UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
Water Resources Division

APPRAISAL OF NEAR-SURFACE SUBSIDENCE CRACKS ON THE PANOCHE CREEK FAN, FRESNO COUNTY, CALIFORNIA

William B. Bull 1930-

OPEN-FILE REPORT

Sacramento, California
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Prepared in cooperation with the
California Department of Water Resources

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By William B. Bull

U. S. Geological Survey, Sacramento, California

INTRODUCTION

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 since burial. About 100 square miles of alluvial-fan deposits in western Fresno County, California, have been affected by manmade near-surface subsidence within the past few decades. Subsidence of 3-5 feet is common and 10-15 feet of subsidence has occurred within small areas. Open cracks form between areas undergoing different amounts of settlement, and are a characteristic feature of compaction due to wetting. Differential settlement occurring within short distances has destroyed or damaged ditches, canals, roads, pipelines, electric-transmission towers, and buildings, and has made the irrigation of crops difficult. The areas of known near-surface subsidence along the alinement of the San Luis Canal-California Aqueduct were compacted by ponding before construction of the canal.

The 11 miles of canal alinement that cross the fan of Panoche Creek were not ponded before construction. Although a few reports of local residents to the California Department of Water Resources indicated that some very small areas of settlement had occurred after irrigation, it was generally considered that the fan would not be susceptible to widespread near-surface subsidence. The irrigated fields did not show the pronounced hummocky relief and subsidence hollows that were typical of the areas of known near-surface subsidence. Just as strong was the evidence from core holes that showed that the deposits, even in areas that had never been irrigated, were roughly at field capacity instead of being moisture deficient. This seemed logical because Panoche Creek had been observed to flow for 1-5 months during years of heavy rainfall, in contrast to the ephemeral flow of streams on the Moreno Gulch fan to the northwest and on the Tumey Gulch fan to the south. It was assumed that if similar flows had occurred in the past, the deposits would have been wetted thoroughly from the land surface to the water table with each major period of flow and deposition.

A map of the Panoche Creek and adjacent fans is shown in figure 1.

Figure 1 near here. Caption on next page.

'he reach of the San Luis Canal-California Aqueduct discussed in this eport includes the Moreno Gulch and adjacent fans, and the Panoche Creek fan northwest of the stream channel. To give the reader an idea of :he location of the canal station numbers, the canal crosses the west boundary of the Panoche Creek fan at station 1820 (1,820 hundred feet from start of canal), and crosses Panoche Creek at station 2010. The liscussion presented in this report refers to observations made along the canal between these stations except when comparison is made with the Moreno Gulch fan.

Nearly all the Panoche Creek fan had been irrigated by 1966 except for several square miles near the fan apex. Parts of the fan have been irrigated for more than 40 years, however, some areas, such as in the vicinity of station 1820 have been irrigated only since 1959.

The areas upslope from the near-surface subsidence areas were unirrigated as of 1961, and are expected to subside when irrigated for the first time. Near-surface subsidence is more intense on the upslope and midslope parts than near the downslope third of the alluvial fans susceptible to compaction due to wetting. Downslope from the lower boundary of the subsidence areas, near-surface subsidence was not visibly apparent at the time of the 1961 mapping.

Figure 1.--Map of study area. Moreno Gulch, Panoche Creek, and Tumey Gulch fans are lettered A, B, and C, respectively. D is location of small near-surface subsidence area shown in figure 5.

The geology of the alluvial-fan deposits exposed in the canal banks was mapped after the banks were trimmed and shortly before they were paved. The mapping of the Panoche fan, and the Moreno Gulch fan, which is known to be susceptible to near-surface subsidence, was done by Merritt Bradley, U.S. Bureau of Reclamation, San Luis Unit. The right bank was mapped first and a few widely spaced cracks filled with clayey material were noted in the deposits of the Moreno Gulch fan. Upon reaching the Panoche Creek fan, the cracks were much more abundant.

The Bureau of Reclamation was concerned about the possible implications of these cracks in the Panoche Creek fan with respect to possible subsidence, and informally asked the Geological Survey to review the evidence. I spent a total of 5 days in May and June 1966 studying the cracks in the canal banks and reviewing the extensive mapping that Merritt Bradley had been able to do despite having to keep ahead of the paving machine. The mapping done by Merritt Bradley has made possible not only the description of the cracks, but also the evaluation of the several possible causes of cracking.

The purpose of this report is to describe the significant features of the cracks, to compare them with near-surface subsidence cracks, to draw conclusions regarding the cause, and to estimate the amount of post-construction settlement that might occur from the same cause that produced the cracking. The findings are significant with respect to maintenance of the canal and distribution systems after water delivery begins.

DESCRIPTION OF THE CRACKS IN THE PANOCHE CREEK FAN

Small-Scale Features

The cracks in the alluvium of the Panoche Creek fan, as exposed in the canal excavation, are filled with clay; no unfilled cracks and only one partially filled crack were observed. The clay fillings range from less than 1.32-inch to 12 inches, but most are 1/4- to 1-inch wide. The width of the crack fillings commonly remains remarkably uniform for most of the distance up the trimmed slopes of the canal banks (80 feet). However, some crack fillings are highly variable in width, repeatedly varying in width from less than 1 to more than 10 inches as one traces them up the slope. Variations in the bearing of the cracks do not occur as they pass through beds of different lithologies. The clay filling the cracks shows no evidence of injection of material laterally between the bedding planes of the fan deposits. The filling may be massive, consisting of clay or sandy clay; or it may have vertical laminations, with matching widths and colors of laminae on both sides of the filling. The central parts of some fillings have been deformed by folding which is seen best in the shrinkage cracks that develop after the filling has dried. The compressional forces causing the miniature folds were exerted inward from the sides of the cracks.

