigated parts of three subsiding fans are shown in table 14.

Individual densities of the deposits of a subsiding fan vary considerably. Sand-pit densities of surface samples from the unirrigated part of the Arroyo Ciervo fan are shown in figure 35. The samples were taken both along a radial line and on a line about parallel to a contour line. Trends in the density of the surface deposits either downslope or across the fan are not apparent. The dashed outline is where the deposits of the 1956–57 and 1957–58 seasons accumulated. Sand-pit density tests within this area were made on materials deposited before 1956. The average dry bulk density for samples from the unirrigated part of the Arroyo Ciervo fan was 76 pounds per cubic foot for sand-pit samples, 76 lbs per cubic foot for 60 samples from the 30-foot core holes shown in figure 35, and 78 lbs per cubic foot for 34 samples deposited during the 1956–57 and 1957–58 seasons.

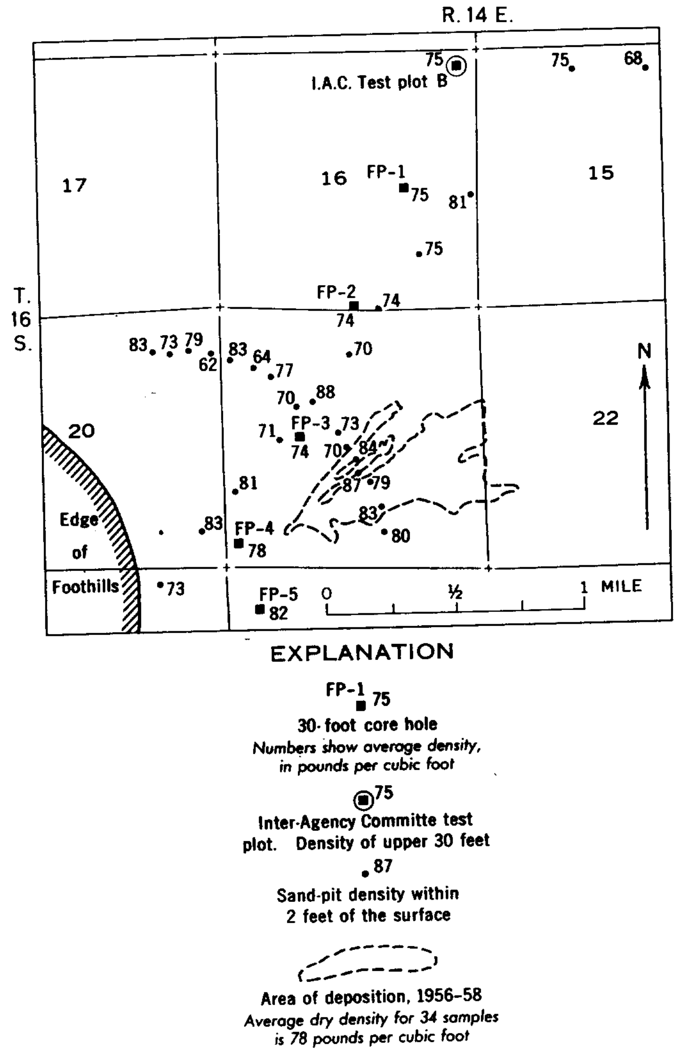



FIGURE 35.—Dry densities of the Arroyo Ciervo fan deposits.

Densities of the upper 300 feet of deposits in the Arroyo Ciervo (test plot B) and Arroyo Hondo (test plot C) fans are plotted in figure 28. One can see that deposits of the Arroyo Hondo fan have higher densities. In general, density increases with depth. Assuming homogeneous conditions, the increase in density with depth is due to the increase in overburden load, which provides progressively more load to compact the deposits, and to an overall increase in the relative moisture, which permits the overburden load to compact the deposits more than if they were drier.

Core-hole samples also were obtained from the deposits of nonsubsiding fans (table 14) such as the large Los Gatos Creek fan, which is adjacent to the southeast edge of the area studied. The average core-hole densities of the nonsubsiding fans and the unirrigated

TABLE 14.—*Dry bulk density of core-hole samples from subsiding and nonsubsiding fans*

| | Dry bulk density (lbs per cu ft) | Number of samples | Depth (ft) |
|---|---|---|---|
| Nonsubsiding fans: | | | |
| Little Panoche Creek | 97 | 21 | 0– 92 |
| Panoche Creek | 91 | 79 | 0–100 |
| Cantua Creek | 90 | 70 | 0–100 |
| Los Gatos Creek | 90 | 136 | 0–100 |
| Subsiding fans: | | | |
| *Before wetting* | | | |
| Moreno Gulch | 89 | 48 | 0– 90 |
| Arroyo Ciervo | 78 | 128 | 0–100 |
| Arroyo Hondo | 92 | 51 | 0–100 |
| *After wetting* | | | |
| Moreno Gulch | 103 | 29 | 0–100 |
| Arroyo Ciervo | 89 | 27 | 0–100 |
| Arroyo Hondo | 96 | 25 | 0–100 |

parts of the subsiding fans are about the same except for the Arroyo Ciervo fan. The average density of 16 sand-pit density tests on 5 nonsubsiding fans was 89 pounds per cubic foot.

Subsidence is caused by a decrease in volume corresponding to the increase in density when deposits are compacted. The density of the upper 100 feet of deposits of subsiding fans should increase 2–5 pounds per cubic foot after wetting. Table 14 shows that the density of the deposits apparently has increased 4–14 pounds per cubic foot. Part of the error may be attributed to the difficulties of obtaining undisturbed core samples from wet clayey deposits.

After compaction due to wetting has occurred, the deposits of some subsiding fans may be slightly denser than the deposits of nonsubsiding fans. The poorly sorted deposits of the subsiding fans have more fine particles in the larger intergranular voids and therefore may have higher densities after attaining a normal state of compaction than do the deposits of nonsubsiding fans.

The low density of the deposits in the Arroyo Ciervo fan and adjacent fans may be caused mainly by an abundance of low-density shale fragments rather than by textural features. The drainage basins of these fans are underlain extensively by diatomaceous Kreyenhagen shale, and chips of this shale are visibly abundant in the fan deposits. A block of diatomite from the Kreyenhagen shale tested by the writer had a dry density of only 55.8 pounds per cubic foot.

A plot of dry density to compaction due to wetting under a simulated 50-foot overburden load for 25 surface samples is shown in figure 36. The samples were

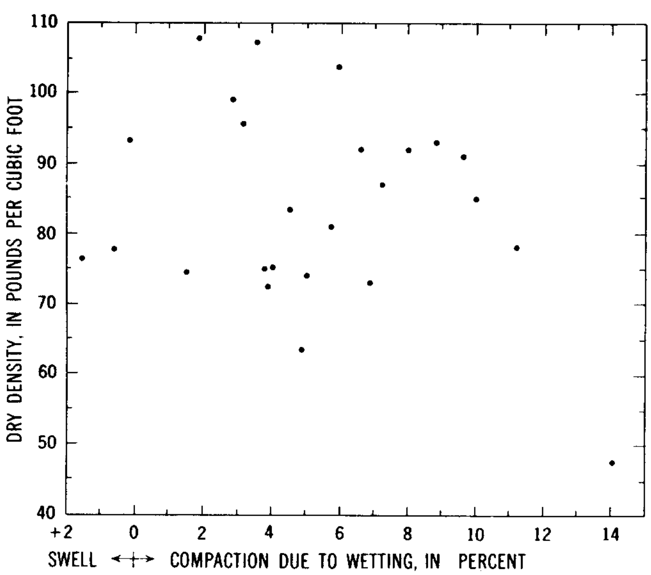



FIGURE 36.—Comparisons of native density to compaction due to wetting under a simulated 50-foot overburden load.

from materials deposited in the 1956–57 and 1957–58 seasons on six subsiding and nonsubsiding fans. All these air-dry samples either compacted or swelled when water was allowed to percolate through them. The points are widely scattered and show no alinement. Some low-density samples showed little or no compaction; other samples, with densities of more than 90 pounds per cubic foot showed 6–10 percent of compaction due to wetting. Most of the samples that had densities greater than 90 pounds per cubic foot had few shale chips, and most of the samples that had densities less than 80 pounds per cubic foot had abundant shale chips. This demonstrates that bulk densities are strongly influenced by the amount of contained shale fragments, decreasing with increase in percentage of shale fragments, and that high percentages of shale fragments will mask the densities of the compactible textural-void matrix.

Most of the nonsubsiding and subsiding fans seem to have about the same dry bulk density. However, low-density deposits may be an indirect sign that a fan may be susceptible to subsidence. Low-density deposits usually indicate the presence of low-density shale fragments and shale in the source area that is a source of clay to give moisture-deficient deposits strength to withstand at least part of the overburden load until the clay is wetted.

