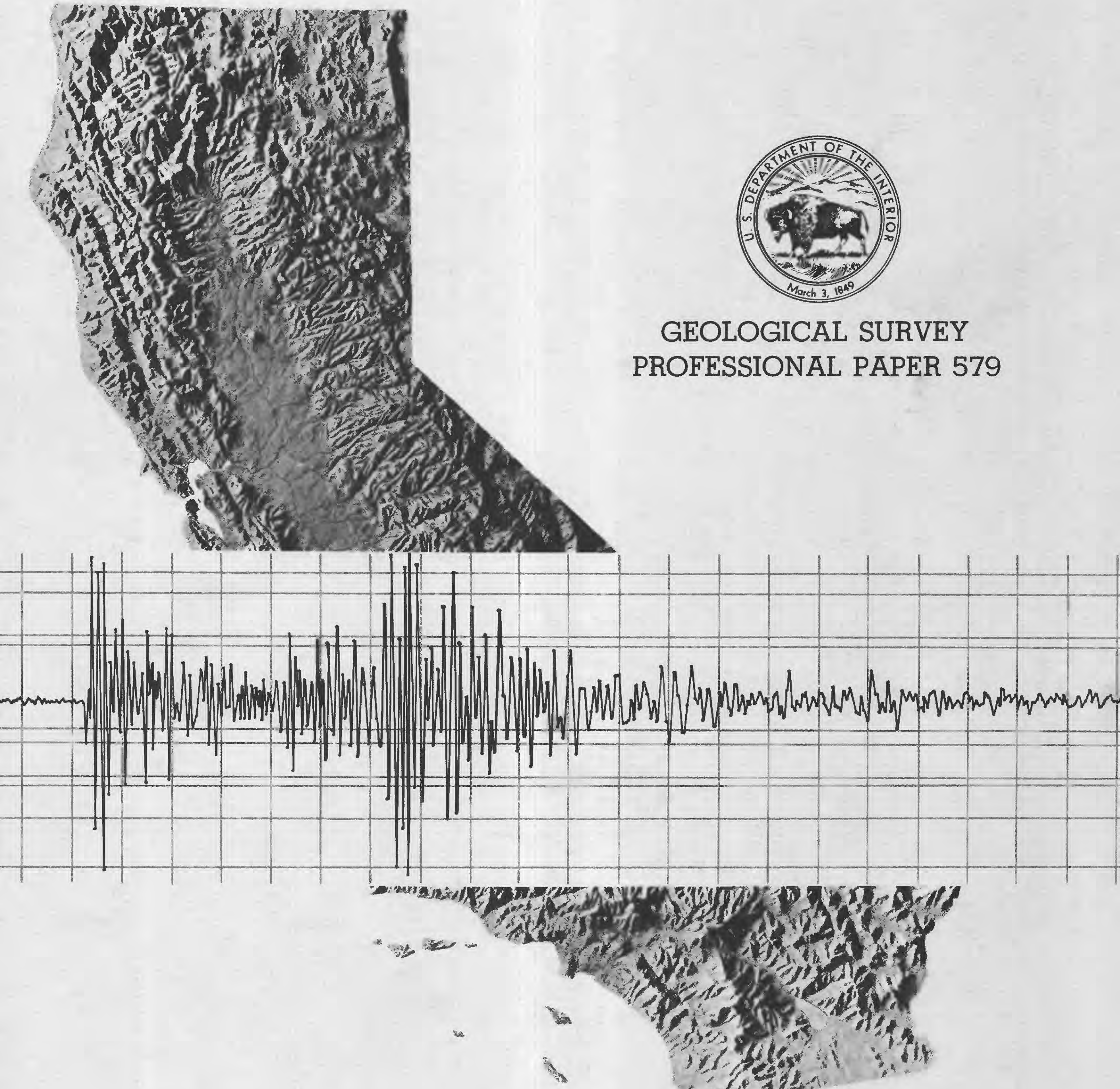
The Parkfield-Cholame California, Earthquakes of June-August 1966



GEOLOGICAL SURVEY
PROFESSIONAL PAPER 579

The Parkfield-Cholame California, Earthquakes of June-August 1966—Surface Geologic Effects Water-Resources Aspects, and Preliminary Seismic Data

By ROBERT D. BROWN, JR., J. G. VEDDER, ROBERT E. WALLACE, EDWARD F. ROTH, R. F. YERKES, R. O. CASTLE, A. O. WAANANEN, R. W. PAGE, *and* JERRY P. EATON

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Results of detailed studies of a moderate magnitude earthquake and its aftershocks

A contribution of the National Center for Earthquake Research of the Geological Survey

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By ROBERT D. BROWN, JR., J. G. VEDDER, ROBERT E. WALLACE, EDWARD F. ROTH, R. F. YERKES, R. O. CASTLE, A. O. WAANANEN, R. W. PAGE, and JERRY P. EATON

ABSTRACT

In the Parkfield-Cholame area of California, an earthquake with a magnitude of 5.5 on the Richter scale occurred on June 27, 1966. This earthquake was preceded by three recordable foreshocks, one of which had a magnitude of 5.1. It was followed by a long series of aftershocks that were monitored for a period of about 2 months by geologists and geophysicists from the National Center for Earthquake Research at Menlo Park, Calif.

Surface tectonic fractures formed in two zones: a main fracture zone 23½ miles long that trends northwest-southeast and a subsidiary fracture zone about 5½ miles long that parallels the main zone and lies about a mile to the southwest. Both zones follow known and previously mapped faults within the San Andreas fault zone.

Fault movement associated with the earthquakes is manifested at the surface chiefly by en echelon fractures. These are oblique (about 30° clockwise) to the trend of the fracture zones, vary in length from a few inches to as much as 20 feet, and exhibit wall separation of an inch or two. The orientation of the en echelon fractures, the separation of recognizable points on fracture walls, and the mounds and pressure ridges in the fracture zones consistently indicate right-lateral strike slip of a few inches. The sense and amount of slip agree with displacement estimates based on geologic evidence and with estimates based on observations of displaced points on the ground.

Fault movement is also shown by other features along the fracture zones—namely, slope failures, offset manmade structures, split or broken trees, sand mounds and sand flows, dust blows and areas of disturbed stones.

Studies of the rates and patterns of progressive slippage, or tectonic creep, for the 2-month period indicate that amounts of displacement range from about 2 inches the first day after the earthquake to 0.01 inch or less per day after a month. Rapid displacements of as much as 0.4 inch may have accompanied an aftershock with a magnitude of about 3. Misalinements of old fences and a bridge record earlier displacements and suggest a rate of between 43 and 80 inches per century, a rate sufficient to account for hundreds of miles of strike slip during Tertiary time.

Of particular significance to engineering geology were the fairly high horizontal ground accelerations (up to 0.5g) and the high Modified-Mercalli intensities (up to VIII or IX) associated with the Parkfield-Cholame earthquake. Tectonic fracturing, ground accelerations, and intensities in this range have generally been correlated with earthquakes having a magnitude of 7 or more on the Richter scale.

Engineering effects of the earthquakes are classed as primary, attributable directly to fault movement, and secondary, attributable to seismic shaking. The primary effects caused minor bending or rending of structures lying athwart the fracture zones, such as a bridge, roads, fences, pipelines, a concrete canal, and a small earthfill dam. Secondary effects caused damage to bridges, chimneys, unreinforced masonry walls, wooden floors and walls, and plumbing fixtures. Both light and heavy objects were shifted, overturned, or thrown in directions approximately normal to the major fracture zones.

The relatively minor damage associated with the earthquakes may be explained by the small number of manmade structures in the area, the narrowness of the fracture zones, and the confinement of the higher intensities to a narrow band in the alluviated Cholame Valley.

There were no indications of significant changes in the base flow of streams, water levels in wells, or quality of water. Fluctuations in water levels were recorded, however, at gaging stations and at ground-water observation wells.

Instrumental seismic studies have shown that the sudden slippage associated with the main Parkfield-Cholame earthquake began about 8 kilometers northwest of Parkfield and extended southeastward along the San Andreas fault. Preliminary results from a detailed study of aftershocks in the southeastern half of the area indicate that hypocenters are 2–12 kilometers deep and are almost directly under the surface trace of the main fracture zone.

INTRODUCTION

By ROBERT D. BROWN, JR.

The Parkfield-Cholame earthquakes of June to August 1966 afforded new and significant insight into earthquake effects and fault movement along the San Andreas fault zone. The earthquakes and their aftershocks were accompanied by horizontal (right-lateral) movement localized along two fracture zones, one of them at least 23½ miles long. Fracturing and displacement along these zones were not instantaneous but were progressive and continued at a decreasing rate for more than a month after the first and strongest earthquakes. In general, the surface effects of the Parkfield-Cholame earthquakes are more extensive and pronounced than in earthquakes of similar magnitude although damage was relatively minor in the lightly populated epicentral area.

This report summarizes surface effects, preliminary seismic data, and effects on water resources that were investigated by the U.S. Geological Survey during the period from June 28 to August 5, 1966. During this period both seismic activity and differential surface movements diminished in intensity and frequency; consequently, the surface measurements and other data presented here are virtually complete. On the other hand, masses of instrumental data from seismograph stations are still being analyzed and interpreted.

The surface effects described here fall into three categories: surface tectonic fracture zones, rates and patterns of deformation, and engineering geology aspects. The surface tectonic fracture zones were located, mapped, and described chiefly by Robert D. Brown, Jr., and J. G. Vedder; Reuben Kachadoorian and Julius Schlocker traced part of the main fracture zone, and many of their observations and conclusions are incorporated. R. E. Wallace provided the detailed maps of the fractures that are included in the section on tectonic fracture zones. Rates and patterns of deformation were determined by repeated measurements at 10 strain quadrilaterals and by observations at other selected localities. The quadrilaterals were installed and measured by Edward F. Roth, assisted by Gary Hamilton. Wallace made supplemental observations and detailed studies of fracture-zone segments, and Wallace and Roth together compiled and interpreted the data on strain rates and patterns. Data pertinent to engineering geology were gathered and interpreted by R. F. Yerkes and R. O. Castle; significant contributions were made by M. G. Bonilla and C. M. Wentworth. Effects of the earthquakes on the water resources of the area were studied by A. O. Waananen and R. W. Page. Jerry Eaton was in charge of the U.S. Geological Survey seismograph network and provided the preliminary seismic data presented here.

The investigations of the U.S. Geological Survey represent a part of the total scientific effort devoted to the Parkfield-Cholame earthquakes. Other Federal and State agencies, several universities, and many individual geologists explored various aspects of the earthquakes; coordination between investigators was arranged informally in the field, largely through personal contact. We gratefully acknowledge the cooperation afforded us by the other investigators, most of whom are cited individually in this report.