The contacts between the crack fillings and the enclosing sediments show that sides of the cracks had a rough, hackly fracture. This is readily seen in excavated pits and by the sharp angles and the changes in direction shown by the crack fillings as exposed on the trimmed surface. Evidence of shearing or smoothing of the broken fan deposits was not noted.

Offset bedding on the opposite sides of the cracks is rare and does not exceed a few inches as exposed on the 2-to-1 slopes of the canal bank, although the bedding is poorly defined and contorted on the 2-to-1 slopes. Furthermore, the frequent watering of the slopes to keep them wet until paved makes a crust of mud that obliterates all but the sharpest features. A trimmed slope that has not been watered is shown in figure 2. One crack parallels the mattock and two smaller

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Figure 2 near here. Caption on next page.

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cracks intersect the first crack above the head of the mattock. The prominent horizontal bands and lines are the result of the trimming operation. The undulating bands are bedding; the moist clayey beds being darker than the drier sandy beds. A possible offset of about 2 inches is shown by the thin clay bed and the top of the thick clay bed in front of the 3-foot mattock handle. Other than this, offset of bedding or cracks is not apparent in the photograph.

Figure 2.--Intersecting crack fillings in trimmed left bank of canal at station 1927+30L

Large-Scale Features

The patterns of the crack fillings were studied on the trimmed 2-to-1 canal banks--a 26 1/2-degree slope. On the 2-to-1 trimmed slope apparent distances and displacements may be different from the actual values. For a crack normal to the centerline of the canal, the horizontal component of a distance between two points is 0.89 the slope distance, and the vertical component is 0.45 the slope distance. As the angle departs from normal, the horizontal component of the distance increases and the vertical component decreases. Thus, for a crack parallel to the canal centerline there is no vertical component, and the horizontal component is equal to the observed distance. The orientation of the cracks with respect to the canal centerline is indicated by the marks left by the trimmer which are parallel to the canal center-line. For examples, see figures 2 and 6B.

Many of the crack fillings extend up to the base of the tilled zone, which in some places had fragments of cotton plants or other vegetation. Compacted artificial fill was above the tilled zone and was easily distinguished from the bedded fan deposits under it. Many cracks died out below the tilled zone, indicating that they were discontinuous. In some reaches, the cracks extended to the tilled zone on one side of the canal but only part way up the other side of the canal (fig. 4A). The crack filling in figure 3 extends to the base of

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Figure 3 near here. Caption on next page.

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the tilled zone. In this case, the horizontal distance is about 65 feet and the vertical distance about 32 feet from the toe of the canal bank to the base of the tilled zone. Note the lack of offset bedding.

Figure 3.--Crack filling at station 1929+40R. Photograph by Merritt Bradley, U.S. Bureau of Reclamation.

The cracks are essentially vertical, although parts may deviate from vertical for a few inches or feet. Small departures from vertical were noted for a few cracks. The overall angle of dip for these cracks was not measured, but it was close to vertical. The vertical nature of the cracks is illustrated excellently between stations 1992 and 2000. In figure 4A the inferred position of the crack fillings is

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Figure 4 near here. Caption on next page.

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shown in the bottom of the canal between these stations. For 800 feet, not only the bearing, but also the number of cracks match from one side of the canal to the other, despite the fact that the banks of the canal slope in opposite directions.

The general orientation of the cracks appears to be roughly normal to the canal centerline, even in reaches where the canal has considerable sinuousity. Most of the cracks, as exposed on the slopes, are within 45 degrees of being normal to the canal centerline, as is shown in figures 4A and 4B. The slopes of the canal banks do not affect the orientation of the cracks because of the near-vertical nature of the crack fillings. Very few cracks are parallel to canal centerline although one crack roughly paralleled the canal alinement for 270 feet.

The density of spacing of the cracks is highly variable and changes abruptly. It varies from about 1 to 7 cracks per 100 feet of canal alinement.

Figure 4.--Crack fillings exposed in the trimmed banks of the San Luis Canal-California Aqueduct on the Panoche Creek and Moreno Gulch alluvial fans.

<u>A</u>. Inferred continuity of crack fillings between stations 1992 and 2000, Panoche Creek fan.

<u>B</u>. Comparison of density of crack fillings on the Panoche Creek and Moreno Gulch fans.

Individual cracks show a variety of patterns. Some divide and oin repeatedly, and others split into many small cracks that die out within a short distance. A few en echelon crack patterns were noted. Many of the cracks end abruptly at another crack, or cannot be traced through a bed that is the same lithology as the crack filling. The cracks usually occur in sets that parallel each other, and in some places two sets occur that intersect each other. Most of the crack intersections do not show displacement on the trimmed slopes. The cracks that are offset usually are displaced less than 3 inches, but displacements of 6, 12, and 21 inches were noted on three cracks. (See fig. 9B.)

The displacement of intersecting cracks does not require a strike-slip type of horizontal component in order to produce the offset. Simple gravity movements along two vertical planes will not produce an offset intersection of the planes. Thus one would not expect to find offset of many crack fillings because most are near vertical. However, if one or more of the planes is not vertical, gravity movements will include a horizontal component and the intersection of the planes will be offset. The magnitude of offset of nonvertical crack fillings as indicated on the 26 1/2-degree slope may be much greater than the true displacements if the trimmed slope and the nonvertical crack dip in the same general direction. The apparent displacement is less than the true displacement if the slope and crack dip in opposite directions.

Buried stream channels of the ancestral Panoche Creek were noted in many places. The maximum depth of the channels was about 13 feet which is about the same as the present-day channel incised into this part of the fan. Widths of compound cut and fill structures were several hundred feet in a few cases. The sediments filling the channels consisted mainly of coarse-grained sands and sandy gravels in contrast to the sheets of finer-grained deposits laid down by a network of braided streams that comprise the bulk of the fan deposits. In general, crack fillings were not observed in the coarse-grained material filling the channel or in the finer grained bedded fan deposits above cut and fill structures. However, in a few cases, crack fillings extended about a foot into the channel fill, which shows that the relation between the cracks and channels is not a simple truncation of preexisting crack fillings.