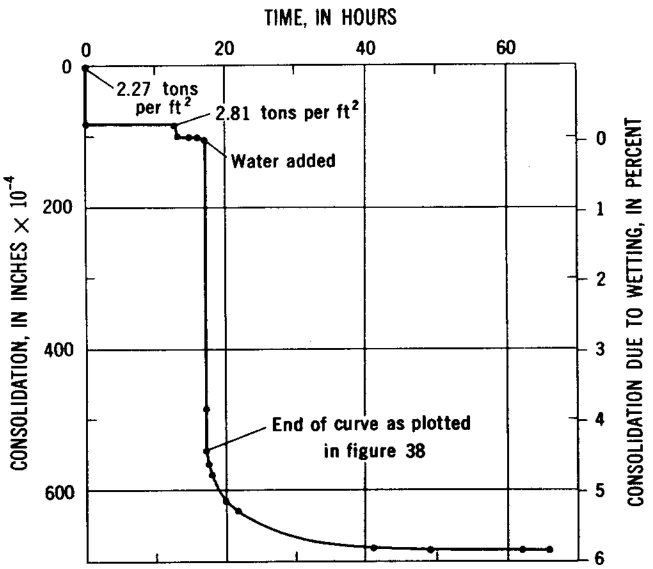
### CONSOLIDATION CHARACTERISTICS

Consolidation tests were made on 28 samples under simulated 50–, 100–, or both 50– and 100–foot overburden loads. The samples were from materials deposited during the 1956–57 and 1957–58 seasons on six subsiding and nonsubsiding fans and ranged from clay to coarse sand.

A few samples showing graded bedding also were tested. Samples with graded bedding had a higher clay content in their upper part than in their lower part, and the upper part of these samples compacted less on wetting than did the lower part. A few samples with graded bedding swelled in the upper part and compacted in the lower part as water percolated through them.

Most of the samples tested had similar consolidation curves. Sample 96, which contains 92 percent sand, 3 percent silt, and 5 percent clay, had an average percentage of consolidation and was selected to represent typical results.

The three increments of the consolidation curve for sample 96 shown in figure 37 represent the compaction caused by dry overburden load, wet overburden load, and water, respectively. This sequence simulates actual field conditions where a deposit under the native overburden load has an added increment of load ap-




SAMPLE 96

Consolidation, in percent

| | | |
|---|---|---|
| Load, dry | 0.84 | |
| Load, wet | .20 | 6.05 |
| Sample, wet | 5.85 | |
| Total | 6.89 | |

FIGURE 37.—Consolidation curve for a sand sample under a simulated 50-foot overburden load.

plied to it by the weight of percolating irrigation water. Then, as the water percolates through the deposit, the overburden load remains the same. The loads used in the laboratory were derived from density tests made by the Inter-Agency Committee before and after the flooding of test plot B. The method of making the consolidation tests and the results of the tests are described in the section "Preparation of samples for consolidation tests," and by Bull (1964c).

The compaction due to wetting (5.85 percent) of sample 96 was caused by a change in moisture from hygroscopic to more than field capacity. The amount of subsidence is the sum of the compaction caused by the weight of the additional water in the overlying deposits and the compaction that occurs as water percolates through the deposits.

Most of the compaction due to wetting occurs as the water front advances through a deposit; after that, the rate of compaction gradually decreases until equilibrium conditions are approached. This is shown by the curve in figure 37, which is very steep immediately after adding water and then gradually flattens as the sample adjusts to the new moisture condition.

Part of the curve for the same sample (No. 96) is shown in figure 38, with the time in minutes instead of hours. The consolidation was measured to the nearest 0.01 percent at time intervals ranging from 10 seconds to 1 minute. The initial collapse after the water was added continued for about 30 seconds and was followed by 8 minutes of steady but rapid compaction. Then the rate of consolidation decreased markedly but continued at a decreasing rate. Water was first seen in the lower pore stone 15½ minutes after it was first added to the sample, but the curve indicates that the water had passed through the sample about 8½ minutes after percolation started. The 8½–15½-minute interval represents the time necessary for water leaving the bottom of the sample to wet the pore stone enough to be seen. More than two-thirds of the compaction due to wetting had occurred by the time the water front had passed through the sample.

Other samples showed the same change in the rate of compaction as sample 96 as the advancing water front reached the bottom of the sample. Sample 13, 1 inch thick, showed the change in the rate of compaction even though 10 hours were required for the water to percolate through it. For the 16 samples in which the appearance of water in the lower pore stone was noted, the average compaction due to wetting was about 60 percent complete by the time the water had reached the pore stone.

After the water front passes through a sample, the consolidation curve shows a gradual decrease in the rate of compaction. Figure 39 shows the average com-compaction due to wetting for eight sandy samples through which the water percolated in an average of 4 minutes. The semilogarithmic plot of the compaction after the water front had passed through the samples shows a normal straight-line relationship.

The various types of voids described in the section "Textural and structural features of alluvial-fan de-

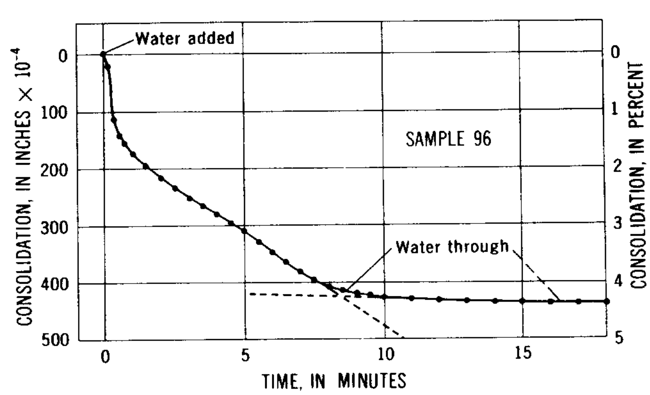



FIGURE 38.—Consolidation curve for a sand sample after water has been added.

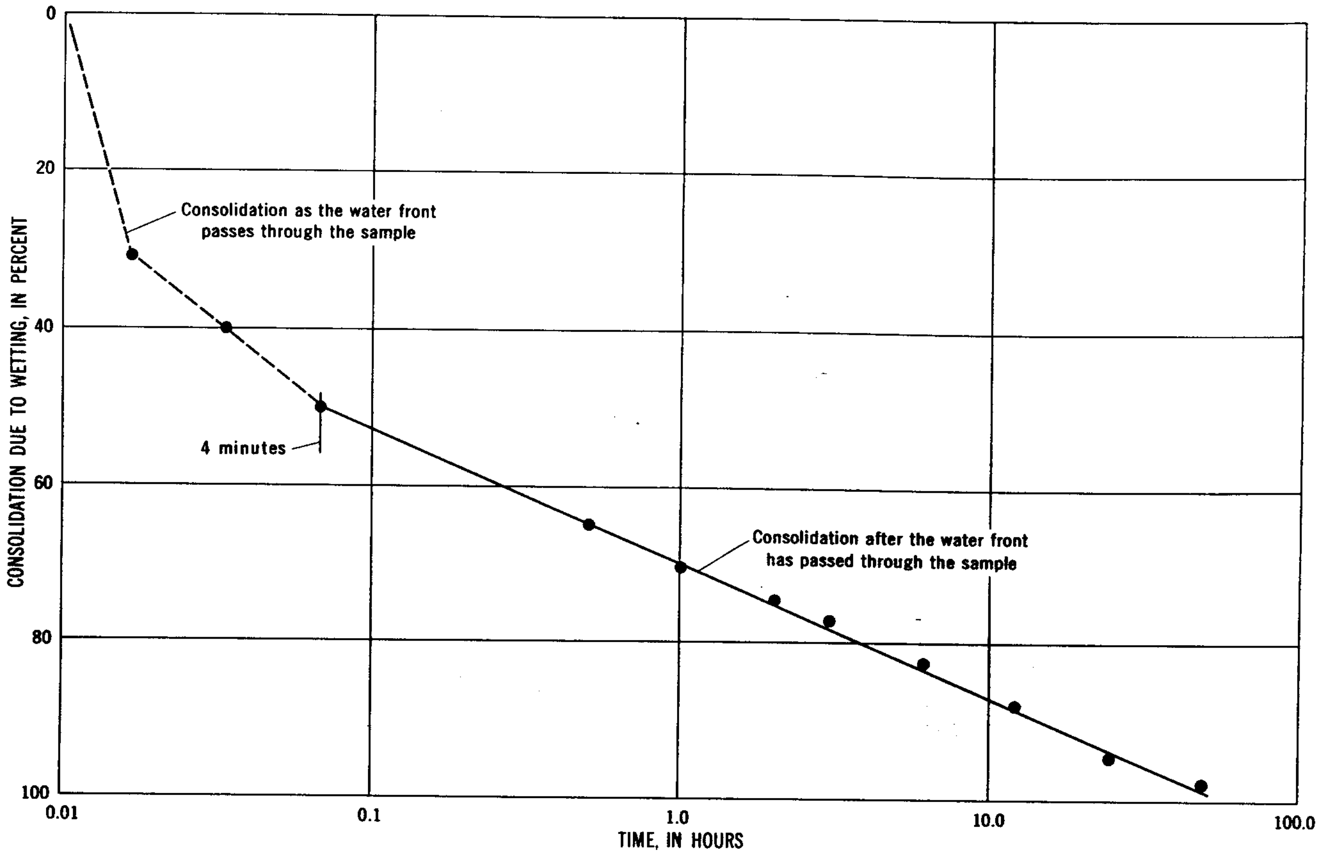



FIGURE 39.—Average consolidation due to wetting for eight samples through which the water percolated in an average of 4 minutes.

posits" (p. A30–A33) collapse under different overburden loads. The following observations on compaction of textural features are based on the responses of samples subjected to various simulated overburden loads.