We are also indebted to many residents of the Parkfield-Cholame area, and to others outside the epicentral area, who freely recounted their observations at the time of the earthquake, permitted us access to private lands, and generously provided information pertinent to this study. A few of these people are named in the pages that follow, many are not, but all contributed significantly to the results reported here.

Only a summary of the vast amount of earthquake data collected by the U.S. Geological Survey can be included in published reports. Scores of photographs, detailed maps, sketches, field notes, seismograph records, and a variety of measurements and random observations which record earthquake effects in detail are too bulky or too repetitious to incorporate in a publication. Yet much of this information may be invaluable to future workers along this segment of the San Andreas fault, for it represents the original source material keyed to specific recoverable points on the ground. Many of these records systematized and cataloged are available for public inspection. An album of photographs and detailed maps of the earthquake effects are on file at the Photographic Library of the U.S. Geological Survey, Denver, Colo., and at the U.S. Geological Survey Library at Menlo Park, Calif.

SURFACE TECTONIC FRACTURES ALONG THE SAN ANDREAS FAULT

By Robert D. Brown, Jr., and J. G. Vedder

RELATION OF THE EARTHQUAKES TO GROUND BREAKAGE

Seven earthquakes of moderate magnitude occurred in the Parkfield-Cholame area of west-central California (fig. 1) during a 45-hour period on June 27, 28, and 29, 1966.[1] These earthquakes, ranging in magnitude from 3.5 to 5.5 on the Richter scale, were among the largest of a complex succession of earthquakes which began with two relatively light foreshocks (magnitude 2–3) at 6:00 p.m. and 6:15 p.m. on June 27 (McEvilly, 1966, p. 967). These were followed at 9:09 p.m. by a much stronger foreshock (magnitude 5.1). The main earthquake, magnitude 5.5, occurred at 9:26 p.m. and was followed by a series of aftershocks that continued for a period of many weeks. Despite the frequency of aftershocks and the duration of the aftershock sequence, most surface fractures were formed

[1] Dates and times are expressed as Pacific daylight time (P.d.t.). Add 7 hours for Greenwich mean time.

during the 45-hour period of earthquakes shown in table 1.

TABLE 1.—*Parkfield-Cholame earthquakes of magnitude 3.5–5.5 June 27–29*

[Data from T. V. McEvilly, University of California Seismographic Station Sept. 14, 1966]

Date	*Time (P.d.t.)*	*Magnitude*
6–27–66	9:09 p.m	5. 1
	9:26 p.m	5. 5
	9:29 p.m	4. 5
	9:32 p.m	3. 5
6–28–66	7:19 p.m	3. 6
6–29–66	12:53 p.m	5. 0
	6:17 p.m	4. 1

Observations along the fracture zones and information supplied by local residents indicate that the surface fracture pattern was formed at somewhat different times in different parts of the Parkfield-Cholame area. The specific time of fracturing could not be determined, but according to Mrs. Louise Kester, fractures in front of the Kester house, 1½ miles northwest of Parkfield, were first noted on the morning of June 28. These fractures probably opened during the earthquakes of the preceding evening.

A cursory examination of the county road to Parkfield, 3.0 miles north of Highway 46, disclosed no cracks in the road on June 29 although tectonic fractures were observed a few hundred feet to the south (Reuben Kachadoorian, oral commun., June 30). The following day, June 30, tectonic fractures were clearly evident in the road surface. Similarly, the ground where pipelines cross Cholame Valley (about 0.2 mile south of the Highway 46–Parkfield road junction) had no obvious fractures on June 28 possibly because the fractures were masked by desiccation cracks; yet on June 29 tectonic fractures were well defined there (R. E. Wallace, oral commun., June 29). Another example of postearthquake fracturing was documented by Mr. Max Wyss, a graduate student at the California Institute of Technology. To measure deformation along the fracture zone, Mr. Wyss occupied a theodolite station ("Parkfield," fig. 2) several times during the period July 7 to August 8. On July 7 and 13 no fractures were visible at this station, but fractures as much as 5 feet long and ½ inch wide were clearly visible when the station was occupied on July 19. By August 8 numerous fractures as much as 2 inches wide were evident (Max Wyss, oral commun., Aug. 10).

Some parts of the fracture zones possibly were formed before the earthquakes, but evidence for preearthquake deformation is sparse. Allen and Smith (1966, p. 966) report that fresh-appearing en echelon cracks were visible along the fault trace 1.7 kilometers (about 1 mile) southeast of Parkfield as early as June 16, 1966, 11 days before the earthquakes. These were estimated to be no more than 1 month old on June 16 (Allen and Smith, 1966, p. 966).

Ground breakage of several kinds resulted from the earthquakes. Much of it resulted from the failure of unstable slopes or the settling of uncompacted materials during ground shaking. Some fractures, however, are closely spaced along narrow linear zones and are clearly the surface manifestations of differential movements at depth. These tectonic fracture zones are characterized by a distinctive en echelon pattern, by uniformity in trends of both the fractures and the zones containing them, by their location along known and previously mapped fault traces, and by abundant evidence of uniform relative movement of the blocks juxtaposed by the fracture zone. This section of the report is concerned chiefly with the surface fractures which are believed to be a direct result of tectonic movements; however, in a few places it is difficult to distinguish clearly between tectonic fractures and fissures formed by subsidence, slope failure, or desiccation within the zone of tectonic movement.

Preliminary determinations of epicenters for 85 Parkfield-Cholame earthquakes of magnitude 2 or greater have been made by McEvilly (1966, p. 968, fig. 5). His data show that the epicenters lie along a zone trending about N. 45° W. and that most of them lie along a 12-mile segment of this zone. The center of this segment is near the town of Parkfield. The epicenters lie along or near the tectonic fracture zones, but they are most numerous in the northern two-thirds of the fracture zones. The three main shocks shown by McEvilly are about 6 miles northwest of Parkfield near the northernmost limit of recognizable tectonic fracture.

SAN ANDREAS FAULT ZONE

Preliminary seismic data (McEvilly, 1966) and the geologic evidence afforded by mapped tectonic fracture patterns show that the Parkfield-Cholame earthquakes were largely, if not entirely, confined to a 23½-mile-long segment of the San Andreas fault zone (fig. 1). This fault zone is 600 miles or more in length and trends generally northwestward from the Gulf of California in northern Mexico to Point Arena on the northern California coast. Rocks of profoundly different character and age are commonly found in juxtaposition on opposite sides of the fault zone. Geomorphic and geologic evidence shows that throughout late Quaternary time, the southwest block has moved northwestward relative to its counterpart across the fault zone. Although the total displacement along the fault zone and its age are both uncertain, available geologic evidence suggests a total right-lateral displacement of more than 150 miles and a record of movement extending at least 60 million years into the past. The largest documented historic displacement from a single earthquake or earthquake sequence—21 feet right-slip—is reported by Lawson (1908, p. 53),[2] but slow tectonic creep of opposing blocks, amounting to a few tenths of an inch per year, has also been observed and measured at several localities along the zone and on related faults branching from it (Steinbrugge and Zacher, 1960; Tocher, 1960, 1966; Whitten and Claire, 1960; Radbruch and Lennert, 1966; Blanchard and Laverty, 1966; Bonilla, 1966; Cluff and Steinbrugge, 1966).

Faulting within the San Andreas zone is distributed along nearly parallel or anastamosing faults that differ in age of movement and in amount of total relative displacement. This complex zone varies in width from a few tens of feet to several thousand feet and in some parts of the Parkfield-Cholame area is as wide as 5,000 feet. Because of its width and complexity, it is termed the "San Andreas fault zone," and in accordance with usage first suggested by Noble (1926, p. 416–417), it is distinguished from the San Andreas fault, the surface trace of most recent (in many places, historic) movement.

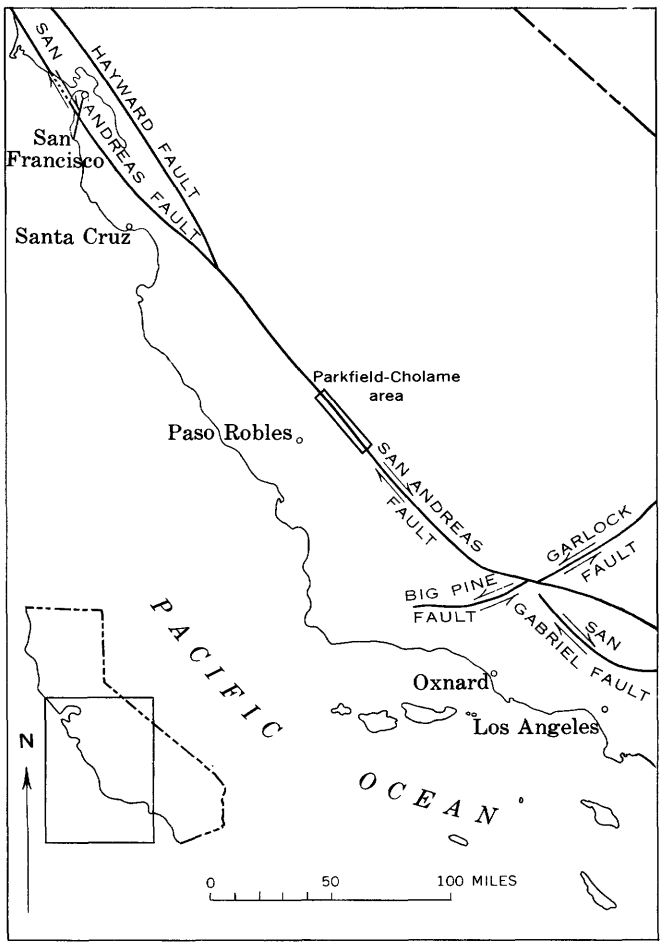

FIGURE 1.—Part of the San Andreas fault zone and the location of the Parkfield-Cholame area.

[2] This figure may be excessive; it seems to be based on statements by G. K. Gilbert (in Lawson, 1908, p. 71). Gilbert reports 20 feet of offset in a road southwest of Point Reyes station, but he points out that the embankment of the road rested on marshy ground, and he suggests that the "exceptionally great offset at this point [probably] is to be explained as a result of horizontal shifting of the surface materials." In the same section Gilbert, without qualification, cites several offsets of about 15 feet, and these may represent a more realistic maximum for the 1906 earthquake.