POSSIBLE CAUSES OF THE CRACKS

The fact that the cracks were open long enough to be filled with what appears to be water-deposited clay is the best evidence that the cracks exposed in the canal banks of the Panoche Creek fan are tension cracks. Additional evidence for tension cracks is the rough, hackly fracture along the sides of the cracks; shear movement would have smoothed out the minor irregularities.

The following working hypotheses were considered as possible causes of the cracks: The cracks were considered to have possibly resulted from construction operations, tectonic folding of the deposits, artesian-head decline, stream-channel entrenchment, dessication, and compaction due to wetting of moisture-deficient alluvial-fan deposits.

Tension associated with areas of uplift or major shear zones is not considered as a cause of the cracks because there is no evidence for these types of movements. Therefore, this discussion will deal primarily with the various types of settlement or subsidence that might be responsible for the cracks. It is assumed that the tension cracks paralleled the area of maximum settlement, and occurred chiefly between the area that settled most and the area that remained stable, or settled to a lesser degree.

Field evidence opposes the hypothesis that the cracks resulted from construction operations. They are filled with clay and extend more than 25 feet below the zone of tillage. The deposits are not disturbed much by the trimmer, despite the size of the machine. In general, there is no visible disturbance of the bedded fan deposits or the crack fillings after one has dug 1 to 3 inches below the trimmed surface.

Tectonic subsidence and folding has occurred on a large scale in the geologic past, as is indicated by the folded lake clays interbedded with the deeper fan deposits. However, the presence of sets of cracks trending in different directions implies a locally variable cause of the cracking. Therefore, it is difficult to explain intersecting cracks that extend to the land surface on the basis of tectonic movements.

More than 20 feet of subsidence due to artesian-head decline has occurred on the Panoche Creek fan, and parts of the fan are subsiding more than a foot per year. If tension cracks did form from this type of subsidence, one would expect them to roughly parallel the lines of equal subsidence. The lines of equal subsidence on the Panoche Creek fan are about normal to the canal centerline, as are the general orientations of the cracks. Aside from this, it is hard to attribute the cracks to this cause. The hypothesis does not explain the abrupt changes in density of cracks within 100-foot distances. Also, the presence of intersecting cracks indicates more than one local settlement.

Both tension and shear cracks are common within 20 feet of the sides of present-day stream channels entrenched as much as 40 feet into the alluvial fans of western Fresno County. The trenching is primarily the result of changes in the daily and seasonal amounts of rainfall since 1850. Repeated trenching and backfilling has occurred on the fans in the geologic past. The present trenching of the streams appears to be as deep or slightly deeper than former trenching exposed in the upper 40 feet of the alluvial fans. The cracks due to failure of the stream banks are temporary and are destroyed by slumpage into the stream channels. Many of these cracks were examined along the banks of Panoche Creek. The most notable feature was that none had clay fillings and very few showed any evidence of water flowing down the crack for more than a few inches below the land surface. Despite their abundance along present-day channels, cracks were not associated with the buried channels seen in the canal banks (fig. 4B).

Many small dessication cracks were noted in the clayey beds exposed in the canal banks. These cracks generally were less than a foot long, and rarely extended into the beds above or below the bed in which the principal cracking occurred. Large-scale dessication cracks are not likely on the alluvial fans of western Fresno County because the overall clay content for a sequence of beds does not change rapidly enough to cause large-scale differential shrinkage between adjacent areas. This is particularly true of the deposits along the canal alinement, which roughly parallels the contour of the fan.

Near-Surface Subsidence

Compaction due to wetting is the only hypothesis that fits the facts presently available. Although the earlier reports of local ranchers of small local areas of near-surface subsidence on the Panoche Creek fan were hard to verify, and did not agree with the bulk of the information about the fan, it now seems likely that they were correct. The location of an area of moderate near-surface subsidence 1/2-mile south of Panoche Creek fan was called to my attention by Mr. Richard Bateman of the Los Banos office of the U.S. Bureau of Reclamation. The photographs of this small near-surface subsidence area shown in figure 5 were taken in June

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Figure 5 near here. Caption on next page.

1966. Most of the observable settlement is along the alinements of one or two former ditches. Undulating topography is not common in the nearby fields, and some of the breaks in slope that can be seen in the fields are remnants of low terraces of Panoche Creek. Although the subsidence hollows shown in figure 5 have been largely filled in the course of agricultural operations, water still floods these low areas when the crops are irrigated. It is estimated that as much as 4 feet of near-surface subsidence may have occurred in this area.

Figure 5.--Near-surface subsidence features on the Panoche Creek fan. Location shown on figure 1.

_A_. Water in subsidence hollow along old ditch alinement. Fan slope is toward the left.

_B_. Powerline poles tilt toward subsidence hollow at old well site. Fan slope is toward the right.

Many aspects of the cracks exposed in the canal banks are the same as for present-day near-surface subsidence cracks. Both occur as roughly parallel sets of tension cracks that are nearly vertical to depths of 25 feet or more, and both show a hackly irregular break along the sides of the cracks. The crack fillings are discontinuous, as are subsidence cracks. Many of the crack fillings appear to have a constant width. This may be the result of a balance between the vertical and horizontal components as exposed in the 2-to-1 trimmed slope. For example, near-surface subsidence cracks tend to pinch out laterally, and to decrease in width below the land surface. These two effects would tend to cancel each other for some cracks that are normal to the canal centerline.

Tension, and then compression, occur in areas of near-surface subsidence, as cracks form between blocks of deposits and then are partly closed as the blocks rotate downward toward the area that is undergoing maximum compaction due to wetting (Bull, 1964b, p. 43-44). The crack fillings indicate the same sequence of events. The fact that the cracks were open long enough to fill with sediment shows their tensional origin. The small folds in the centers of some crack fillings indicates that compression occurred after the crack was filled.