The load needed to collapse voids at a given moisture condition is dependent mainly on the size and shape of the voids and on the clay content of the surrounding deposit. A smaller load is needed to collapse large voids than small voids. The shape of voids, such as interlaminar openings and bubble cavities, partly determines the load needed to collapse them. Flat interlaminar voids are the weakest, and spherical bubble cavities are the strongest; intermediate shapes have strengths between these two. The strength of a void, such as a bubble cavity, decreases with a decrease in clay content of the deposit.

Buried, but unfilled, polygonal cracks are found in clay-rich deposits that swell upon application of water, and the swelling reduces the amount of void space that can be collapsed to cause subsidence. Buried, but unfilled, cracks would not be a significant compactible type of void if swelling completely closed them when the deposits were wetted without load. The following experiment was made to determine the changes in crack width due to swelling.

Part of a 3-inch-thick mudflow on the Arroyo Hondo fan was covered with 10 layers of burlap, and water was allowed to percolate through the burlap mat, mudflow, and the underlying deposits. A sample from the mudflow contained 29 percent clay. Ten cracks ranging in width from 0.2 to 1.0 inch were measured before and after the test. The water penetrated about a foot during a 3-hour period. Three measuring points sloughed during the test, but at the end of the 3-hour wetting period the width of the remaining cracks averaged 70 percent of the original width. The test results indicate that even under a condition of no load the deposits did not swell enough to close the cracks. Therefore, buried, but open, polygonal cracks constitute a type of void into which material can move when wetted under sufficient load.

Two samples with open cracks were tested in the consolidometer. One, a sample with 29 percent clay (No. 81, table 17) from the mudflow discussed above, was tested under a load equivalent to 100 feet of overburden, and the cracks closed as water percolated through the sample. The other, sample 71, with a clay content of 30 percent, was tested under a simulated 50-foot overburden load, and the cracks also closed as water percolated through the sample.

### EFFECT OF LITHOLOGY AND SALTS

The lithology of the grains of sand and silt size and the amount of soluble salts in the deposits are variables that probably have a minor influence on magnitude of compaction, compared to clay and moisture content. Most of the sand-size material consists of quartz, feldspar, hard rock fragments, and soft shale fragments.

Abundant shale fragments in a deposit may decrease or increase the amount of compaction. Only two samples that consisted mainly of shale fragments were tested in the consolidometer. The plots for these samples are marked with an *S* in figure 33 and show that one sample (No. 98) compacted only about two-thirds of the average and that the other sample (No. 57) compacted about 2½ times the average. The rate of compaction for sample 57 did not decrease markedly after the water front had passed through the sample but instead continued on a rapid but ever-decreasing trend. This type of consolidation suggests that plastic deformation of the shale chips occurred as they became wet. Sample 57 (bulk density 48 lbs per cubic ft) had more pore space into which the shale chips could be deformed than did sample 98 (bulk density 73 lbs per cubic ft). Most of the mudflow samples contained some shale fragments, but there was no evidence of plastic deformation of these scattered fragments. Shale fragments were scarce in most water-laid sediments, but some, such as sample 98 consisted almost entirely of shale chips. Several samples that had no visible shale fragments compacted 5–10 percent when wetted under load.

Soluble salts such as gypsum are common in some alluvial-fan deposits, as is shown in figure 28 and table 15. In the area studied, the uppermost 100 feet of deposits of subsiding fans contain several times as much gypsum as do the deposits of nonsubsiding fans. Thus, in this area, gypsum content can be used as a general indicator of deposits that may subside on wetting. However, gypsum content cannot be used exclusively as a positive indicator that deposits will compact to cause subsidence, and solution of gypsum does not seem to be a major cause of the subsidence. Samples from the basal area of a subsiding fan can average 2 percent gypsum yet not subside when wetted, and this indicates that high gypsum content is associated with certain types of sediments but not necessarily with subsidence characteristics (Inter-Agency Committee, 1958, p. 54). The deposits of the basal areas of some subsiding fans may not compact when wetted because they have a high clay content. Two test plots installed by the California Division of Highways on the piedmont plain south of the Capita Canyon fan illustrate the effect of clay content on subsidence. One test plot was installed in the middle area of the fan and subsided 1 foot. The other test plot, installed 1⅓ miles downslope in the basal area of the fan, had a higher clay content than the upslope plot and showed a net swell when water percolated through the deposits.

TABLE 15.—*Gypsum content of subsiding and nonsubsiding fans*

[Analyses made by the Univ. California at Davis and the California Div. Highways]

| Alluvial fan | Average gypsum content (percent of dry weight) | Number of samples (depth interval 0-100 feet) |
|---|---|---|
| *Subsiding fans* | | |
| Moreno Gulch | 1.5 | 68 |
| First fan south of Capita Canyon fan | 1.1 | 9 |
| Tumey Gulch | 1.9 | 45 |
| Arroyo Ciervo | 3.2 | 58 |
| Arroyo Hondo | 2.2 | 95 |
| Average gypsum content | 2.0 | |
| Total samples | | 275 |
| *Nonsubsiding fans* | | |
| Little Panoche Creek | .7 | 6 |
| Panoche Creek | .6 | 54 |
| Cantua Creek | .03 | 19 |
| Los Gatos Creek (Adjacent to south side of area studied) | .01 | 15 |
| Average gypsum content | 0.4 | |
| Total samples | | 94 |

The gypsum content of subsiding fans in the area of this report is high because the rocks in their drainage basins provide more gypsum than the rocks in drainage basins of nonsubsiding fans. Slopes underlain by shale commonly are littered with plates and fragments of gypsum, and detrital gypsum is common in the stream channels of shale-rich basins. The basins of nonsubsiding fans have about half as many clay-rich rocks as the basins of subsiding fans (table 4), and this indicates fewer gypsiferous rocks in their source areas. In addition, some of the gypsum in the deposits of nonsubsiding fans may have been removed by water percolating from streams.

A test was made to see if an appreciable quantity of soluble salts could be flushed from a representative sample. Distilled water was allowed to percolate through sample 96 during two consolidation tests to determine which salts would be dissolved. The equipment (including pore stones) was washed with distilled water after each test. Water percolating through the sample for 49 hours during the first test removed 0.72 gram of salts, and water percolating through the sample for 90 hours during the second test removed 1.41 grams of salts. The 1.41 grams of salts represents 1.2 percent of the original sample weight. A chemical analysis[4] of the effluent from the first test shows that about 80 percent of the salts dissolved was calcium and magnesium sulfate.

| | *ppm* | *epm* |
|---|---|---|
| Calcium (Ca) | 305 | 15.22 |
| Magnesium (Mg) | 39 | 3.21 |
| Sodium (Na) | 94 | 4.09 |
| Potassium (K) | 7.6 | .19 |
| Carbonate ($CO_3$) | 0.0 | --- |
| Bicarbonate ($HCO_3$) | 23 | .38 |
| Sulfate ($SO_4$) | 983 | 20.47 |
| Chloride (Cl) | 1.6 | .05 |
| Calculated from the determined constituents | 1,440 | |

Removal of salts by leaching represents not only the removal of mass but also the weakening or removal of cement. Irrigation water probably would not remove as much soluble salt from the deposits as did the distilled water, because percolating irrigation water already is partly charged with salts. Some solution probably occurs, but the amount of salts removed is so small that the percentage of gypsum in core samples from deposits beneath adjacent irrigated and unirrigated fields is about the same.

Most of the clays probably have adsorbed calcium ions that affect the amount of adsorbed water and strength of the clay. The loose, friable nature of many deposits susceptible to subsidence may be due in part to the flocculative effect of the gypsum (Klein, 1964). Results of analyses shown in figure 28 indicate that the gypsum and calcium carbonate content does not change appreciably in the upper 300 feet of the deposits.

Sodium is the predominant cation in most of the well water that is used for irrigation, and many well waters contain as much as several hundred parts per million sodium. The proposed canals will carry water that probably will have more sodium than calcium. If sodium ions replace the adsorbed calcium ions, the strength of the clay in the deposits of subsiding fans may be changed.

Distilled water was used for all the consolidation tests, but salt solutions were added to two samples after the compaction rate in the wetted samples had decreased greatly. A sodium chloride solution with 700 ppm sodium ions was allowed to percolate through sample 45, but the sample showed no change during the 4 days following the addition of the solution. A calcium chloride brine that was added to sample 68 also made no change in the consolidation characteristics. The excess solution was removed and a saturated sodium chloride brine was allowed to percolate through the sample. The addition of the sodium ions doubled the rate of consolidation. These results suggest that if the deposits susceptible to near-surface subsidence are preconsolidated by wetting before a canal is built, the chemical character of the water used for preconsolidation may influence the amount and rate of compaction.

[4] Analysis made by the U.S. Geological Survey, Quality of Water Branch.

### SUMMARY OF NEAR-SURFACE SUBSIDENCE

Near-surface subsidence results chiefly from the compaction of deposits by an overburden load as the clay bond supporting the deposits is weakened by water percolating through the deposits for the first time. Subsidence has damaged ditches, canals, roads, pipelines, electric-transmission towers, and buildings, and has made the irrigation of crops difficult in more than 80 square miles in western Fresno County.