In the Parkfield-Cholame segment of the San Andreas fault zone, two fault traces were easily recognizable, both on the ground and on aerial photographs, before the June 1966 earthquakes. Parts of these traces had been identified as active strands of the San Andreas as early as 1908 (H. W. Fairbanks, in Lawson, 1908, p. 40, pls. 19B, 20A, B), and both traces showed evidence of geologically recent movement as judged by such criteria as stream and terrace offsets, shutter ridges, offset fence lines, sag ponds, and other alined topographic features.

The most continuous trace, here considered the main trace of the San Andreas fault (fig. 2), trends approximately N. 40–45° W. From north to south, this trace closely parallels and in places follows the crest of Middle Mountain, passes beneath the highway bridge 0.3 mile south of Parkfield, and extends along the northeast side of Cholame Valley southward to Cholame Ranch. Before the June 1966 earthquakes, this trace was ill defined from Cholame Ranch southeastward to a point about 2½ miles northwest of Highway 46. Southeast of that point alined topographic features clearly marked the trace.

The second trace, nearly parallel to the first and less than a mile southwest of it, extends about 7 miles, from a point on the Parkfield-San Miguel road 1.8 miles northwest of Parkfield southeasterward to the Cholame Ranch Grant Boundary in the upper part of Cholame Valley.

The faults associated with both of these traces were reactivated during the June 1966 earthquakes, and both traces formed loci for tectonic fracturing of the ground at the surface. With a few exceptions, the mapped tectonic fracture zones precisely followed the trace of the earlier fault movements.

GEOLOGY

Two crustal blocks with strikingly different geologic characteristics are brought together by the San Andreas fault (fig. 3). The geology of these two blocks is known from surface mapping and from a few drill holes, but no comprehensive summary of these data is available. The geological summary presented here is based on published data by Jennings (1958), Marsh (1960), Dickinson (1963, 1966a, b), Hay (1963), and Smith (1964) and on unpublished geologic maps and other data supplied by T. W. Dibblee, Jr.

In the crustal block southwest of the fault trace, granitic rocks of late Mesozoic age (Curtis and others, 1958, p. 9–14) crop out locally, or are buried to depths no greater than 6,000 feet below sea level (Smith, 1964). The upper surface of these rocks in much of the Parkfield-Cholame area is 1,000–5,000 feet below sea level; however, the rocks crop out northwest and west of Parkfield and about 8 miles south of Cholame. Geologic maps and records of several drill holes show that the granitic rocks are unconformably overlain by marine and nonmarine sedimentary and volcanic rocks of Tertiary (chiefly middle and late Miocene and Pliocene) age and by Quaternary deposits that are chiefly nonmarine in origin. These stratified rocks are tightly folded along northwest-trending axes near the San Andreas fault zone, but a mile or so away from the fault zone the folds are open and have dips of 10°–20°. The intensity of structural deformation decreases southwestward away from the fault zone. The stratified rocks of Quaternary age, which at the surface are the most widely distributed geologic units, dip a few degrees toward the south or southwest. A part of this dip is due to regional tilting although some of it may be initial. The relatively simple structure and stratigraphy of the southwestern block are apparently related to the strength and stability of the granitic basement.

The block northeast of the San Andreas fault exhibits evidence of a far more complex geologic history. In this block, the depth to crystalline basement rock is unknown, but available geologic data indicate it is well in excess of 14,000 feet. Crystalline rocks of varied composition and origin that crop out along the northeast side of the San Andreas fault, particularly in Middle Mountain and at Gold Hill, are probably slivers enclosed by older branches of the San Andreas fault. One of these at Gold Hill has a radiometric age of at least 143 million years (Hay, 1963, p. 113). The original site of these rocks is uncertain; they may have been derived by faulting from the block that now lies west of the San Andreas fault, or they may be fault slices derived from crystalline basement rocks that underlie the eastern block. In either event, their proximity to the San Andreas fault and their relations to surrounding rock units suggest that they have been shifted laterally for great distances from their original position.

Apart from these crystalline rock masses, the oldest confidently dated exposed rock unit northeast of the San Andreas fault in the Parkfield-Cholame area is a thick relatively uniform sequence of marine siltstone and sandstone of Cretaceous age. In the Orchard Peak area, about 10 miles northeast of Cholame, these rocks are at least 20,000 feet thick (Marsh, 1960, p. 3), and similar or greater thicknesses have been recorded at widely separated localities northeast of the San Andreas fault. The Cretaceous strata are unconformably overlain by a thick and varied succession of marine strata of Tertiary age, chiefly Eocene, Miocene, and Pliocene. Some continental deposits are interbedded in this sequence, and they are relatively common in the upper part. The strata of Tertiary age are lithologically diverse and are characterized by both vertical and horizontal facies changes, local and regional unconformities, and extreme variations in thickness and in stratigraphic relations. Because of their variability, thickness estimates are approximate, but a cumulative average thickness of 15,000 feet seems probable throughout much of the Parkfield-Cholame area. Continental deposits of Quaternary age overlie the Tertiary rocks in most places with angular unconformity. The youngest of the Quaternary lithologic units are coextensive with similar units southwest of the San Andreas fault, but rocks of early Quaternary age are steeply tilted and disrupted along the fault and are difficult to match across it.

Structural relations in the northeastern block are complex. The rocks are moderately to strongly folded along northwest-trending axes. They are broken by a system of northwest-trending faults that have sinuous traces and that exhibit evidence of right-lateral displacement. The intensity of deformation increases southwestward, and near the San Andreas fault overturned folds and folded structural trends are common. In addition to the many high-angle faults, most of which branch from or are subparallel to the San Andreas fault zone, major faults separate the Cretaceous strata and younger rocks from an intensely brecciated and cataclastically reconstituted mélange, which, together with tabular serpentine masses and mafic volcanic rocks, constitutes the lowest known structural unit in the northeastern block. These intensely deformed rocks have been considered a stratigraphic unit—the Franciscan Formation or Group of various workers. Dickinson (1966a, p. 462; 1966b, p. 709) considers the unit to be a megabreccia formed along a folded thrust fault of regional extent. This interpretation appears to fit the field relations in the Parkfield-Cholame area better than any other. Although a full evaluation of the theories regarding the Franciscan problem is beyond the scope of this report, these rocks clearly record a history of complex deformation that is not evident in the southwestern block.

Landslide deposits are distributed sporadically on both sides of the San Andreas fault and are particularly

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EXPLANATION

Tectonic fracture zone
Solid where pattern is clearly defined and continuous; dotted where it could not be followed with confidence

F–1
Data collection point

R–1
Brass markers showing main fracture zone; no R–4

QD
Strain quadrilateral

×
C I T Parkfield
California Institute of Technology theodolite station

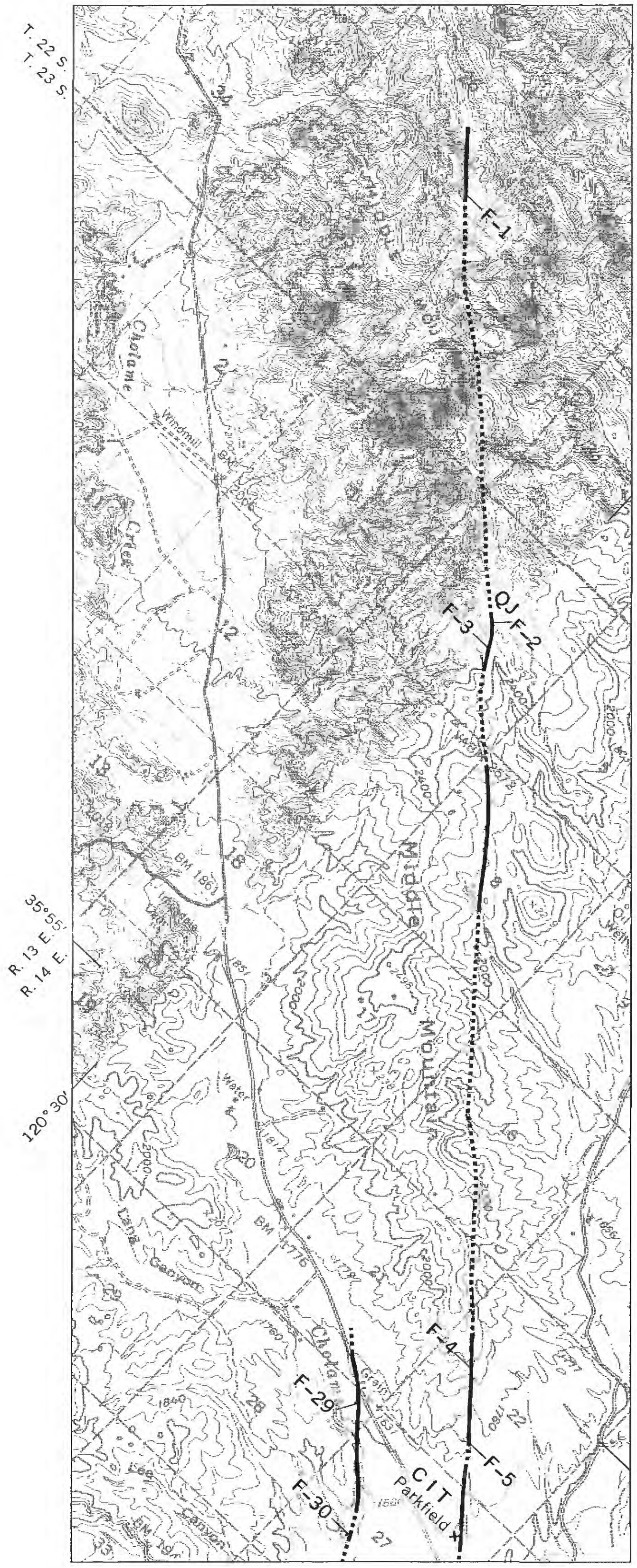
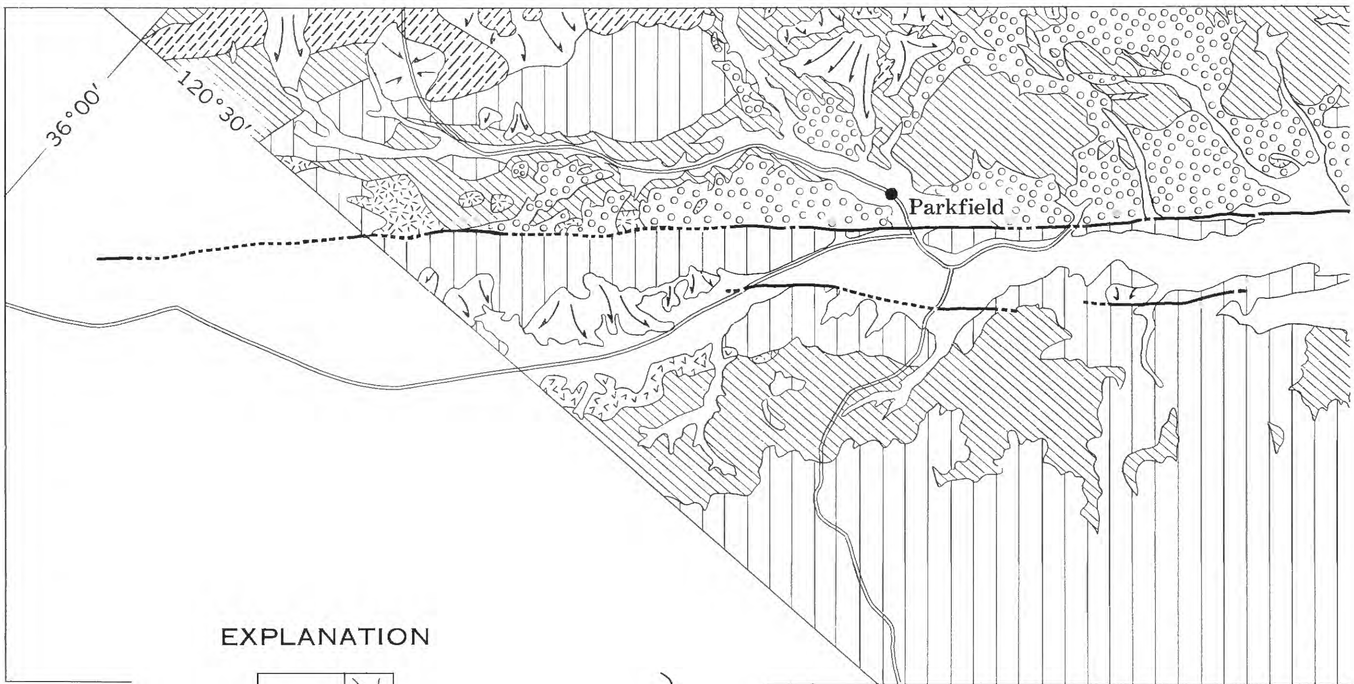