The differential subsidence that accompanies compaction due to wetting varies markedly within short distances, and is dependent on many factors including the permeability and compactibility of the deposits. The patterns of the crack fillings in the canal banks also indicate a locally variable type of settlement, as is shown by the intersecting cracks and the density of the crack fillings which, within short distances, varies from closely spaced cracks to only an occasional crack.

Displacement of bedding was small or lacking adjacent to many of the crack fillings exposed in the canal banks, but the amount of displacement could not be ascertained in most cases because the bedding was not apparent, or because of the contorted nature of the bedding as exposed on the 2-to-1 slope. The small displacements of bedding on opposite sides of the crack fillings are not in disagreement with what has been observed in near-surface subsidence areas. In areas of intense near-surface subsidence, displacement on opposite sides of a crack may exceed 1 foot, particularly if the adjacent land has not been affected by compaction due to wetting. In areas of less intense near-surface subsidence the displacement across subsidence cracks is much less. For example, at Inter-Agency Committee near-surface subsidence test plot D (on the Moreno Gulch fan), the <u>maximum</u> vertical displacement of the land surface across a crack was only three-eighths of an inch after 1 1/2 feet of subsidence had occurred, and the cracking had extended more than 60 feet from the edge of the ponded area. Because the process of near-surface subsidence involves rotation and settlement of blocks of material, the displacement of cracks or bedding, especially where large areas have been wetted, is dependent more on the differential settlement of adjacent blocks than on the magnitude of subsidence that occurred. If two adjacent blocks settled 3.00 and 3.05 feet, the vertical offset between them would be only 0.05 foot.

Both the crack fillings and modern near-surface subsidence cracks have the same small-scale patterns, as is shown by the photographs in figures 6-9. The similarity of the types of patterns is readily apparent despite the fact that the cracks in the canal banks could be observed mainly on the 2-to-1 slopes. The Mendota Test Site, about 7 miles south of the Panoche Creek fan in an area of intense near-surface subsidence, was operated by the California Department of Water Resources to determine the best method of precompacting sediments susceptible to near-surface subsidence. Typical near-surface subsidence cracks developed at this test site afford an excellent opportunity to compare the cracks in the Panoche Creek fan with modern subsidence cracks (figs. 6-9). In figure 6A,

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Figure 6 near here. Caption on next page.

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the crack width is a function of both variation in separation of the crack, and of slumpage of material into the crack. Figure 6B shows a similar crack in the canal bank that has been filled with clay. Cracks that divide and join, such as those shown in figure 7A, usually are the result of sec-

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Figure 7 near here. Caption on next page.

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ondary slumping that occurs after the primary crack has opened. Similar features were common in the canal banks. En echelon crack patterns are one of the less common patterns, but can be observed both around test plots and in the canal banks, as is shown by figure 8. Cracks that intercept and

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Figure 8 near here. Caption on next page.

Figure 6.--Variation in width of near-surface subsidence cracks.

A. Mendota Test Site.

B. Panoche Creek fan. Looking down 2-to-1 slope of canal bank at station 1921 L.

Figure 7.--Anastomosing near-surface subsidence cracks.

A. Mendota Test Site.

B. Panoche Creek fan. Looking down 2-to-1 slope of canal bank at station 1923+40L.

Figure 8.--En echelon near-surface subsidence cracks.

A. Mendota Test Site.

B. Panoche Creek fan. Looking up 2-to-1 slope of canal bank at station 1846+83L. Photograph by Merritt Bradley, U.S. Bureau of Reclamation.

end abruptly at another crack are common both at test plots and along the canal on the Panoche Creek fan. An example at the Mendota test site is shown in figure 9A. Intersecting cracks resulting from near-

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Figure 9 near here. Caption on next page.

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surface subsidence occur only when the cracks encircle two or more adjacent centers of maximum differential settlement. Cracks around a single source of wetting, such as a test plot, do not intersect. Intersecting near-surface subsidence cracks have been observed in the vicinity of two adjacent test plots, and near irrigation ditches that were used at different times and were at right angles to one another. Intersecting cracks were fairly common along the canal--cracks without offset are shown in figure 2 and cracks with offset are shown in figure 9B.

Figure 9.--Near-surface subsidence crack junctures.

A. Intercepting cracks at the Mendota Test Site.

B. Intersecting cracks on the Panoche Creek fan. Looking up the 2-to-1 canal bank at station 1974+65L.

Historic and Prehistoric Subsidence

If the cracks in the Panoche Creek fan were formed as a result of near-surface subsidence, was the subsidence a result of man's activities, or to wetting by the stream in prehistoric times? Most likely, it was the result of both. The presence of small areas of visible near-surface subsidence (fig. 5) shows that at least part of the settlement has resulted from irrigation, but strong evidence exists to show that the majority of the settlement resulted from prehistoric stream flows. The evidence for prehistoric near-surface subsidence will be presented in this and the next section.

The absence of widespread undulating farmlands, and the presence of deposits already wetted to field capacity, even in areas that have not been irrigated, strongly suggest prehistoric wetting and settlement of the fan deposits.

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

The patterns of intersecting cracks can be explained by the presence of water fronts moving laterally in different directions from the meandering channel of the ancestral Panoche Creek to produce intersecting tension alinements. The channel shown in figure 1 has both meandering and straight reaches.

The absence of crack fillings in or above large buried channels, and the presence of crack fillings adjacent to buried channels, is what one would expect if the cracks were the result of prehistoric subsidence. Flow concentrated in the channel would promote sufficient deep percolation that would complete the compaction due to wetting before the channel was back filled. Channel entrenchment also would promote continuous flows of water to the lower parts of the fan. The thin-bedded sheet deposits above many channels would not have enough overburden load to undergo visible compaction due to wetting. Studies by Bull (1964a, p. 117-125) show that two periods of channel trenching since 1850 were the result of above normal annual and daily rainfall. During wetter times such as have occurred in the past century, the flow would be concentrated by the channel, in contrast to drier times of no channel trenching when the flows would spread out on the fan surface nearer the mountain front.