Settlement of the land surface and formation of subsidence cracks are two diagnostic features of near-surface subsidence. Three to 5 feet of settlement is common, and more than 10 feet of subsidence has occurred within small areas. The rate of subsidence is as much as one-quarter of a foot per day and is controlled partly by the rate at which the water front advances through the deposits. Subsidence cracks are vertical fissures that commonly have vertical and horizontal displacements of several inches. The older cracks close as new cracks open farther away from the irrigated area.

The amount of compaction that causes the subsidence increases in proportion to the overburden load, but most known compaction due to wetting has occurred in the upper 200 feet of deposits. Data obtained from the subsurface bench marks of Inter-Agency Test Plot B show that the compaction varies directly with the amount of overburden under uniform gross lithologic and moisture conditions.

The moisture conditions of most subsiding and nonsubsiding fans are markedly different. Groups of samples from unirrigated parts of subsiding fans have an average relative moisture of 45 percent, which is indicative of wilting coefficient moisture conditions. Groups of samples from irrigated parts of subsiding fans and most groups of samples from nonsubsiding fans have average relative moistures of 70 to more than 100 percent, which is indicative of field capacity moisture conditions.

The type, amount, and moisture condition of clay distinctly influence the amount of subsidence. The predominant clay mineral on all the subsiding fans is montmorillonite, which is stronger at a given moisture content than other clay minerals. Subsiding fans usually have higher clay contents than nonsubsiding fans of the same size. Deposits with low clay contents do not have enough dry strength to preserve voids supported by a clay binder as overburden load increases naturally; and deposits with high clay contents do not compact much because the clay, even when wetted, partly supports the voids and because the clay swells. Maximum compaction of deposits whose moisture content is increased from hygroscopic to field-capacity conditions occurs at a clay content of about 12 percent. The moisture condition of the deposits of subsiding fans approximates the wilting coefficient, and compaction occurs as the moisture content of these clayey deposits is increased to a moisture condition that approximates field capacity.

The average dry bulk densities of the nonsubsiding fans and the unirrigated parts of the subsiding fans are about the same (about 90 lbs per cubic foot) except for the unirrigated part of the subsiding Arroyo Ciervo fan (about 78 lbs per cubic foot). The bulk densities of the Arroyo Ciervo fan and some nearby fans are strongly influenced by low-density shale fragments. Bulk density decreases with an increase in percentage of shale fragments, and high percentages of shale fragments will mask the density of compactible matrix which does not have shale fragments.

The uppermost 100 feet of subsiding fans contains several times as much gypsum as the same thickness in deposits of nonsubsiding fans. The shale-rich rocks in the basins of subsiding fans contain more gypsum than the sandstone-rich rocks in the basins of nonsubsiding fans. The average gypsum content of 275 samples from subsiding fans is 2.0 percent, and the average gypsum content of 94 samples from nonsubsiding fans is 0.4 percent. Although, in the area studied, gypsum content is a rough indicator of deposits that will subside on wetting, some gypsum-rich deposits did not subside when wetted; gypsum content, therefore, is not a positive criterion. The removal of salts by leaching represents removal of mass and cement, but the similar gypsum contents of sets of samples from irrigated and unirrigated fields indicates that well water has caused little or no leaching during the decade or more of irrigation.

The chemical character of water used for irrigation or for preconsolidation of canal alinements may affect the amount and rate of compaction. Calcium is the predominant adsorbed ion of the montmorillonite of subsiding fans. The application of a sodium chloride brine during a consolidation test increased the amount and rate of compaction. However, a sodium chloride solution (70 ppm sodium ion) that was as concentrated as some well waters did not affect the compaction in the 4 days allowed for part of a consolidation test.

## METHODS OF MAKING GRAIN-SIZE ANALYSES AND DENSITY TESTS

Grain-size analyses were made on 102 surface samples deposited on the alluvial fans of western Fresno County during the 1956–57 and 1957–58 seasons. The samples had two characteristics that made it difficult to obtain the actual grain-size distribution of the sediments. These were (1) the presence of soluble salts such as gypsum, which tended to cause flocculation of the clay-size particles during the hydrometer test, and (2) fragments of sedimentary rocks, particularly chips of diatomaceous shale, which tended to be disaggregated if included in the mixing phase of the hydrometer test.

The following procedure seemed to give the best results from these particular samples:

1. The amount of sample varied with its clay and silt content, because most hydrometers do not measure amounts of suspended sediment in excess of about 60 grams per liter. The greater the clay and silt content, the smaller the sample. In general, samples ranged in weight from 50 to 500 grams.
2. The air-dry sample was washed on a No. 200 sieve, and the silt and clay-sized fraction that washed through the sieve was collected in two 1-liter evaporating dishes. If the sample obviously contained clay, water was poured slowly over it to slake it gradually in the sieve. This method was more efficient than soaking the sample before sieving because the sieve was less apt to become blocked and the sample required less agitation. Also, the shale fragments would have been softer if the sample had been soaked beforehand, but this would have made them more susceptible to attrition.
3. After a few hours most of the water was decanted from the evaporating dishes, and the remaining slurry was put in a single smaller evaporating dish. The soluble salts aided this step because they flocculated the clay which then settled to the bottom of the dishes. Most of the soluble salts were removed by decanting, and many of the flocculation troubles that might have occurred later during the hydrometer test were usually prevented.
4. Both the sand-size fraction and the finer fraction were oven dried at 110° C for at least 12 hours.
5. The sand-size fraction was run through a nest of sieves using a Rotap for 7 minutes.
6. The material caught on each sieve was weighed to the nearest 0.1 gram, and the total was weighed for a check.
7. The small amount of material that passed the No. 200 sieve was added to the finer fraction, which was then weighed.

TABLE 16.—*Comparison of hydrometer methods*

| Sample | Percent clay (less than 4 microns) | | Trask sorting coefficient $\sqrt{Q_3/Q_1}$ | |
|---|---|---|---|---|
| | Sand-size fraction separated before hydrometer test | Sand-size fraction included in hydrometer test | Sand-size fraction separated before hydrometer test | Sand-size fraction included in hydrometer test |
| 45 | 42 | 52 | 14 | 7.5 |
| 46 | 16 | 26 | 2.6 | 13 |
| 47 | 30 | 48 | 13 | 13 |
| 50 | 25 | 35 | 11 | 15 |
| 53 | 18 | 30 | 4.1 | 12 |
| 56 | 12 | 29 | 3.6 | 14 |
| 64 | 76 | 78 | -------- | -------- |
| 65 | 56 | 56 | -------- | -------- |
| 66 | 31 | 41 | 9.3 | -------- |
| 67 | 25 | 41 | 8.0 | 10 |
| 69 | 23 | 42 | 6.4 | -------- |
| 74 | 17 | 40 | 3.3 | 14 |
| Average | 31 | 43 | 7.5 | 12 |

8. The finer fraction was soaked for at least 15 hours in a solution containing sodium tripolyphosphate, a dispersing agent, and then mixed in a standard mixing cup (with vanes) for 5 minutes.
9. The suspension was washed into a settling tube, distilled water was added, and then the two were mixed by inverting the tube 30 times in one minute.
10. Hydrometer and temperature readings were taken at the desired time intervals.

Some laboratories have made grain-size analyses by the same process except that the coarse fraction was included in the hydrometer test and then separated for sieving. The soaking of the shale fragments in a dispersing solution and the mechanical chewing of the mixer reduces part of these sand-size and coarser grains to clay-size particles. Twelve comparative tests were made by the author on a variety of samples. The percent clay and the sorting are listed in table 16 for the pair of tests made on each sample: in one test the coarse-grained fraction was separated before the hydrometer test; in the other test the coarse-grained fraction was mixed in the beater and included in the hydrometer test.

The comparison of the two hydrometer methods (table 16) shows that when sand-size shale fragments are included in the mixing process the clay content increases and the sorting decreases. The attrition of silt-size fragments probably is small compared to sand-size shale fragments. Sample 74 was the only one that consisted mainly of shale fragments, and many of these fragments were changed from sand- to clay-size particles. This change was accompanied by a marked increase in the Trask sorting coefficient. Other samples, such as 53 and 56, which consisted mainly of sand-size fragments of quartz and feldspar with a small amount of shale chips, showed a marked change in the percent clay and in grain-size distribution by the two methods. Although the harder grains were not broken, they probably acted like balls in a ball mill, because the shale chips were virtually obliterated. Sample 45 consisted mainly of silt and clay, and the reduction of part of the sand-size fraction to silt and clay improved the sorting. Although separating the sand-size fraction before making the hydrometer test is preferable to including it in the test, neither of these methods may be the best possible. The method might be further improved by using an air-tube method of dispersion and by using lower oven-drying temperatures (Bull, 1964d).

Tables 17 and 18 show the basic data on the grain-size distribution and density of alluvial-fan deposits and the basic data on the grain-size distribution of samples from 30-foot core holes in the Arroyo Ciervo fan, respectively.

## PREPARATION OF SAMPLES FOR CONSOLIDATION TESTS

To measure the amount of compaction when the samples were subjected to various overburden loads and wetting, a one-dimensional consolidometer with a floating ring was used. The 1.5-pound brass ring was 1 inch thick and had an inside diameter of 2½ inches. Porous discs called porous stones were placed above and below the sample. Water entered through the top stone, percolated through the loaded sample, and left through the bottom stone. The diameter of the porous stones was slightly smaller than the ring; so the stones moved into the ring as the sample was reduced in volume.