FIGURE 2.—Location of tectonic fracture zones and points used for strain measurement.

FIGURE 2.—Continued



EXPLANATION

Alluvium and landslide debris

3 subunits recognized:
Alluvium, flood-plain and stream deposits (unpatterned) of unconsolidated sand, silt, and gravel
Landslide debris. Arrows show inferred direction of movement
Older alluvium, flood-plain and stream deposits (circled pattern) of semiconsolidated sand, silt, and gravel; in most places near or along existing drainage systems

QUATERNARY

Paso Robles Formation

Sedimentary rocks of continental origin; chiefly poorly consolidated clay, silt, sand, and gravel. May contain some strata assignable to units other than the Paso Robles

Sedimentary rocks

Well to moderately indurated clastic rocks variable in lithology but dominantly sandstone, shale, and conglomerate. Chiefly of marine origin except in upper part. Tertiary part of unit contains numerous unconformities and is characterized by abundant facies changes. Contains strata of Cretaceous age only on the northeast side of the San Andreas fault

Volcanic rocks

Rhyolite and obsidian of Miocene (?) age

TERTIARY

CRETACEOUS

Crystalline rocks of intrusive and metamorphic origin

Hybridized metamorphic and igneous rocks along and within the San Andreas fault zone

JURASSIC AND JURASSIC(?)

ROCKS OF UNCERTAIN STRATIGRAPHIC POSITION

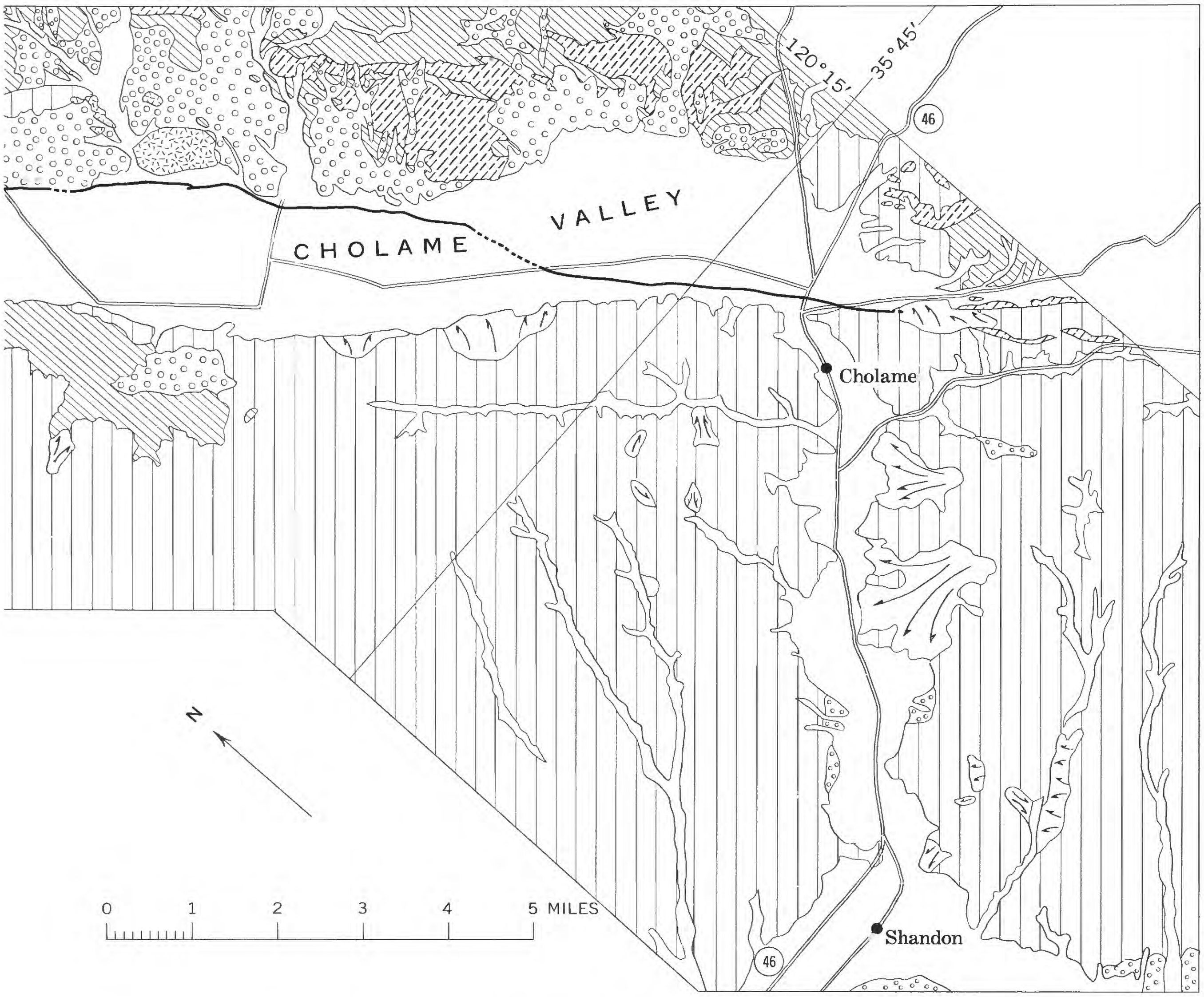
Tectonic complex

Megabreccia and shear-zone debris derived chiefly from sedimentary and igneous rocks generally assigned to the Franciscan Formation. Includes tabular and lenticular bodies of serpentine. Confined to San Andreas fault zone and area northeast of it

Fracture zone of June–July 1966

Dotted where location is uncertain (other faults are not shown)

FIGURE 3.—Generalized geologic map of Parkfield-Cholame area, modified from Jennings (1958), Marsh (1960), Dickinson (1963, 1966a, b) and unpublished maps by T. W. Dibblee, Jr.



FIGURE—3. Continued

widespread and abundant on Middle Mountain and in the area northeast, east, and southeast of Parkfield. Many of the landslides show evidence of geologically recent preearthquake movement, and most of these were reactivated during the June earthquakes.

HISTORICAL EARTHQUAKES ACCOMPANIED BY SURFACE FRACTURE

January 9, 1857.—The earliest known record of surface fracture by earthquakes in the Parkfield-Cholame area is in unpublished field notes by H. R. Johnson written in 1905. These notes apparently were taken during an interview with a resident of the district who had observed the effects of the great Fort Tejon earthquake. From these notes, it can be surmised that fractures were traced near the head of Cholame Creek. A partial quotation follows:

> Oak tree on crack cut off at stump and thrown toward west—head of tree dropped on stump. Corral [rectangular sketch] 150 by 100 [offset in a right-lateral sense on sketch] vert. shift of about 2 feet. Mr. Tracy in '61 traced crack into San Benito County. Above Duasno [?] (Peach Tree Ranch) near Indian Creek not so well defined.

H. W. Fairbanks (in Lawson, 1908, p. 41) was informed by people living in Cholame Valley that the

> first settler in Cholame Valley was erecting his cabin at the time, and it was shaken down. The surface was changed and springs broke out where there had been none before.

March 2, 1901.—According to Townley and Allen (1939, p. 114), H. F. Reid informed Homer Hamlin that there were surface cracks, some of which were hundreds of feet long and 6–12 inches wide; at places there was vertical offset of 1 foot. A resident of Cholame Valley told H. W. Fairbanks (in Lawson, 1908, p. 40–41) that an opening formed that was traceable for several miles. Near Parkfield a crack formed in a road and was successively reopened or widened by aftershocks. Mr. F. M. Van Horn of Parkfield recalls having seen newly formed cracks on the west side of Cholame Valley after this earthquake, and water spouts at several points in the valley.

March 10, 1922.—Cracks 6–12 inches wide opened in the ground for a quarter of a mile in Cholame Valley (Townley and Allen, 1939, p. 224).

June 7, 1934.—Two earthquakes about 18 minutes apart rocked the Parkfield district. According to Graham B. Moody (in Byerly and Wilson, 1935, p. 233)

> two zones of cracks were developed in the soil on the northeast and southwest edges of the crest of Middle Mountain for a distance about 2 miles northwest of Parkfield. These zones paralleled and were close to the surface traces of two faults in the San Andreas zone. The zones of cracks were about 25 feet wide. The individual cracks were arranged en echelon. The longest single crack was about 55 feet long, 9 inches wide, and 18 inches deep. There was no evidence that the cracks penetrated into the underlying sandstones and shales, nor of vertical or horizontal displacement along the cracks.