Crack fillings also were found in the banks of Panoche Creek. Cracks in reaches of the stream which was trenched as of 1854 cannot be attributed to irrigation by man, because the stream had the same course in 1854 that it does now, and irrigation did not begin until the 1880's. One of the prehistoric crack fillings is shown in figure 10.

Figure 10 near here. Caption on next page.

The crack fillings are similar to those in the canal banks. They are filled with laminated clay, which has a polygonal pattern of cracking normal to the plane of the crack, are vertical, and trend roughly normal to the contours of the fan. Exposures of the cracks are not common in the banks of the stream because the cracks roughly parallel the overall stream course. Those that were found were in meandering reaches of the stream.

Figure 10.--Prehistoric near-surface subsidence crack filling in the bank of Panoche Creek.

COMPARISON OF THE CRACKS IN THE PANOCHE CREEK AND MORENO GULCH FANS

A comparison of the crack fillings as exposed in the canal banks in the Panoche Creek and Moreno Gulch fans is interesting because the Moreno Gulch fan is an area of known near-surface subsidence caused by irrigation, in which as much as 15 feet of near-surface subsidence has occurred. One's first impression is that the crack fillings in the two fans are essentially the same, but further investigation reveals some important and interesting differences.

On the Panoche Creek fan the lithology of the fillings is mainly clay. On the Moreno Gulch fan the lithology of the fillings ranges from clay to sand, clayey sand being the most common lithology, although the overall lithology of the Moreno Gulch fan is more clay-rich than the Panoche Creek fan.

Some of the cracks on the Moreno Gulch fan are only partly filled, even at depths of as much as 30 feet below the original land surface. This indicates that flow down the cracks has not been prolonged as on the Panoche Creek fan.

The density of spacing of the cracks is very low on the Moreno Gulch and adjacent fans. The parts of these fans shown in figure 4B are representative of the crack spacing on the Moreno Gulch fan farther to the northwest. On the central part of the Moreno Gulch fan only 30 cracks were mapped in the left bank in 5,500 feet. Figure 4B shows that the distance between crack fillings decreases abruptly as the canal enters the Panoche Creek fan. The difference in the density of the cracks can be explained by differences in the application of water. On the Moreno Gulch fan, large areas were brought under irrigation at the same time, and because the deposits tended to be wetted uniformly, differential settlement was at a minimum. Maximum differential settlement probably occurred along supply ditches because they were flooded more of the time than the fields. Compaction due to prehistoric flows on Panoche Creek would produce a high density of cracking even if the amounts of subsidence were less than on the Moreno Gulch fan. Large areas would not be wetted at the same time by the stream; instead, different sections of the fan would be wetted along radial lines as the stream changed position on the fan. Cracks would form between the areas that settled and the areas that remained stable.

Intersecting cracks are not common on the Moreno Gulch fan, and offset of intersecting cracks is rare. The difference might be the result of a more uniform direction of application of water, as compared to infiltration of water from the meandering ancestral Panoche Creek.

A few of the crack fillings on the Moreno Gulch fan extend into and continue above buried channel fills, indicating that prehistoric channel flow did not penetrate below the root zone and cause compaction due to wetting. One crack filling extended 6 feet into a channel fill, and others were observed to extend above the channel fills from adjacent areas.

Although the general orientation of the crack fillings on the Moreno Gulch fan is roughly normal to the canal centerline, many cracks have an orientation that is either north-south or east-west. Examples would be the crack fillings in the left bank at station 1797 in figure 4B. Cracks with these orientations are practically nonexistent on the Panoche Creek fan, except where the canal alinement is east or south; for example, stations 1820 to 1850 on figure 4B. The north-south and east-west cracks on the Moreno Gulch fan probably are related to irrigation ditches having these orientations. Cracks not having these orientations on the Moreno Gulch fan may be the result of subsidence hollows in the fields, or of subsidence along contour ditches which were used in part of the area. The lack of cracks having these orientations on most of the Panoche Creek fan can be attributed to prehistoric instead of historic near-surface subsidence. Prehistoric subsidence cracks would be controlled by infiltration along the stream course, which would be associated with north-south and east-west cracking only where the stream flowed north or east. For most of the fan the overall direction of stream flow would be northeast.

ESTIMATED FUTURE NEAR-SURFACE SUBSIDENCE ON THE PANOCHE CREEK FAN

In addition to subsidence due to artesian-head decline which exceeds 1 foot per year along parts of the canal where it crosses the Panoche Creek fan, the potential extent and amount of near-surface subsidence in areas that were not ponded before construction started is of interest in relation to the problem of canal maintenance.

The evidence available strongly suggests that most of the settlement that caused the cracking was near-surface subsidence resulting from prehistoric flows along Panoche Creek. The small areas of present-day near-surface subsidence indicate the presence of small pockets of moisture-deficient deposits as a result of the erratic nature of prehistoric percolation from Panoche Creek. Along the canal alinement, these pockets of material susceptible to near-surface subsidence probably have been precompacted by wetting that has occurred as a result of 20 years of agricultural operations. Extensive percolation of irrigation water is suggested when one compares the depth to the water table in 1952 and 1965. The water table along most of the canal alinement on the Panoche Creek fan has risen between these dates--the maximum rise being 30 feet.