An air-dry sample was trimmed carefully to a 2½-inch cylindrical shape with hacksaw blades and sandpaper. The sample was then coated with melted paraffin. The temperature of the melted paraffin was kept low enough so the wax congealed on the outside of the cool sample instead of penetrating into the sample. The ring was heated to a temperature less than the melting point of the paraffin, and the sample was pushed slowly into the warm ring. A snug fit was made as the warm wax filled the space between the sample and the ring, and the excess wax was forced out of the ring. The preparation of the sample was completed by trimming and leveling the ends of the sample protruding from the ring.

The amount of wax used varied with the composition of the sample; some clay-rich samples required less than 2 percent (volume of sample and wax) wax, but a few friable sandy samples needed as much as 10 percent wax. The wax was usually a thin film around the sample; but in 2 of the 33 samples, small resistant pebbles that could not be trimmed were removed and replaced with wax. This method of preparing samples for consolidation tests permitted the testing of undisturbed sand samples that had as little as 2 percent of dry clay binder.

TABLE 17.—*Basic data on the grain-size distribution and density of alluvial-fan deposits*

[Classification field: M, mudflow deposits; S, water-laid sediments; I, deposits intermediate between mudflow and water-laid sediments. Grain size, in microns: C, coarsest percentile; $Q_{75}$, coarsest quartile; $Q_{50}$, median quartile; $Q_{25}$, finest quartile. Sorting: $S_o$, Trask sorting coefficient; $\sigma_\phi$, phi standard deviation; $QD_\phi$, phi quartile deviation]

| Sample | Alluvial fan | Location | Classification | | Distribution (percent) | | | | | Grain size in microns | | | | Sorting | | | Dry density (lbs per ft³ at 110° C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Field | Grain size | Gravel | Sand | Silt | Clay | Silt and clay | C | $Q_{75}$ | $Q_{50}$ | $Q_{25}$ | $S_o$ | $\sigma_\phi$ | $QD_\phi$ | |
| 1 | Unamed | SE¼NE¼ sec. 27, T. 13 S., R. 11 E. | S | Silty gravel | 70 | 15 | 7 | 8 | | 18,500 | 6,500 | 4,400 | 1,200 | 2.3 | 3.4 | 1.2 | |
| 2 | do | NW¼NE¼ sec. 27, T. 13 S., R. 11 E. | S | Sand | 4 | 82 | 7 | 7 | | 4,000 | 490 | 310 | 160 | 1.7 | 1.6 | .80 | 93.6 |
| 3 | do | do | S | do | | 83 | 11 | 6 | | 550 | 275 | 200 | 100 | 1.7 | 1.3 | .73 | 92.8 |
| 4 | Moreno Gulch | SW¼NW¼ sec. 31, T. 13 S., R. 12 E. | I | Gravel-sand-clay | 22 | 55 | 16 | 7 | | 6,000 | 1,900 | 1,100 | 88 | 4.6 | 4.0 | 2.2 | |
| 5 | Panoche Creek | SW¼SW¼ sec. 11, T. 15 S., R. 12 E. | S | Sand | 6 | 91 | 1 | 2 | | 5,000 | 600 | 410 | 340 | 1.3 | .82 | .42 | 99.2 |
| 6 | Tumey Gulch | SW¼NE¼ sec. 28, T. 15 S., R. 13 E. | M | Sand-silt-clay | 1 | 47 | 23 | 29 | | 2,100 | 220 | 52 | 2 | 10 | | 3.4 | 100.6 |
| 7 | do | NE¼SE¼ sec. 29, T. 15 S., R. 13 E. | M | Clay | | 1 | 26 | 73 | | 60 | 4 | 1.2 | | | | | 86.7 |
| 8 | Unnamed | NE¼SW¼ sec. 16, T. 16 S. R. 13 E. | M | Silty clay | | 2 | 24 | 74 | | 75 | 3.2 | | | | | | 87.2 |
| 9 | do | do | M | Clayey sand | | 44 | 18 | 38 | | 1,000 | 140 | 27 | 1.2 | 12 | | 3.6 | 87.1 |
| 10 | Arroyo Ciervo | SW¼NE¼ sec. 21, T. 16 S., R. 14 E. | M | Silty clay | | 20 | 31 | 49 | | 300 | 35 | 4.5 | .5 | 8.5 | | 3.1 | 74.4 |
| 11 | do | SE¼SW¼ sec. 21, T. 16 S., R. 14 E. | M | Sand-silt-clay | 3 | 34 | 24 | 39 | | 8,000 | 180 | 17 | .9 | 11 | | 3.5 | 65.7 |
| 12 | do | NE¼SW¼ sec. 21, T. 16 S., R. 14 E. | M | Clayey sand | 2 | 62 | 14 | 22 | | 4,000 | 240 | 170 | 8 | 5.5 | 4.0 | 2.4 | 74.8 |
| 13 | do | do | M | do | 10 | 54 | 13 | 23 | | 7,000 | 440 | 160 | 6.5 | 8.2 | 4.8 | 3.0 | 74.7 |
| 14 | do | do | M | Sand-silt-clay | | 31 | 24 | 45 | | 1,200 | 90 | 6.5 | .6 | 13 | | 3.7 | 67.4 |
| 15 | do | do | I | Clayey sand | 8 | 63 | 14 | 15 | | 7,000 | 460 | 132 | 29 | 4.0 | 3.7 | 2.0 | 79.4 |
| 16 | do | SE¼SW¼ sec. 21, T. 16 S., R. 14 E. | M | do | 15 | 54 | 12 | 19 | | 8,000 | 930 | 230 | 18 | 7.2 | 4.9 | 2.8 | 69.5 |