Based on field evidence he further states (p. 235) that the

> epicentral area may be considered to extend about 7 miles northwest and about 5 miles southeast of Parkfield.

In August 1966, Mr. Herbert H. Durham of Parkfield took R. E. Wallace to the site of fractures that he remembered were produced during the earthquake of 1934. Mr. Durham noted that the 1934 fracture zone crossed the Turkey Flat road about 25 feet west of the present fracture zone and that in 1934 the cracks were from 6 to 8 inches wide, so wide "that I couldn't get my team to cross." Both in 1922 and 1934, water came to the surface in the dry creek bed at this point and flowed for several months. Although he remembered fractures at the same locality after the earthquake of 1922, he was not so certain of their exact position with respect to the recent fracture zone. In 1934, Mr. Durham photographed a fissure produced during the earthquake (fig. 4). Where the fissure was photographed in 1934, an 8-inch-high scarplet formed in 1966. The scarplet is at the head of a small landslide in the NE¼ sec. 7, T. 24 S., R. 15 E.

Within the same region, shocks of magnitude 5 occurred on December 24, 1934, December 28, 1939, and November 16, 1956 (McEvilly, 1966, p. 970).

It is evident that the Parkfield district is one of the most seismically active segments of the San Andreas fault zone, a condition that was noted by H. W. Fairbanks as early as 1908 (in Lawson, 1908, p. 40).

FIGURE 4.—Landslide fissure produced by the Parkfield earthquake of June 7, 1934; this landslide was reactivated by the 1966 earthquakes. Photograph by Herbert H. Durham.

METHODS OF STUDY

The fracture zones were traversed on foot during the period June 29 to July 15, 1966. The data gathered in all well-defined parts of the zones were plotted on vertical aerial photographs (approx. scale, 1:5,000) taken on March 3, 1966, by the U.S. Geological Survey; or where photographic coverage was incomplete, on 1:24,000 topographic maps.

Several months before the earthquake, the inferred traces of recent faults in the Cholame Valley area, as determined by photointerpretation and field checking, were plotted. These lines proved very useful in locating and tracing the recent fracture zones.

To a person on foot, recognition of the zones and observation of the details of fracture relations within them was hindered by his low angle of view, by the absence in most places of any significant vertical displacement on the fractures, and by grass and other vegetation which effectively screened the smaller fractures. These obstacles were partly overcome by using low-altitude photographs. These were taken by the U.S. Geological Survey at approximately 600 feet above the terrain (scale about 1:1,200) on July 30, 1966. The photographs show the fracture pattern at many places and are useful for estimating measurements; cracks as narrow as 2 inches and as short as 4 feet are visible.

Another useful technique, one that permits detailed analysis of the fracture pattern within segments of the zone as much as 400 feet long, consisted of taking vertical photographs of short sections of the fracture pattern from a 5-foot stepladder. By tracing overlapping exposures, relatively accurate sketch maps of fracture relations were compiled.

A 4-mile segment of the main fracture zone was marked with brass markers (fig. 2) attached to 5-foot steel rods. These were set within the fracture zone to be used as future reference marks.

FRACTURE ZONES

GENERAL RELATIONS

Two well-defined fracture zones were mapped. The longest, here referred to as the main fracture zone, was traced almost continuously for 23½ miles. A discontinuous subsidiary zone, about 5½ miles long, approximately parallels the main fracture zone, and lies 0.6–0.9 mile southwest of it; it is here referred to as the southwest fracture zone. The location of both zones is shown in figure 2. The fracture zones are indicated by solid lines to avoid excessive exaggeration of zone widths; in the field, the fracture zones are defined in most places by en echelon fractures. Both zones vary somewhat in width along their trends, but in most places they are no more than 10 feet wide. The maximum width observed was about 20 feet at locality F18 (fig. 2 and table 2).

Both fracture zones are along preexisting fault traces within the San Andreas fault zone, and generally they follow topographic lineaments marked by sag-pond depressions, low scarplets, narrow benches, shallow swales, and offset drainages. The recent fracture zones, however, do not always show a consistent relationship to topography. In some places they extend along the base of a scarplet, in others along its steeper face or crest, and in many places the zones are slightly oblique to the trend of topography and cross topographic features transversely (fig. 5*A*). In Cholame Valley,

TABLE 2.—*Characteristics of fractures along the main and southwest fracture zones*

Locality (fig. 2)	Trend of fracture zone	Width of fracture zone (feet)	Trend of fracture	Maximum length of fractures (feet)	Spacing of fractures (feet)	Maximum fracture wall separation (inches)	Right-lateral separation (inches)	Remarks	Date (1966) and observer [1]
Main fracture zone									
F1	N. 37° W.	2	N. 14° W.	5				Irregularly spaced fractures.	7-13/JV
F2	N. 37° W.	3-4	N. 13° W. to 17° W.	12					7-13/JV
F3	N. 41° W.	6	N. 9° W.	6	2-3	2			7-13/RB
F4	N. 30° W.	3	N. 15° E.	3	1½	1			7-7/RB
F5	N. 38° W.	2	N. 6° W. to N. 12° W.	8		2-3			7-6/JV
F6	N. 43° W.		N. 10° W.	15	1½	1			7-6/RB
F7	N. 40° W.	10	N. 15° W.	8-10	1-2	1-2	None		7-6/RB
F8	N. 40° W.	6	N. 20° W.	20	2-3	2-3	None		7-6/BR
F9	N. 44° W.	2-3	N. 5° W. to N. 11° W.	6	1-3	½			7-6/JV
F10	N. 44° W.	4	N. 10° W. to N. 15° W.	1-8	1½	½		Parkfield-Cholame road (paved).	7-6/JV
F11	N. 42° W.		N. 5° W. to N. 15° W.	4-6	3½	½		Wooded; thick grass cover.	7-6/JV
F12	N. 42° W.	3-4	N. 23° W.	6-12	1-5	1½			7-6/JV
F13	N. 50° W.	3	N. 20° W.	2		1		In unimproved ranch road.	7-6/RB
F14	N. 40° W.	2	N. 10° W.	2	3				7-6/RB
F15	North to N. 40° W.	2	North to N. 40° W.	20	2-6	1		Linear fractures.	7-6/RB
F16	N. 50° W.	6	N. 10° W.	2	2-10	1½			7-6/RB
F17	N. 5° E.	2½-3	N. 5° E.	2-3+				Linear fractures.	7-6/RB
F18	N. 40° W.	20+	N. 10° W.	20	1-3	2	1½-2½	(Duplicate note by JS on 7-1 shows less fracturing.) Mole tracks and pressure ridges.	7-5/RB
F19	N. 40° W.		N. 15° W.	4-12		1-2		Thick grass cover.	7-5/RB
F20	N. 12° W.	1-5	N. 10° E. to N. 40° E.	3-4	3-4	½		Parkfield-Cholame road (paved). Cracks not found on 6-30.	7-1/JS
F21	N. 35° W.	5	N. 5° W to N. 15° E.	20	1-50	1			6-30/JS
F22	N. 30° W.	5½	N. 5° W. to N. 10° E.		2-5	4	2-3	Scissors movement—east walls raised 1-2 in. at south end, lowered 1-2 in. at north end.	6-30/JS
F23	N. 38° W.		N. 12° W. to N. 12° E.	15	7	5½	2	Scissors movement—east walls raised 1.4 in. at south end, lowered 1.2 in. at north end.	6-30/JS
F24	N. 37° W.	3-4	N. 5° W. to N. 10° W.	6	2-10	3		Mole track at places NW of here.	7-1/JV
F25	N. 37° W. to N. 45° W.	5-15	North to N. 16° W.	10				Mole track.	6-30/JS
F26	N. 36° W.	4		15+	2-5			Linear cracks SE of here, down on SW.	6-30/JV
F27	N. 29° W.	10	N. 20° W. to N. 25° W.	7	2-6	1.2	1-1.4	Meng road (paved). SE side raised 1 in.	7-1/JS
F28	N. 35° W.		N. 5° W. to N. 15° W.	3		2	½	Irregularly spaced fractures.	7-1/JS
Southwestern fracture zone									
F29	N. 49° W.	6	North	4-5	1	½	½	Cholame-San Miguel road (paved).	7-14/RB
F30	N. 35° W.	6	N. 10° W.	6	1-3	½			7-14/RB
F31	N. 40° W.	12	N. 5° E.					Hog Canyon road (paved).	7-7/RB
F32	N. 40° W.	15	N. 20° W.	15	1½	½			7-14/RB
F33	N. 25° W.	3	North	6-8	1-2	2	1		7-12/RB

[1] Observers are RB, R. D. Brown; JS, Julius Schlocker; JV, J. G. Vedder.