The probability of subsidence is greater in two fairly small areas in which the water table has remained unchanged or has declined as much as 25 feet between 1952 and 1965. These areas are the 2-3 miles of canal alinement near the south edge, and the 1 mile near the north edge (the area shown in fig. 4B) of the Panoche Creek fan. Even in these areas, I would expect only negligible or minor near-surface subsidence after construction of the canal. The presence of extensive near-surface subsidence cracks near the north edge of the fan indicates that considerable prehistoric compaction due to wetting has occurred already. Also, both of these areas have been irrigated for at least 7 years. Although this is not as long as the history of irrigation on most of the fan, any deposits that were not wetted by prehistoric flows along Panoche Creek should have been largely wetted by irrigation waters.

The distribution systems to be built southwest of the canal alinement may cross pockets of moisture-deficient deposits that will be more susceptible to compaction due to wetting than the deposits along the canal alinement. Much of this area has been irrigated for about 10 years but parts of it have never been irrigated. In addition, there are some areas that have not been irrigated for half a century. The first irrigation of the fan was in 1887 when the Panoche Development Company dammed the stream and diverted water from it. Many dams and diversions were made in the next 2 decades, but the venture failed during the dry years at the beginning of this century.

Several feet of near-surface subsidence may occur on certain parts of the fan that have not been irrigated before. I would not expect subsidence to exceed 3-4 feet, however, even in areas of moisture-deficient deposits that have never been irrigated before.

There are several reasons for expecting a lower magnitude of compaction due to wetting on the Panoche Creek fan than on the adjacent fans where as much as 15 feet of present day near-surface subsidence has occurred. Nearly all the deposits of the adjacent fans contain considerable clay, whereas the Panoche Creek fan contains many beds of clean sand. A lack of clay in a bed means that there will be little decrease in strength when the bed is wetted for the first time under load. For a more detailed discussion of the relation of clay content to compaction due to wetting, see Bull, 1964b, p. 54-56.

The thickness of deposits susceptible to near-surface subsidence on the Panoche Creek fan is important because compaction due to wetting increases in proportion to overburden load. As much as 300 feet of moisture-deficient deposits have accumulated on some of the fans subject to present day near-surface subsidence, but I do not think that such thicknesses have ever occurred on the Panoche Creek fan. One factor is that the rate of accumulation has been slower on the Panoche Creek fan than on the fans derived from drainage basins that are underlain by a greater proportion of easily eroded clay-rich rocks. An analysis of the effect of drainage-basin lithology on fan area, slope, and thickness is given by Bull, 1964a, p. 94-95.

The occurrence of prehistoric near-surface subsidence on the Panoche Creek fan shows that there was at least one period during which water did not percolate below the root zone as sediments were deposited on the fan. This period was followed by wetter times during which water percolated below the root zone to wet the moisture-deficient deposits. Accumulation of large thicknesses of moisture-deficient deposits would have been prevented if more than one period of prehistoric wetting had occurred.

Deposition of alluvial fans in western Fresno County occurred mainly during the Pleistocene--a time in which one would have expected fluctuations in the rainfall and runoff. Apparently, increase of precipitation and runoff never was severe enough to cause percolation below the root zone on the Moreno Gulch and Tumey Gulch fans. The Panoche Creek fan would have been more susceptible to changes in streamflow percolation as a result of climatic change because it is an intermittent (instead of ephemeral) stream that flows over a permeable sandy bed, in contrast to clayey deposits underlying the channels of the ephemeral streams on the adjacent fans.

I would not expect the deposits at the apex of the fan (upslope from the 480-foot contour on fig. 1) to be susceptible to compaction due to wetting, because the stream remained on this part of the fan regardless of where it coursed downfan. No prehistoric subsidence crack fillings were found in the banks of Panoche Creek near the fan apex, indicating that moisture-deficient deposits never had accumulated.

Tests made on samples obtained from core holes along the distribution systems should indicate if the deposits are susceptible to appreciable near-surface subsidence. The most useful in my opinion, are tests for moisture content, moisture equivalent, particle-size distribution, and short-term consolidation due to wetting. The moisture-content and moisture-equivalent tests are helpful in determining whether the deposits are at field capacity or are moisture deficient; and will help define the thickness of susceptible materials. The particle-size distribution provides information about the deposits that might be susceptible to compaction due to wetting, but most important, it tells the amount of clay present, which is the element that causes the decrease in strength when the sediment is wetted under load. Short-term consolidation tests provide a useful way of simulating field conditions for those samples considered to be susceptible to compaction due to wetting.

CONCLUSIONS

The Panoche Creek fan was affected by extensive near-surface subsidence in prehistoric times. The erratic distribution of percolation from the stream left a few pockets of deposits susceptible to compaction due to wetting. Such pockets, if they existed along the canal alinement probably have been wetted by agricultural operations, but as much as 3-4 feet of subsidence may occur locally along the distribution systems upslope from the canal in areas that have never been irrigated.

The Panoche Creek fan probably was not the only fan in western Fresno County to be affected by widespread prehistoric near-surface subsidence. I would expect crack fillings, similar to those on the Panoche Creek fan to be found on the Los Gatos Creek fan and possibly on the Cantua Creek fan.

Some of the fans, consisting largely of moisture-deficient deposits, such as the fans of Martinez Creek and Arroyo Hondo, may have local compaction due to wetting as a result of prehistoric flows. The permeable sandy deposits of both of these fans may have allowed some of the longer streamflows to percolate below the root zone on some parts of the fans.

REFERENCES CITED

Bull, W. B., 1964a, Geomorphology of segmented alluvial fans in western Fresno County, California: U.S. Geol. Survey Prof. Paper 352-E, p. 89-129.

_____ 1964b, Alluvial fans and near-surface subsidence in western Fresno County, California: U.S. Geol. Survey Prof. Paper 437-A, p. A1-A71.