| 17 | do | do | M | do | 6 | 61 | 12 | 21 | | 5,000 | 430 | 200 | 10 | 6.6 | 4.3 | 2.7 | 72.4 |
| 18 | do | do | M | Sandy gravel | 42 | 38 | 8 | 12 | | 18,000 | 5,400 | 900 | 160 | 5.8 | 4.4 | 2.5 | 65.2 |
| 19 | do | do | M | Sand-silt-clay | 1 | 44 | 21 | 34 | | 2,000 | 180 | 39 | 1.5 | 11 | | 3.5 | 71.6 |
| 20 | do | SW¼SW¼ sec. 21, T. 16 S., R. 14 E. | M | Clayey sand | 11 | 52 | 13 | 24 | | 9,000 | 380 | 150 | 5 | 8.7 | 5.0 | 3.1 | 71.5 |
| 21 | do | do | I | Gravelly sand | 39 | 42 | 8 | 11 | | 16,000 | 3,300 | 1,200 | 170 | 4.4 | 3.5 | 2.1 | 66.5 |
| 22 | do | SE¼SE¼ sec. 20, T. 16 S., R. 14 E. | I | Clayey sand | 18 | 56 | 10 | 16 | | 8,500 | 1,220 | 260 | 50 | 4.9 | 4.6 | 2.3 | 72.5 |
| 23 | do | SW¼NE¼ sec. 29, T. 16 S., R. 14 E. | M | Gravel-sand-clay | 20 | 54 | 10 | 16 | | 7,500 | 1,550 | 350 | 56 | 5.3 | 4.6 | 2.4 | 74.5 |
| 24 | do | SE¼NE¼ sec. 21, T. 16 S., R. 14 E. | M | Clayey sand | 2 | 57 | 14 | 27 | | 3,200 | 280 | 125 | 2.8 | 10 | 4.3 | 3.3 | |
| 25 | do | NE¼SW¼ sec. 21, T. 16 S., R. 14 E. | S | Sand | | 85 | 11 | 4 | | 700 | 240 | 170 | 100 | 1.5 | 1.1 | .58 | 82.1 |
| 26 | do | NW¼SW¼ sec. 22, T. 16 S., R. 14 E. | M | Sand-silt-clay | | 43 | 23 | 34 | | 500 | 140 | 30 | 1.6 | 9.4 | | 3.2 | 82.8 |
| 27 | do | NE¼SE¼ sec. 21, T. 16 S., R. 14 E. | M | Clayey sand | 4 | 62 | 13 | 21 | | 4,800 | 310 | 170 | 12 | 5.1 | 4.1 | 2.4 | 87.4 |
| 28 | do | do | I | do | 12 | 62 | 10 | 16 | | 35,000 | 510 | 240 | 55 | 3.0 | 4.1 | 1.6 | 83.0 |
| 29 | do | SW¼SE¼ sec. 21, T. 16 S., R. 14 E. | M | do | 13 | 57 | 14 | 16 | | 17,000 | 550 | 210 | 18 | 5.5 | 4.1 | 2.5 | 84.3 |
| 30 | do | NW¼SE¼ sec. 21, T. 16 S., R. 14 E. | M | do | 5 | 60 | 12 | 23 | | 4,000 | 370 | 165 | 5.5 | 8.2 | 4.6 | 3.0 | 80.7 |
| 31 | do | NE¼SE¼ sec. 21, T. 16 S., R. 14 E. | M | do | 11 | 48 | 13 | 28 | | 10,000 | 390 | 135 | 2.5 | 12 | 4.9 | 3.6 | 80.8 |
| 32 | do | NW¼SE¼ sec. 21, T. 16 S., R. 14 E. | S | Sand | | 92 | 5 | 3 | | 550 | 175 | 160 | 140 | 1.1 | .54 | .29 | 81.0 |
| 33 | do | SE¼NE¼ sec. 21, T. 16 S., R. 14 E. | M | Clayey sand | 7 | 63 | 10 | 20 | | 7,000 | 430 | 190 | 15 | 5.4 | 4.3 | 2.4 | 84.9 |
| 34 | do | NW¼SE¼ sec. 21, T. 16 S., R. 14 E. | S | Sand | 3 | 76 | 7 | 14 | | 4,000 | 340 | 200 | 95 | 1.9 | 3.0 | .92 | 84.8 |
| 35 | do | do | I | Clayey silt | | 19 | 52 | 29 | | 400 | 48 | 19 | 2.4 | 4.5 | 3.1 | 2.2 | 68.4 |
| 36 | do | NE¼SW¼ sec. 21, T. 16 S., R. 14 E. | M | Clayey sand | 9 | 62 | 10 | 19 | | 10,000 | 500 | 200 | 18 | 5.3 | 4.5 | 2.4 | 87.8 |
| 37 | do | do | S | Sand | | 92 | 4 | 4 | | 1,000 | 310 | 220 | 155 | 1.4 | .77 | .50 | 84.0 |
| 38 | do | SW¼NE¼ sec. 21, T. 16 S., R. 14 E. | I | Clayey sand | 1 | 63 | 15 | 21 | | 1,800 | 230 | 130 | 12 | 4.3 | 3.9 | 2.1 | 81.2 |
| 39 | do | NE¼SW¼ sec. 21, T. 16 S., R. 14 E. | M | do | 11 | 54 | 11 | 24 | | 8,000 | 510 | 160 | 5 | 10 | 5.1 | 3.3 | 80.5 |
| 40 | do | do | M | do | 6 | 62 | 11 | 21 | | 5,000 | 380 | 165 | 12 | 5.6 | 4.3 | 2.5 | 87.6 |
| 41 | do | do | I | do | 14 | 58 | 10 | 18 | | 16,000 | 570 | 210 | 30 | 4.4 | 4.6 | 2.1 | 87.1 |
| 42 | do | SE¼SW¼ sec. 21, T. 16 S., R. 14 E. | M | do | 8 | 56 | 13 | 23 | | 7,000 | 500 | 150 | 6.2 | 9.1 | 4.8 | 3.2 | 86.5 |
| 43 | do | do | M | do | 14 | 51 | 12 | 23 | | 18,000 | 570 | 180 | 6 | 9.7 | 5.2 | 3.3 | 82.3 |
| 44 | do | SW¼SW¼ sec. 21, T. 16 S., R. 14 E. | M | Gravel-sand-clay | 22 | 44 | 10 | 24 | | 18,500 | 1,400 | 220 | 5 | 17 | 5.9 | 4.1 | 80.4 |
| 45 | Unnamed | NE¼NE¼ sec. 28, T. 16 S., R. 14 E. | M | Sand-silt-clay | 1 | 33 | 24 | 42 | | 1,200 | 140 | 11 | 1 | 14 | | 3.8 | 76.6 |
| 46 | do | do | I | Sand | 5 | 72 | 7 | 16 | | 4,700 | 630 | 340 | 90 | 2.6 | 3.8 | 1.4 | 74.4 |
| 47 | do | do | M | Clayey sand | 8 | 50 | 12 | 30 | | 9,500 | 370 | 160 | 2.4 | 13 | | 3.6 | 71.2 |
| 48 | do | NW¼NE¼ sec. 28, T. 16 S., R. 14 E. | M | Sandy clay | 9 | 31 | 19 | 41 | | 8,000 | 300 | 17 | .5 | 25 | | 4.6 | 57.3 |
| 49 | do | do | M | Gravel-sand-clay | 30 | 48 | 8 | 14 | | 25,000 | 2,900 | 400 | 110 | 5.1 | 4.2 | 2.4 | 68.5 |