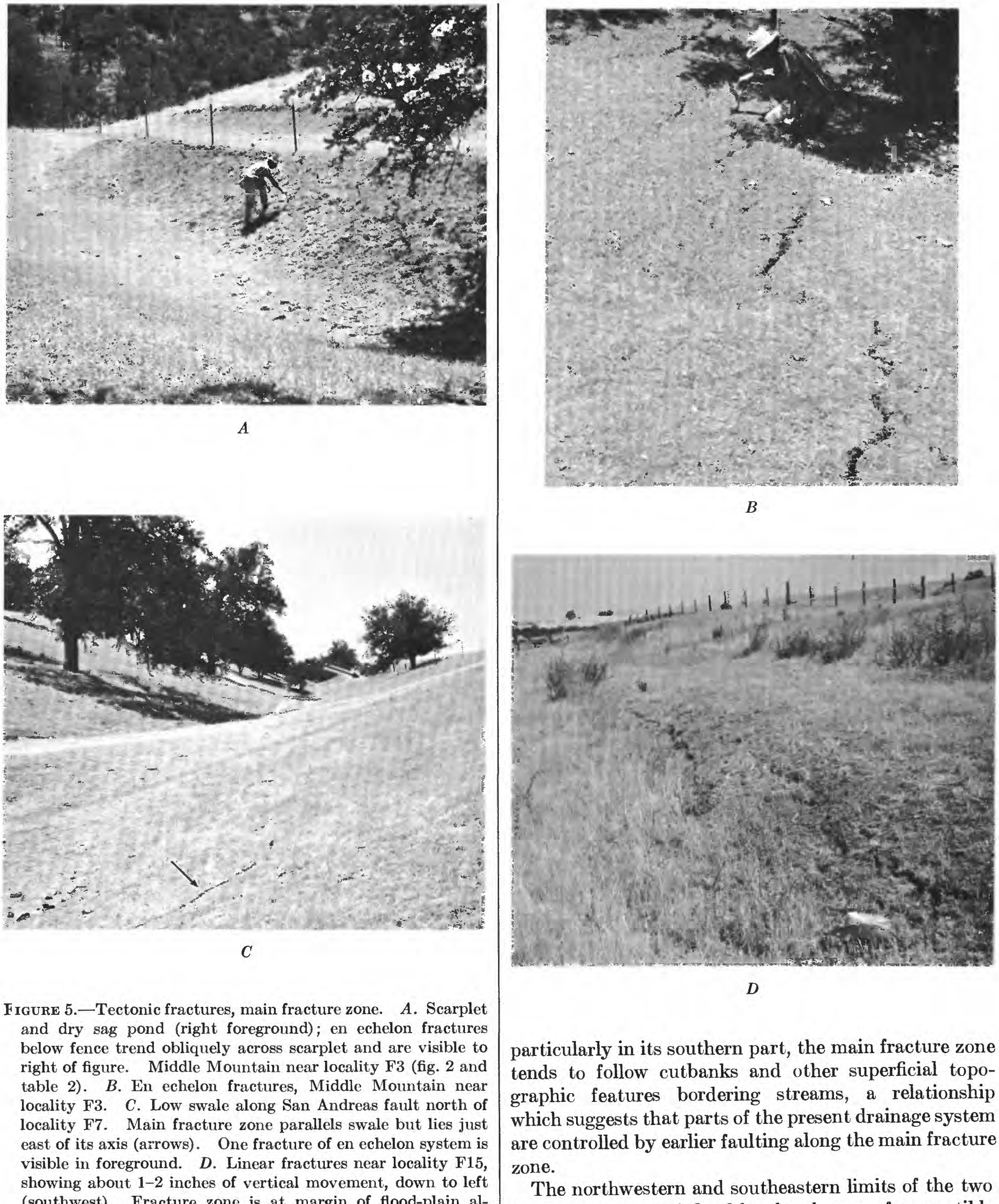


FIGURE 5.—Tectonic fractures, main fracture zone. *A*. Scarplet and dry sag pond (right foreground); en echelon fractures below fence trend obliquely across scarplet and are visible to right of figure. Middle Mountain near locality F3 (fig. 2 and table 2). *B*. En echelon fractures, Middle Mountain near locality F3. *C*. Low swale along San Andreas fault north of locality F7. Main fracture zone parallels swale but lies just east of its axis (arrows). One fracture of en echelon system is visible in foreground. *D*. Linear fractures near locality F15, showing about 1–2 inches of vertical movement, down to left (southwest). Fracture zone is at margin of flood-plain alluvium (to left) and closely follows contact with terrace deposits (to right).

particularly in its southern part, the main fracture zone tends to follow cutbanks and other superficial topographic features bordering streams, a relationship which suggests that parts of the present drainage system are controlled by earlier faulting along the main fracture zone.

The northwestern and southeastern limits of the two fracture zones are defined by the absence of perceptible ground fractures for a quarter of a mile or more. It is possible, however, particularly at the northwestern end of the main fracture zone, that a wider and more intensive search would disclose that tectonic fractures extend farther. Fractures of questionable tectonic origin were found as far north as the north boundary of sec. 7, T. 22 S., R. 13 E. Rather careful and detailed studies were made at the other zone termini, and for these it is unlikely that fracturing extends significantly farther.

A set of cracks of uncertain origin crosses the Parkfield-Coalinga road in Little Cholame Valley about 2.5 miles northwest of Parkfield. Although this northwest-trending set of cracks is about 1,000 feet long and occurs in an area of low relief on the valley floor, it does not have the typical en echelon arrangement and orientation of fractures observed along the preexisting fault traces. These cracks may have resulted from differential compaction of unconsolidated sediments rather than from tectonic movement.

MAIN FRACTURE ZONE

The main fracture zone, clearly evident for most of its length, is difficult to trace on Middle Mountain, particularly where it lies within large landslide areas. Most of the landslides on Middle Mountain are active, and many of them moved during the Parkfield-Cholame earthquakes, producing a variety of fissure patterns. These include slide fissures, expanded desiccation cracks in soil, and linear fractures of uncertain origin.

Many of these fissures and cracks form crudely arcuate patterns that approximately parallel nearby landslide scars. The general absence of en echelon or linear tectonic fractures in the landslide areas, together with the multitude of nontectonic fissures and cracks, suggests that tectonic movements were distributed along preexisting fissures which interlaced the landslide masses. Typical tectonic fracturing, marked by en echelon cracks, is shown at several places on Middle Mountain (fig. 5*B*) and, where present, is easily recognized. Moreover, all the tectonic fractures on Middle Mountain lie along a single trend (approx. N. 45° W.), and therefore the zone of fracturing can be confidently interpolated across landslide areas.

From Middle Mountain southeast to California Flats Canyon, the main fracture zone is nearly straight and trends about N. 45° W. En echelon fractures are persistent and well defined, and the fracture zone closely follows a line of scarplets, benches, sag ponds, and other topographic faultline features (fig. 5*C*). There are very few gaps in the fracture zone, and most of them are in stubble fields or in freshly plowed ground, where tectonic fractures are probably present but are unidentifiable. One gap, between localities F9 and F10, is in a landslide area cut by steep gully walls, and the gaps between localities F12 and F13 are in small landslides.

The main fracture zone from California Flats Canyon to the southeastern end of Cholame Valley crosses an area of low relief where faultline topographic features are fewer and less obvious than to the north. The average trend of this segment of the fracture zone (about N. 30° W.) departs significantly from the trend farther north, but the local trend of the zone and the style of fracturing both vary considerably (table 2). En echelon fractures are the most common and are especially well formed on the southwest side of Cholame Valley; the trend of these varies with the orientation of the fracture-zone segment in which they occur. Linear cracks are common in some areas where en echelon fractures are absent (fig. 5*D*).

The main fracture zone is interrupted by a gap as it crosses Cholame Valley; in this gap, despite a careful search, no fractures were found. North of Cholame Creek the gap lies in cultivated and irrigated fields where small fractures might be obscured. South of the creek, open grazing land provides a favorable environment for the preservation of fractures; yet, none were found. A few sand mounds along the projected trace of the fracture zone suggest that the zone crosses Cholame Valley at depth.

SOUTHWEST FRACTURE ZONE

The southwest fracture zone trends approximately N. 45° W. from a point 0.3 mile south of Covington Lake to the Parkfield–San Miguel road. Although it is locally marked by very well defined en echelon fractures (fig. 6), they are less persistent than those in the main fracture zone. In several places where terrain conditions are favorable to their recognition and preservation, the fractures, if present, are imperceptible. Elsewhere the zone crosses land that is either ungrazed grassland or under cultivation; in either place, identification and tracing of the zone are hindered. Scarplets benches, swales, sag ponds, and wind gaps alined along this fracture zone appear older and more modified by erosion than those along the main fracture zone.

TYPES OF FRACTURES

EN ECHELON FRACTURES

En echelon fractures (figs. 5*B*, 6, 7) are the most typical and the most reliable for indicating tectonic fracturing. They were mapped discontinuously along the main fracture zone from the crest of Middle Mountain near the head of Nelson Creek southeast to a point about 1 mile due east of Cholame. The fracture relations and dimensions cited here are those observed between June 29 and July 15, 1966, unless otherwise

FIGURE 6.—En echelon fractures, southwest fracture zone near locality F33.

FIGURE 7.—En echelon fractures in surfaced county road from Highway 46 to Parkfield, at locality F10.

stated. Allen and Smith (1966, p. 966) note that some of these fractures were observed about 1 mile southeast of Parkfield 11 days before the earthquake. On the other hand, those near locality F26 may not have formed until June 29, and those in the county road to Parkfield at locality F20 may not have formed until late in the day on June 30. Repeated measurements at selected localities along the fracture zone have shown that individual cracks continued to widen and to show increased right-lateral offset for several weeks after the earthquakes. A small part of this deformation may be due to desiccation at depth along the fracture surfaces, but most of it is certainly tectonic. An analysis of the rate and pattern of deformation with time is given in this report under the section "Rates and patterns of progressive deformation."

The en echelon cracks display certain uniform characteristics throughout the area mapped (table 2). Their trend is oblique to the fracture zone (fig. 8), in most places about 30° in a clockwise sense, and they have a distinctive en echelon pattern (figs. 5*B*, 6). Compared to the length of the fracture zones, the length of individual en echelon fractures is small; most are less than 10 feet long, and none are much longer than 20 feet. Separation of the walls is also relatively small; in most fractures, it amounts to an inch or two. Few fractures narrower than half an inch were recorded, probably because narrow ones were unnoticed in the grass and uneven ground.

The general pattern of en echelon fractures loses its character at the ends of the zones and where the zones cross landslide areas, plowed fields, and ground that is deeply cracked by drying, but the pattern is consistently retained across surfaced and unsurfaced roads, across variations in topography and in soil or bedrock, and across such artificial features as earthen dams, levees, and ditches. The en echelon pattern is most easily seen in surfaced roads (figs. 7, 9*A*, *B*), where it generally appears more intricate than in open fields or pastureland (figs. 5*B*, 10).

The en echelon fracture system divides the ground within the fracture zone into a series of elongate subparallel blocks. In many places, adjacent blocks show evidence of relative right-lateral movement amounting to as much as a few inches (figs. 11*A*, *B*). Relative movement of adjacent blocks is also shown by compressional features formed between parallel and overlapping fractures. Pressure ridges (figs. 11*C*, *D*) and raised wedges of soil (fig. 11*E*) are evidence of local compressional effects within the fracture zone. For about a mile south of locality F23, these features are so abundant that the fracture zone, when viewed from a few hundred feet away, resembles a low raised welt or mole track several inches high (fig. 12). In this area and at a few other places along the main fracture zone, the ends of some en echelon cracks show microrelief in which the ground west of the crack is raised slightly (½–2 in.) at the north end and lowered an equal amount at the south end. This effect may represent an early stage in the formation of pressure ridges (fig. 12 inset).