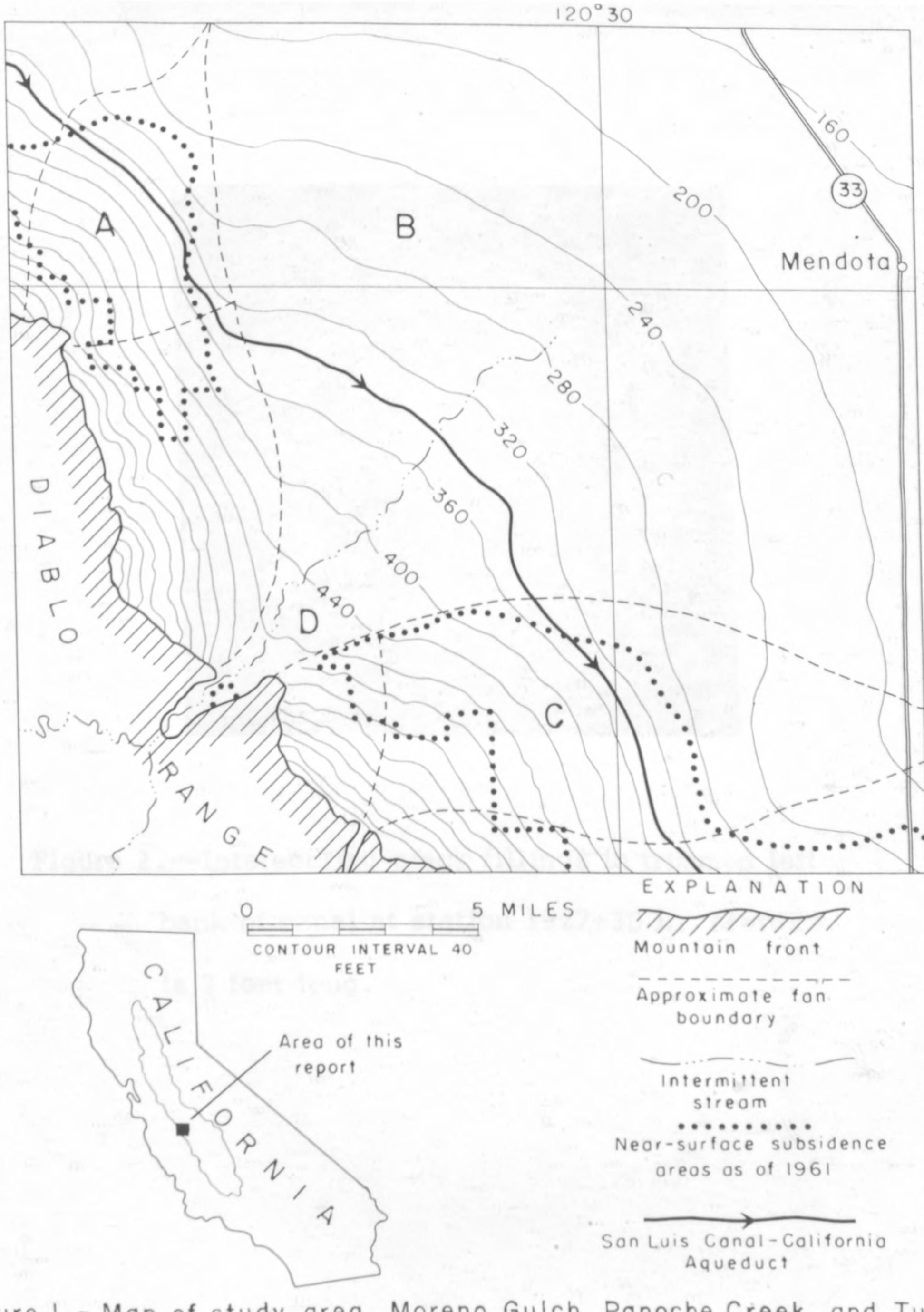

Figure 1.- Map of study area. Moreno Gulch, Panoche Creek, and Tumey Gulch fans are lettered A, B, and C respectively. D is location of small subsidence area shown on figure 5

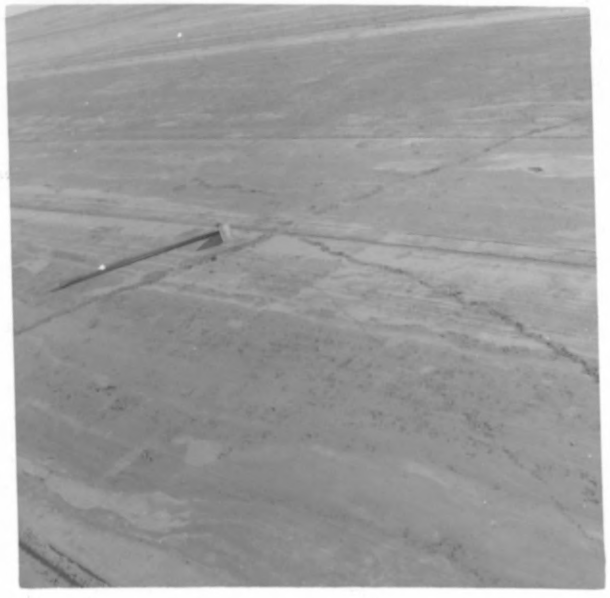

Figure 2.--Intersecting crack fillings in trimmed

bank of canal at station 1927+30 L. Ma

is 3 feet long.

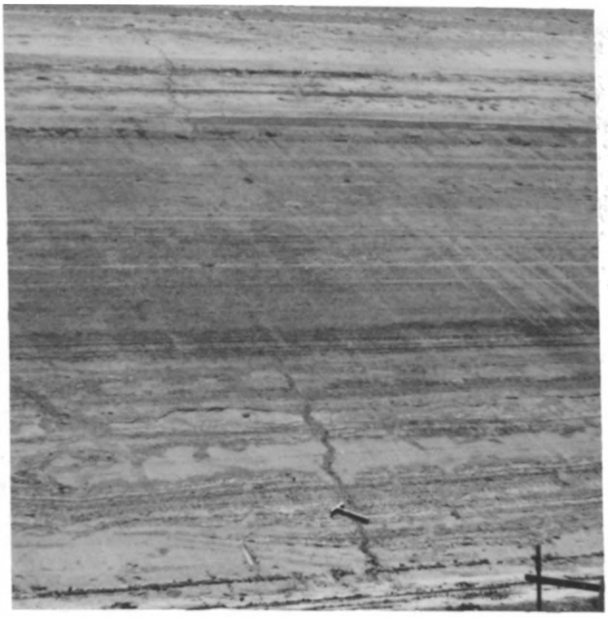

Figure 3.--Crack filling at station 1929+40R. Photograph by Merritt Bradley, U.S. Bureau of Reclamation.