TABLE 17.—*Basic data on the grain-size distribution and density of alluvial-fan deposits*—Continued

| Sample | Alluvial fan | Location | Classification | | Distribution (percent) | | | | | Grain size in microns | | | | Sorting | | | Dry density (lbs per ft³ at 110° C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Field | Grain size | Gravel | Sand | Silt | Clay | Silt and clay | C | $Q_{75}$ | $Q_{50}$ | $Q_{25}$ | $S_o$ | $\sigma_\phi$ | $QD_\phi$ | |
| 50 | Unnamed | SE¼NW¼ sec. 28, T. 16 S., R. 14 E. | M | Clayey sand | 10 | 54 | 11 | 25 | | 9,000 | 500 | 200 | 4.0 | 11 | 5.0 | 3.5 | 63.3 |
| 51 | do | NE¼SW¼ sec. 28, T. 16 S., R. 14 E. | M | Gravel-sand-Clay | 23 | 47 | 10 | 20 | | 18,000 | 1,600 | 290 | 18 | 9.4 | 6.2 | 3.3 | 75.3 |
| 52 | do | SW¼SW¼ sec. 28, T. 16 S., R. 14 E. | M | Clayey sand | 7 | 59 | 12 | 22 | | 5,000 | 480 | 190 | 7.5 | 8.0 | 4.6 | 3.0 | 74.1 |
| 53 | do | NE¼NE¼ sec. 32, T. 16 S., R. 14 E. | I | do | 12 | 62 | 8 | 18 | | 14,000 | 820 | 300 | 50 | 4.1 | 4.7 | 2.0 | 92.1 |
| 54 | do | SE¼NW¼ sec. 32, T. 16 S., R. 14 E. | M | do | 13 | 52 | 11 | 24 | | 14,500 | 650 | 200 | 1.1 | 25 | | 4.7 | 75.6 |
| 55 | do | NE¼NW¼ sec. 6, T. 17 S., R. 14 E. | M | do | 14 | 50 | 10 | 26 | | 17,000 | 600 | 200 | 1 | 24 | | 4.6 | 69.3 |
| 56 | do | do | I | Gravelly sand | 25 | 57 | 6 | 12 | | 17,000 | 1,900 | 320 | 150 | 3.6 | 3.3 | 1.8 | 63.7 |
| 57 | do | do | I | Clayey sand | 8 | 66 | 7 | 19 | | 9,500 | 650 | 270 | 55 | 3.4 | 4.5 | 1.8 | 47.6 |
| 58 | do | NE¼NE¼ sec. 28. T. 16 S., R. 14 E. | S | Sand | 8 | 83 | | | 9 | 7,000 | 600 | 370 | 220 | 1.7 | 1.3 | .72 | |
| 59 | do | do | S | do | 1 | 88 | | | 11 | 1,000 | 300 | 280 | 160 | 1.4 | .81 | .46 | |
| 60 | do | NW¼SW¼ sec. 28, T. 16 S., R. 14 E. | S | Gravelly sand | 32 | 65 | | | 3 | 14,000 | 3,200 | 660 | 370 | 2.9 | 2.1 | 1.6 | |
| 61 | do | do | S | Sand | | 94 | 4 | 2 | | 550 | 330 | 260 | 180 | 1.4 | .67 | .44 | 95.7 |
| 62 | do | SE¼SE¼ sec. 21, T. 16 S., R. 14 E. | S | do | | 89 | 9 | 2 | | 530 | 190 | 160 | 125 | 1.2 | .75 | .47 | 95.4 |
| 63 | do | do | S | do | | 83 | 13 | 4 | | 550 | 220 | 150 | 90 | 1.6 | 1.1 | .60 | 81.2 |
| 64 | do | SE¼NW¼ sec. 34, T. 16 S., R. 14 E. | M | Clay | | 3 | 21 | 76 | | 150 | 3.7 | | | | | | 68.7 |
| 65 | do | do | M | Silty clay | | 13 | 31 | 56 | | 570 | 21 | 2.5 | | | | | 77.9 |
| 66 | do | do | M | Sand-silt-clay | 1 | 42 | 26 | 31 | | 2,000 | 160 | 36 | 1.9 | 9.3 | | 3.2 | 78.5 |
| 67 | do | SW¼NW¼ sec. 34, T. 16 S., R. 14 E. | M | do | 9 | 44 | 22 | 25 | | 18,000 | 290 | 95 | 4.5 | 8.0 | 4.5 | 3.0 | 76.6 |
| 68 | do | do | M | Clayey sand | 4 | 51 | 19 | 26 | | 7,500 | 240 | 90 | 3.4 | 8.4 | 5.0 | 5.0 | 74.6 |
| 69 | do | do | M | do | 2 | 61 | 14 | 23 | | 3,000 | 270 | 180 | 6.5 | 6.4 | 4.1 | 2.7 | 78.8 |
| 70 | do | do | S | Sand | | 87 | 5 | 8 | | 1,200 | 360 | 270 | 125 | 1.7 | 1.2 | .78 | 92.1 |
| 71 | do | do | M | Sand-silt-clay | | 46 | 24 | 30 | | 1,300 | 175 | 45 | 2.0 | 9.4 | | 3.2 | 77.8 |
| 72 | Unnamed | SW¼NW¼ sec. 34, T. 16 S., R. 14 E. | S | Gravelly sand | 22 | 68 | 4 | 6 | | 17,000 | 1,900 | 720 | 300 | 2.5 | 2.1 | 1.3 | 91.2 |
| 73 | do | do | I | Clayey sand | 2 | 65 | 12 | 21 | | 3,000 | 360 | 200 | 18 | 4.5 | 4.0 | 2.2 | 83.4 |
| 74 | do | SE¼NE¼ sec. 33, T. 16 S., R. 14 E. | I | do | 4 | 70 | 9 | 17 | | 7,000 | 600 | 230 | 55 | 3.3 | 4.1 | 1.7 | 59.4 |
| 75 | do | do | S | Sand | 8 | 87 | 3 | 2 | | 4,700 | 850 | 560 | 430 | 1.4 | 1.1 | .50 | 107.4 |
| 76 | do | SW¼SE¼ sec. 34, T. 16 S., R. 14 E. | S | do | | 93 | 5 | 2 | | 1,100 | 360 | 330 | 280 | 1.1 | .48 | .15 | |
| 77 | do | do | S | Gravelly sand | 25 | 72 | | | 3 | 17,000 | 2,000 | 600 | 365 | 2.3 | 2.0 | 1.2 | |
| 78 | Arroyo Hondo | SE¼NE¼ sec. 11, T. 17 S., R. 14 E. | I | Sand-silt-clay | | 47 | 28 | 25 | | 600 | 125 | 54 | 5 | 5.0 | 3.7 | 2.3 | 81.8 |
| 79 | do | do | S | Silty sand | 4 | 70 | 18 | 8 | | 6,500 | 380 | 210 | 120 | 1.8 | 1.6 | .84 | 83.7 |
| 80 | do | do | M | Sand-silt-clay | | 24 | 40 | 36 | | 300 | 60 | 14 | 1.4 | 6.6 | | 2.7 | 96.1 |
| 81 | do | do | M | do | | 41 | 30 | 29 | | 600 | 100 | 39 | 2.4 | 6.4 | | 2.7 | 80.4 |
| 82 | do | do | S | Gravelly sand | 28 | 60 | 4 | 8 | | 16,000 | 2,200 | 800 | 230 | 3.1 | 2.3 | 1.6 | 65.7 |
| 83 | do | do | I | Sand | 16 | 63 | 8 | 13 | | 6,000 | 1,500 | 520 | 150 | 3.2 | 3.5 | 1.6 | 74.2 |
| 84 | do | do | M | Sand-silt-clay | | 21 | 35 | 44 | | 400 | 48 | 7 | 1 | 6.9 | | 2.8 | 103.3 |
| 85 | do | do | M | Silty clay | | 10 | 31 | 59 | | 400 | 14 | 2.3 | .5 | 5.3 | | 2.4 | 79.6 |
| 86 | do | NE¼NE¼ sec. 11, T. 17 S., R. 14 E. | S | Sand | | 90 | 5 | 5 | | 1,000 | 330 | 300 | 190 | 1.3 | .75 | .40 | 102.3 |
| 87 | do | NE¼SE¼ sec. 12, T. 17 S., R. 14 E. | M | Clayey sand | 7 | 64 | 11 | 18 | | 7,000 | 460 | 220 | 18 | 5.1 | 4.2 | 2.3 | 91.1 |
| 88 | do | do | S | Sand | 15 | 75 | 4 | 6 | | 7,000 | 1,200 | 430 | 280 | 2.1 | 1.7 | 1.1 | 77.1 |
| 89 | do | do | S | do | | 92 | | | 8 | 700 | 300 | 260 | 160 | 1.4 | .75 | .46 | 85.9 |
| 90 | do | NE¼SW¼ sec. 12, T. 17 S., R. 14 E. | S | Silty sand | | 74 | 17 | 9 | | 1,000 | 210 | 145 | 58 | 1.9 | 1.6 | .93 | 84.6 |
| 91 | do | SW¼NW¼ sec. 12, T. 17 S., R. 14 E. | S | Sand | 1 | 90 | 3 | 6 | | 2,000 | 380 | 300 | 230 | 1.3 | .84 | .36 | 95.2 |
| 92 | do | SE¼NW¼ sec. 12, T. 17 S., R. 14 E. | S | Silty sand | | 72 | 17 | 11 | | 800 | 180 | 145 | 50 | 1.9 | 1.9 | .92 | 85.4 |
| 93 | do | NE¼SE¼ sec. 11, T. 17 S., R. 14 E. | S | Sand | 2 | 77 | 9 | 12 | | 3,000 | 350 | 250 | 97 | 1.9 | 2.4 | .92 | 77.8 |
| 94 | do | SE¼NE¼ sec. 11, T. 17 S., R. 14 E. | S | do | | 89 | 4 | 7 | | 1,000 | 430 | 310 | 210 | 1.4 | 1.0 | .52 | 92.8 |
| 95 | do | do | M | Sand-silt-clay | 4 | 40 | 20 | 34 | | 8,000 | 470 | 39 | 1.3 | 14 | | 3.9 | 93.2 |
| 96 | do | SE¼NE¼ sec. 11, T. 17 S., R. 14 E. | S | Sand | | 92 | 3 | 5 | | 1,500 | 530 | 380 | 240 | 1.5 | .90 | .57 | 103.8 |
| 97 | do | do | S | Silty sand | | 73 | 21 | 6 | | 290 | 135 | 100 | 60 | 1.5 | 1.0 | .58 | |
| 98 | do | SE¼NW¼ sec. 12, T. 17 S., R. 14 E. | S | Gravelly sand | 20 | 65 | 6 | 9 | | 6,000 | 1,750 | 530 | 235 | 2.7 | 2.4 | 1.4 | 73.1 |
| 99 | do | do | S | Silty sand | | 55 | 35 | 10 | | 240 | 115 | 70 | 32 | 1.9 | 1.4 | .92 | 78.1 |
| 100 | Cantua Creek | NE¼SE¼ sec. 35, T. 17 S., R. 14 E. | S | Sand | | 84 | 12 | 4 | | 580 | 210 | 170 | 96 | 1.5 | 1.0 | .56 | |
| 101 | Domengine Creek | NW¼SE¼ sec. 23, T. 18 S., R. 15 E. | S | Gravelly sand | 47 | 52 | | | 1 | 36,000 | 7,900 | 1,500 | 340 | 4.8 | 2.8 | 2.3 | |
| 102 | do | do | S | Sand | | 93 | | | 7 | 650 | 220 | 210 | 140 | 1.3 | .69 | .32 | |

TABLE 18.—*Basic data on the grain-size distribution of samples from 30-foot core holes in the Arroyo Ciervo fan*

[Samples obtained by the California Department of Water Resources. Grain-size analyses made by the Denver Hydrologic Laboratory of the U.S. Geological Survey. Grain size in microns: C, coarsest percentile; $Q_{75}$, coarsest quartile; $Q_{50}$, median grain size; $Q_{25}$, smallest quartile. Sorting: $S_o$, Trask sorting coefficient; $\sigma_\phi$, phi standard deviation; $QD_\phi$, phi quartile deviation. Location of core holes is shown in figure 18]