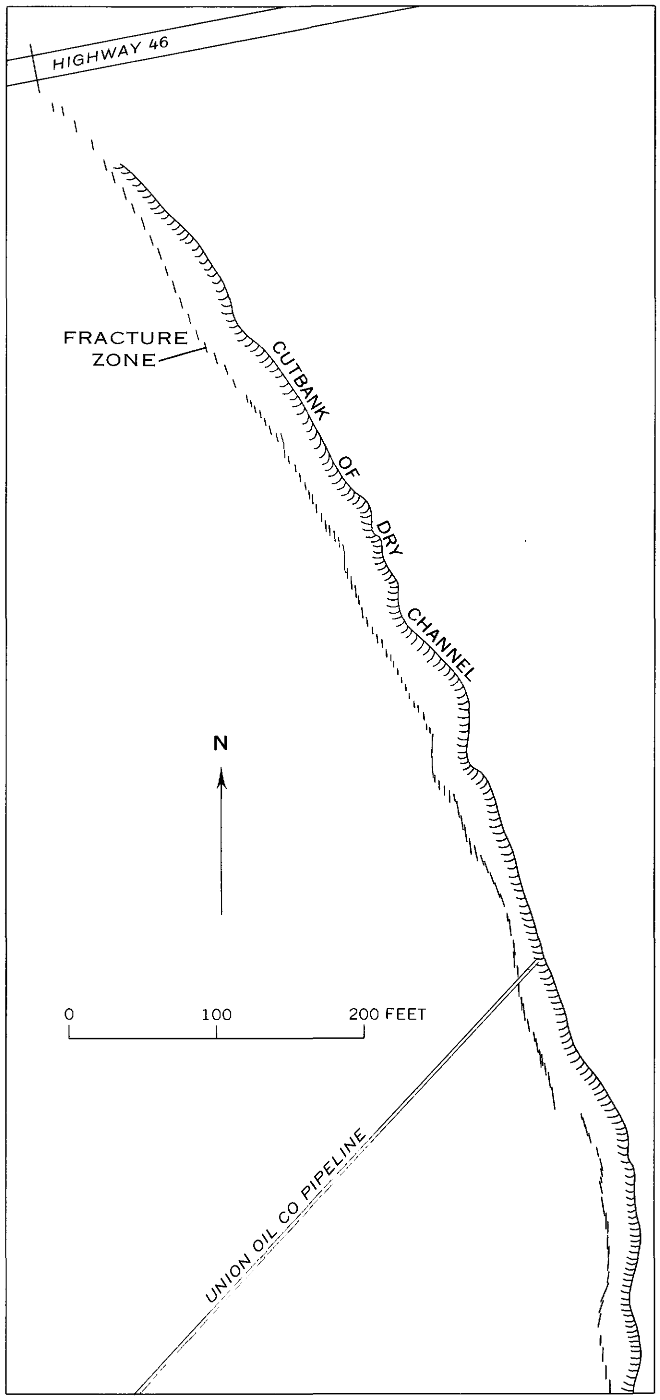


FIGURE 8.—Diagram of en echelon and linear fractures southeast of Highway 46 as they appear on vertical aerial photographs taken on June 30, 1966. Note how the fracture zone parallels the streambank. Downdropping on the southwest side of the linear fractures suggests differential compaction of unconsolidated flood-plain deposits and partly consolidated incised alluvium.

Relations of en echelon cracks in the vertical dimension are difficult to obtain, except in streambanks and other steep faces. Moreover, such exposures are atypical since the environment may influence the orientation of the tectonic fracture pattern. Most of the fractures observed in such exposures appeared to be vertical (fig. 13); Reuben Kachadoorian and Julius Schlocker report two fractures with dips of 75°–79° E. in a gully wall between localities F23 and F24. Several other fractures, probed with a steel rod by Kachadoorian and Schlocker, were all practically vertical.

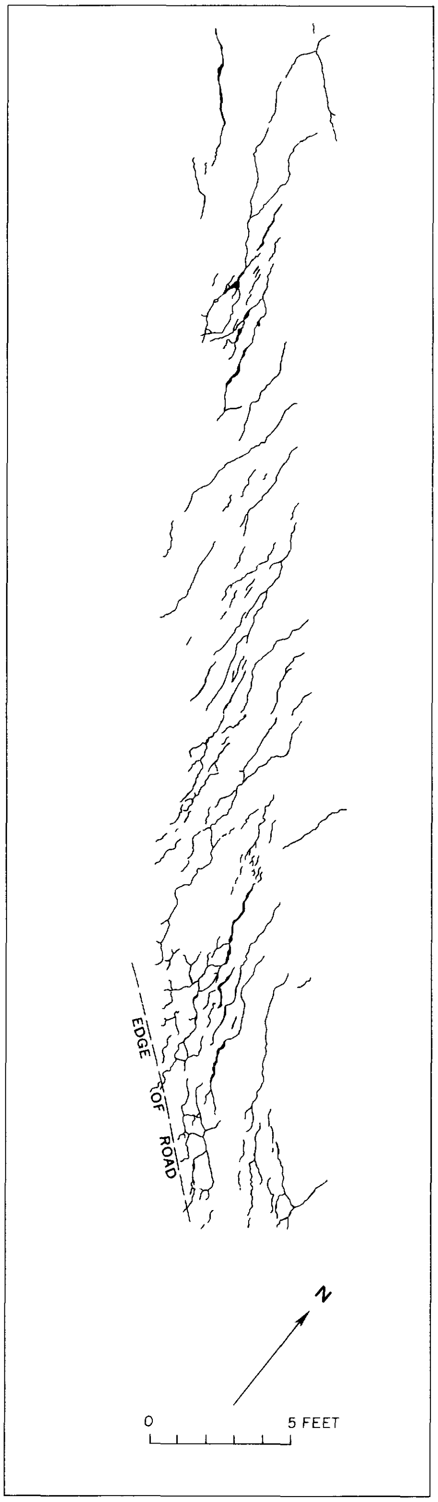
LINEAR FRACTURES

Linear or slightly arcuate fractures are less common than the en echelon type and are found locally between segments of en echelon fracturing. They are particularly well defined at two localities: one about a mile northwest of Cholame Ranch at locality F15 (fig. 5*D*), the other about 1½ miles southeast of the ranch. At the locality southeast of the ranch linear fractures extend along the main fracture zone for about 1,200 feet. The linear fractures parallel or nearly parallel the fracture zone and vary from a nearly continuous single break to slightly en echelon discontinuous short strands. They average 20 feet long and 1 inch wide and have a maximum observed length of about 60 feet and a width of 3½ inches. Most of them show a vertical component of movement and as much as 3 inches of displacement.

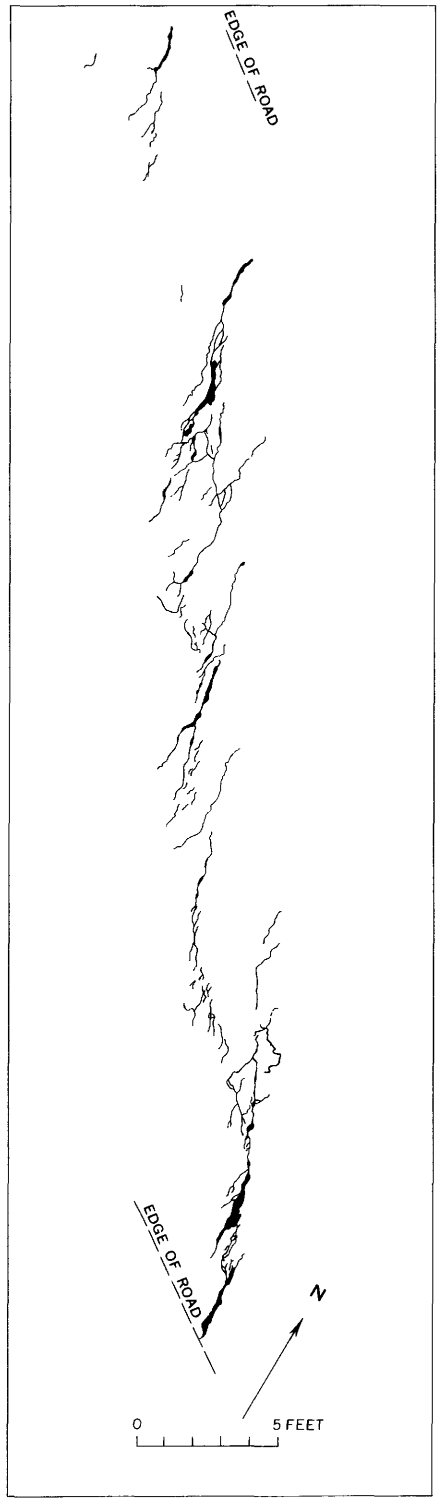
In both localities near Cholame Ranch, the linear fractures lie at the base of a southwest-facing slope which separates the alluvium of the Cholame Creek flood plain from the terrace deposits and bedrock in a bench 6–12 feet above flood-plain level. Relative vertical movement along the fractures is down to the southwest, toward Cholame Creek. Unlike the en echelon fractures, which may cross topographic features obliquely, the linear fractures follow the flood-plain margin even where it is sinuous or arcuate in plan. The relationship of these fractures to topography and the relative vertical displacements are probably indicative of differential compaction in which the surface of the flood-plain deposits has subsided an inch or so relative to the adjoining terrace. If this interpretation is correct, the linear features are not entirely tectonic in origin; however, their location along the main fracture zone implies tectonic fracturing or movement at depth.

OTHER TYPES OF GROUND CRACKS

Cracks presumably attributable to slightly reactivated landslides and to slope failures are common in areas of relatively steep relief along the fracture zones. Most streambanks, high roadcuts, older scarps, and older landslides along the fault traces show evidence of this type of cracking; it is also common well away from the fracture zones (p. 41).



A



B

FIGURE 9.—En echelon fractures in asphalt. *A*. Across Parkfield road (loc. F10) 1.4 miles southeast of Turkey Flat road intersection. Fractures were traced from vertical photographs taken at 10:30 a.m. on July 22, 1966. *B*. Across Meng road (loc. F27) 0.6 mile southeast of Highway 46. Fractures were traced from vertical aerial photographs taken at 7:30 a.m. on July 22, 1966.