FIGURE 4.—CRACK FILLINGS EXPOSED IN THE TRIMMED BANKS OF THE SAN LUIS CANAL—CALIFORNIA AQUEDUCT ON THE PANOCHE CREEK AND MORENO GULCH ALLUVIAL FANS

Figure 5.--Near-surface subsidence features on the Panoc
fan. Location shown on figure 1. A. Water in sub
hollow along old ditch alinement. Fan slope is tow
B. Powerline poles tilt toward subsidence hollow a
site. Fan slope is toward the right.

Figure 6.--Variation in width of near-surface subside

A. Mendota Test Site.

B. Panoche Creek fan, looking up 2-to-1 slop

bank at station 1921L.

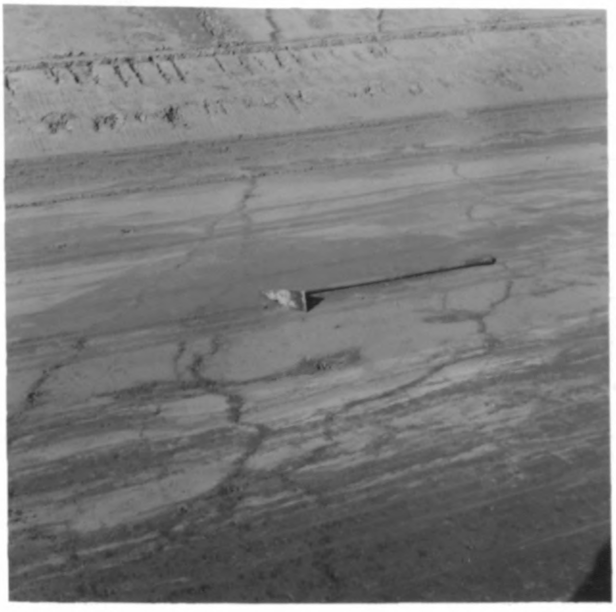

Figure 7.--Anastomosing near-surface subsidence crac

A. Mendota Test Site.

B. Panoche Creek fan. Looking down 2-to-1 s

bank at station 1923+40L.

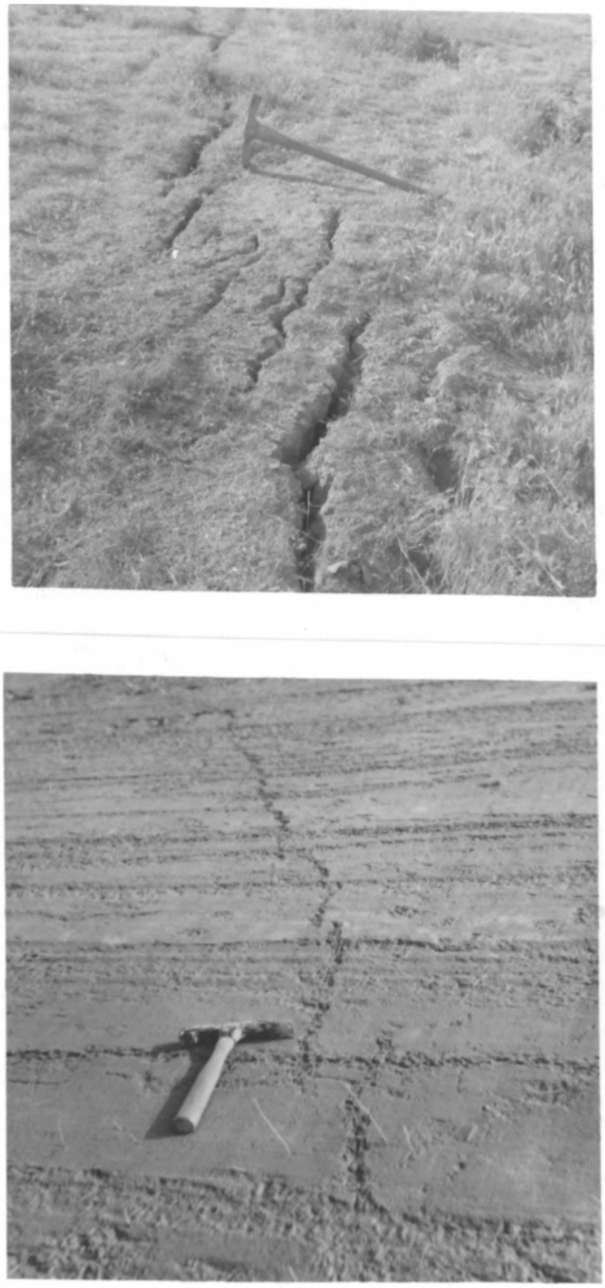

Figure 8.--En echelon near-surface subsidence cracks.

A. Mendota Test Site.

B. Panoche Creek fan. Looking up 2-to-1 slope
bank at station 1846+83L. Photograph by M
Bradley, U.S. Bureau of Reclamation.

Figure 9.--Near-surface subsidence crack junctures.

A. Intercepting cracks at the Mendota Test Site

B. Intersecting cracks on the Panoche Creek fa

up the 2-to-1 canal bank at station 1974+

Figure 10.--Prehistoric near-surface subsidence crack filling in the bank of Panoche Creek.