| Core hole | Sample (59 Cal-) | Classification (after Shepard) | Grain size, in microns | | | | Distribution (percent) | | | | Sorting | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | C | $Q_{75}$ | $Q_{50}$ | $Q_{25}$ | Gravel | Sand | Silt | Clay | $S_o$ | $\sigma_\phi$ | $QD_\phi$ |
| FP-1 | 491 | Clayey sand | 2,200 | 260 | 130 | 1.9 | 1 | 59 | 12 | 28 | 12 | 4.2 | 3.6 |
| | 492 | do | 4,000 | 310 | 150 | 22 | 2 | 67 | 13 | 18 | 3.8 | 4.0 | 1.9 |
| | 493 | Silty sand | 2,200 | 220 | 98 | 10 | 1 | 57 | 24 | 18 | 4.7 | 3.5 | 2.2 |
| | 494 | Clayey sand | 6,000 | 330 | 165 | 20 | 2 | 65 | 15 | 18 | 4.1 | 3.8 | 2.0 |
| FP-2 | 495 | Silty sand | 2,900 | 240 | 125 | 13.5 | 2 | 61 | 21 | 16 | 4.2 | 3.3 | 2.1 |
| | 496 | Clayey sand | 4,000 | 260 | 115 | 4.5 | 2 | 57 | 17 | 24 | 7.6 | 4.3 | 2.9 |
| | 497 | Sand | 8,300 | 410 | 210 | 62.5 | 7 | 68 | 11 | 14 | 2.6 | 3.2 | 1.4 |
| | 498 | Silty sand | 3,300 | 230 | 140 | 38 | 2 | 69 | 15 | 14 | 2.5 | 2.9 | 1.3 |
| | 499 | Clayey sand | 3,400 | 290 | 150 | 39 | 2 | 69 | 14 | 15 | 2.7 | 3.0 | 1.4 |
| | 500 | Silty sand | 4,500 | 200 | 96 | 16 | 3 | 58 | 23 | 16 | 3.5 | 3.1 | 1.8 |
| FP-3 | 501 | do | 3,600 | 260 | 140 | 36 | 2 | 68 | 17 | 13 | 2.7 | 2.8 | 1.4 |
| | 502 | Sand | 1,800 | 280 | 180 | 84 | 1 | 79 | 14 | 6 | 1.8 | 1.7 | .9 |
| | 503 | Silty sand | 1,500 | 280 | 160 | 30 | 0 | 70 | 15 | 15 | 3.1 | 3.0 | 1.6 |
| | 504 | do | 3,200 | 250 | 120 | 17 | 3 | 60 | 20 | 17 | 3.8 | 3.5 | 1.9 |
| | 505 | do | 12,000 | 250 | 70 | 1 | 6 | 45 | 29 | 20 | 16 | ------ | 4.0 |
| | 506 | do | 5,300 | 290 | 130 | 14 | 5 | 57 | 21 | 17 | 4.6 | 3.4 | 2.2 |
| | 507 | Clayey sand | 7,800 | 270 | 125 | 14 | 5 | 60 | 15 | 20 | 4.4 | 4.1 | 2.1 |
| FP-4 | 508 | do | 3,400 | 260 | 150 | 17 | 2 | 65 | 15 | 18 | 3.9 | 4.0 | 2.0 |
| | 509 | do | 14,000 | 270 | 130 | 20 | 6 | 61 | 13 | 20 | 3.7 | 3.9 | 1.9 |
| | 510 | Gravelly sand | 16,000 | 5,000 | 400 | 120 | 36 | 48 | 4 | 12 | 6.5 | 3.6 | 2.7 |
| | 511 | Silty sand | 3,500 | 250 | 120 | 11 | 2 | 59 | 20 | 19 | 4.9 | 3.5 | 2.2 |
| | 512 | Clayey sand | 4,000 | 240 | 100 | 4.3 | 2 | 55 | 19 | 24 | 7.5 | 4.1 | 2.9 |
| | 513 | do | 1,800 | 560 | 240 | 6 | 1 | 60 | 17 | 22 | 9.6 | 4.6 | 3.3 |
| | 514 | Silty sand | 12,000 | 200 | 85 | 12 | 4 | 54 | 24 | 18 | 4.1 | 3.4 | 2.0 |
| | 515 | do | 5,200 | 330 | 180 | 56 | 4 | 70 | 13 | 13 | 2.4 | 3.0 | 1.3 |
| | 516 | Sand | 1,600 | 320 | 200 | 90 | 1 | 79 | 11 | 9 | 1.9 | 1.8 | .9 |
| | 517 | Clayey sand | 8,500 | 310 | 120 | 10 | 7 | 56 | 18 | 19 | 5.6 | 4.1 | 2.5 |
| | 518 | Silty sand | 900 | 170 | 60 | 7 | 0 | 49 | 31 | 20 | 4.9 | 3.3 | 2.3 |
| FP-5 | 519 | do | 15,000 | 250 | 100 | 9 | 7 | 50 | 24 | 19 | 5.3 | 3.6 | 2.4 |
| | 520 | do | 11,000 | 260 | 94 | 11 | 6 | 50 | 26 | 18 | 4.9 | 3.5 | 2.3 |
| | 521 | Clayey sand | 3,500 | 230 | 95 | 4.5 | 3 | 54 | 19 | 24 | 7.1 | 3.9 | 2.8 |
| | 522 | Gravel-sand-clay | 30,000 | 4,000 | 320 | 70 | 32 | 44 | 11 | 13 | 7.6 | 4.9 | 2.9 |
| | 523 | Silty sand | 2,900 | 220 | 80 | 8 | 2 | 52 | 28 | 18 | 5.2 | 3.4 | 2.4 |
| | 524 | do | 4,500 | 290 | 150 | 42 | 4 | 67 | 18 | 11 | 2.6 | 2.7 | 1.4 |
| | 525 | do | 5,000 | 480 | 310 | 45 | 3 | 70 | 14 | 13 | 3.3 | 3.0 | 1.9 |
| | 526 | do | 5,200 | 260 | 130 | 30 | 4 | 63 | 23 | 10 | 2.9 | 2.6 | 1.6 |
| | 527 | do | 13,000 | 440 | 180 | 58 | 12 | 62 | 18 | 8 | 2.8 | 2.7 | 1.5 |
| | 528 | Sand | 9,000 | 420 | 220 | 135 | 7 | 82 | 8 | 3 | 1.8 | 1.4 | .8 |
| | 530 | do | 5,500 | 700 | 210 | 73 | 11 | 65 | 13 | 11 | 3.1 | 3.2 | 1.6 |
| | 531 | Silty sand | 6,500 | 310 | 140 | 23 | 5 | 62 | 18 | 15 | 3.7 | 3.2 | 1.9 |

The average sample tested had 5 percent wax and compacted 7 percent. On the assumption that none of the wax moved past the porous stones, the unmeasured compaction due to lateral movement of the wax would be 0.35 percent. The lateral displacement of the sides of the sample would average only 0.002 inch.

Extremely little time lag was caused by adjustment of the wax under load. The detail and abrupt changes of the consolidation curves show that frictional effects due to paraffin were negligible.

Quantitative correlations between the percentage of compaction due to wetting obtained from test-plot and laboratory tests are good. Depth bench marks at 25-foot intervals beneath Inter-Agency Committee test plot B showed that after 42 months the deposits at a depth of 50 feet had compacted 6½ percent, and that those at a depth of 100 feet had compacted 10 percent. The results of laboratory consolidation tests on 10 samples whose lithology was similar to that of the sediments beneath test plot B showed that 4–8 percent compaction occurred under a load equivalent to 50 feet of overburden, and that 7–11 percent compaction occurred under a load equivalent of 100 feet of overburden.

The results of the consolidation tests are shown in table 19.

TABLE 19.—*Basic data on the consolidation of alluvial-fan deposits*

[Sample locations listed in table 17. Overburden loads are simulated]

| Sample | Consolidation, in percent, at indicated overburden load | | | | | Consolidation due to wetting, in percent | | Time required for water front to pass through sample (Minutes) | Consolidation due to wetting, in percent, during the time required for the water front to pass through the sample (2.81 tons per square foot) |
|---|---|---|---|---|---|---|---|---|---|
| | 50-foot dry overburden load (2.27 tons per square foot) | 50-foot wet overburden load (2.81 tons per square foot) | 100-foot wet overburden load applied to wet sample after end of 50-foot test | 100-foot dry overburden load (4.21 tons per square foot) | 100-foot wet overburden load (5.80 tons per square foot) | 2.81 tons per square foot | 5.80 tons per square foot | | |
| 3 | 0.99 | 0.45 | | | | 8.47 | | 2.5 | 4.0 |
| 5 | 2.98 | .53 | | | | 2.34 | | 2.0 | 1.0 |
| 13 | 1.41 | .23 | | | | 3.54 | | 600 | 2.9 |
| 17 | .89 | .28 | | | | 3.62 | | 300 | 2.3 |
| 41 | 2.08 | .34 | | | | 6.90 | | | |
| 45 | .86 | .14 | | | | [1] +1.70 | | | |
| 46 | | | | 1.09 | 0.25 | | 4.91 | | |
| 50 | 1.57 | .46 | | | | 4.43 | | | |
| 51 | .86 | .19 | | | | 3.85 | | | |
| 52 | 1.18 | .27 | | | | 4.74 | | | |
| 53 | 3.43 | 1.09 | 4.15 | | | 6.95 | | | |
| 57 | 2.97 | .45 | | | | 14.12 | | 42 | 6.5 |
| 61 | 1.64 | .26 | | 2.08 | .09 | 2.95 | 2.49 | 1.0 | 1.4 |
| 63 | 2.98 | .17 | | | | 5.60 | | 4.0 | 3.7 |
| 68 | 2.35 | .22 | 4.05 | | | 1.28 | | | |
| 70 | .55 | .09 | | | | 6.55 | | 8.0 | 2.7 |
| 71 | .59 | .10 | 2.01 | | | [1] +.69 | | | |
| 72 | 1.63 | .49 | 3.06 | | | 9.18 | | 7.5 | 4.7 |
| 73 | 1.60 | .33 | 3.65 | | | 4.26 | | 77 | 2.7 |
| 75 | 2.33 | .51 | | | | 3.09 | | 2.0 | [1] +1.1 |
| 76 | 2.66 | .29 | | | | 1.63 | | 2.5 | 1.0 |
| 80 | | | | 1.61 | .07 | | 3.59 | | |
| 92 | 1.40 | .41 | | 3.55 | .55 | 9.63 | 12.87 | 90 | 6.9 |
| 93 | 1.46 | .25 | | 2.40 | .43 | 11.00 | 13.54 | 3.0 | 7.8 |
| 95 | 1.30 | .14 | | 1.98 | .27 | [1] +.22 | 2.94 | | |
| 96 | .84 | .20 | | 1.86 | .27 | 5.85 | 7.37 | 8.5 | 4.4 |
| 98 | 3.73 | .39 | | | | 6.48 | | .5 | 4.8 |

[1] Plus sign indicates expansion of sample.

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The U.S. Geological Survey Library has cataloged this publication as follows:

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Alluvial fans and near-surface subsidence in western Fresno County, California. Washington, U.S. Govt. Print. Off., 1964.

vii, 71 p. illus., maps (1 col.) diagrs., profiles, tables. 30 cm. (U.S. Geological Survey. Professional Paper 437–A)

Studies of land subsidence.

Part of illustrative matter fold. in pocket.

Prepared in cooperation with the California Dept. of Water Resources.

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