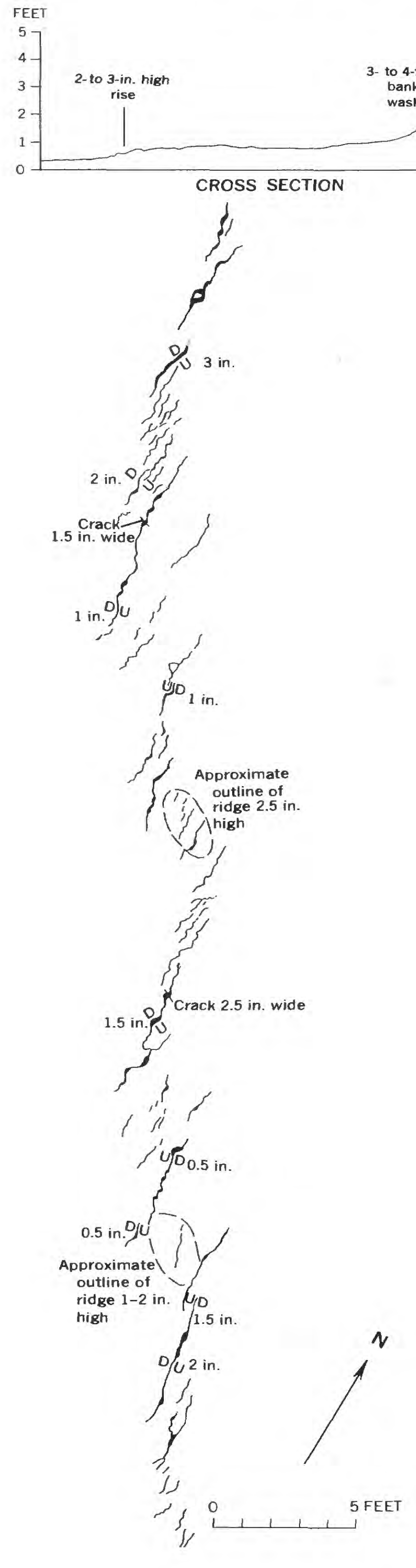


FIGURE 10.—En echelon fractures in fine sandy silt approximately 350 feet south of Highway 46. Fractures were traced from vertical aerial photographs taken 6:30 p.m. July 21, 1966.

The fissures are irregular and occur either as a single arcuate trace or as several subparallel arcuate cracks separated by narrow steplike slices of ground. Such cracks are numerous and well defined within the older landslides just east of the crest of Middle Mountain about 3 miles northwest of Parkfield and between the fracture zones south of the Parkfield cemetery.

Expanded desiccation cracks occur in dry sag ponds, streambeds, and poorly drained open fields where these features lie athwart the fracture zones. Examples of this type of fracture were noted along Cholame Creek between a quarter of a mile and half a mile northwest of Highway 46. Separation seems to have been greatest along cracks that most nearly parallel the en echelon trend.

Under some conditions landslide fissures and desiccation cracks could be mistaken for tectonic fractures, but the en echelon pattern of the two fracture zones in the Parkfield-Cholame area is so distinctive that few such mistakes could be made.

OTHER CRITERIA FOR LOCATING TECTONIC FRACTURING

Several other criteria were useful in locating and identifying the zones of tectonic fracturing. None of these criteria are in themselves indicative of tectonic fracture, but they are listed here because of their possible usefulness in future studies of similar earthquakes.

Slope failures in soil, alluvial deposits, and poorly consolidated rocks of Quaternary age are widely distributed in a belt several miles wide on either side of the mapped fracture zones (fig. 35). They are especially abundant along fracture zones or within a few hundred feet of them, particularly where the fracture zones cross or follow a steep streambank cut in alluvium, as they do in many places along Cholame Creek (fig. 14*A*).

Offset manmade features are found along the fracture zones, and many of these display far more lateral movement than can be ascribed to the Parkfield-Cholame earthquakes. A fence that is 20 years old showed right-lateral displacement of 12–14 inches (p. 33), and some roads crossing the fault trace show evidence of repeated repairs. Recent movement is most clearly demonstrated by surfaced roads and by newly constructed steel-stake barbed-wire fences. Many of these fences show right-lateral offset of 2–3 inches, accompanied by tensional effects due to extension across fracture zones (fig. 14*B*). Power and telephone lines are stretched tightly in spans that cross the fracture zones, yet hang relatively loosely away from the zones.

Broken or toppled trees and fallen limbs were observed at several places along both fracture zones. An especially interesting example of tree damage was

A

B

C

D

E

FIGURE 11.—Evidence of strike slip, main fracture zone *A*. Strike slip exhibited along fracture wall in county road at locality F20. Matching points in fracture wall show about one-half inch of strike slip as shown near 6-inch rule. *B*. Strike slip exhibited along fracture wall in pastureland near locality F23. Approximately 4 inches of strike slip. *C*. Pressure ridge between adjacent en echelon fractures about one-half mile southeast of locality F23. Ridge is about 5 inches high. *D*. Pressure ridges formed along en echelon fractures in compact alluvium, bed of Cholame Creek at locality F18. *E*. Wedge of soil at end of en echelon fracture near locality F18 is raised and thrust to the right about 4 inches.

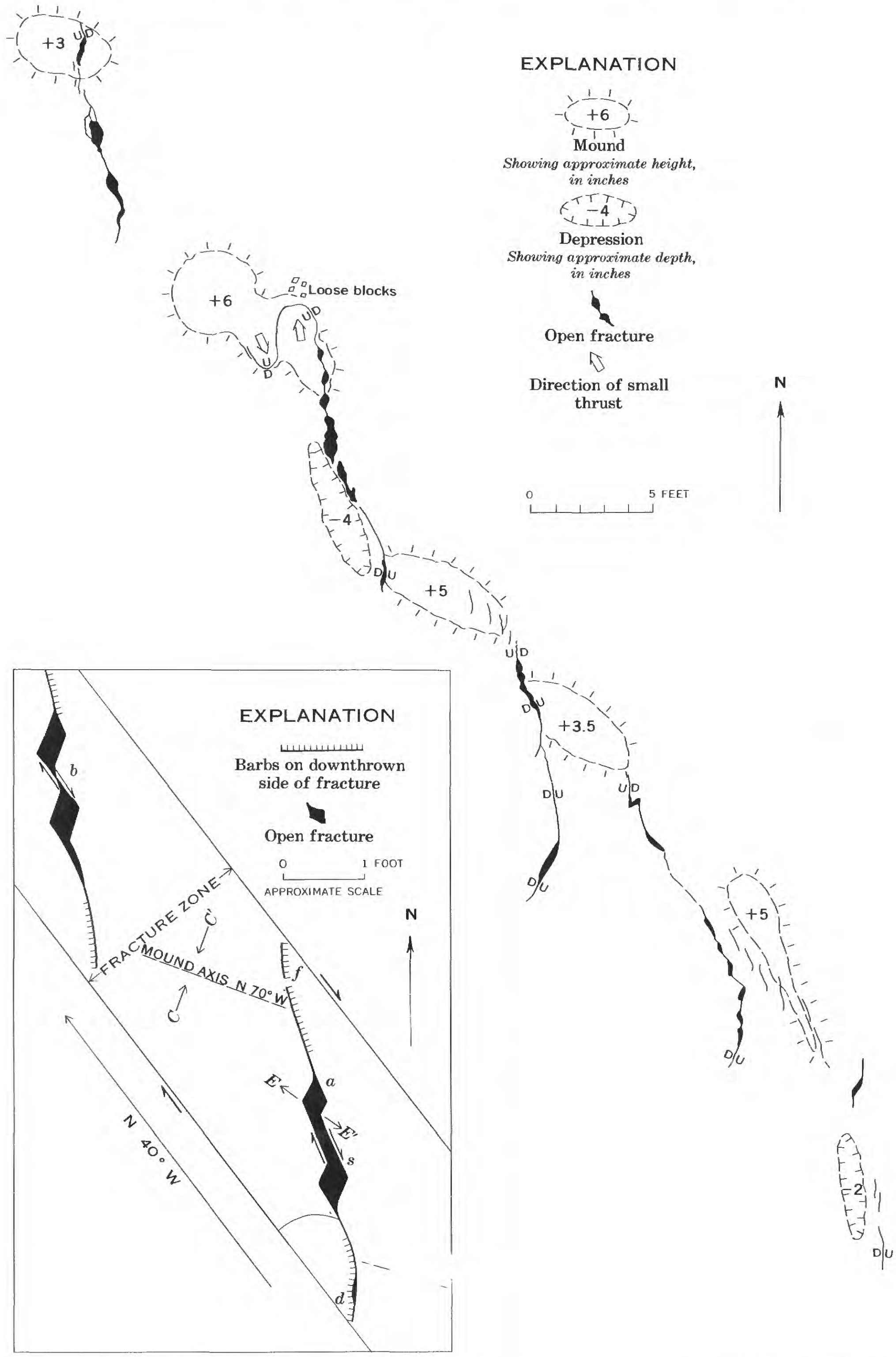


FIGURE 12.—Sketch map of en echelon fractures and accompanying mounds or pressure ridges, which together make up mole tracks 640–700 feet southeast of F23 (fig. 2). Fractures mapped by R. E. Wallace on July 21, 1966. U, upthrown; D, downthrown. Inset is a diagram of the fracture system and related pressure ridges where individual fractures result from a composite of shear and extension movement, alternating in a steplike arrangement as at *a*, *s*, and *b*. Note the sigmoid pattern formed by the bowed ends at *d* and *f*. Mound relief is compensated by vertical displacement indicated at *d* and *f*. Greatest extension is between *E–E′* nearly parallel to the mound axes or normal to the shortening direction *C–C′*.

FIGURE 13.—Nearly vertical en echelon fracture, left bank of Cholame Creek at locality F14. View looking northwest.

observed and photographed by Edward F. Roth near locality F2. There the lower trunk of a living, apparently healthy, oak tree less than a foot in diameter is split vertically from ground level upward for at least 3 feet (fig. 14*D*). The fresh crack in the oak tree merges at ground level with one of the en echelon fractures of the main fracture zone, and the tree obviously was split by the same mechanism that fractured the ground surface. An oak tree more than 3 feet in diameter was split and toppled near locality F10. This tree also was in the main fracture zone and was probably damaged in the same way as the tree near F2, but the evidence is not conclusive.

Damage to trees was confined largely to the two fracture zones and to trees that were diseased or partly dead. Although comparatively little damage was observed outside the fracture zones, a larger earthquake with more severe ground shaking would probably damage trees over a wider area.

Sand mounds and sand flows, caused by the extrusion of water-saturated well-sorted sand and silt from beneath the surface, were apparently rare during the Parkfield-Cholame earthquakes, possibly because these earthquakes occurred during the dry season when water tables were relatively low. Sand mounds, which are domelike or mammilliform masses of sand and silt a few inches high and about a foot in diameter, were noted near the highway bridge 0.3 mile southeast of Parkfield and on the northeast side of a levee which parallels the road through Cholame Valley. Sand flows, which are deltalike sand and silt deposits, were noted in Cholame Creek about 500 feet north of Highway 46 (fig. 14*C*). Each of these localities is along the trend of the zone of fracturing or within a few feet of it, and this position suggests that the fracture zone itself was a conduit for the upward movement of water-saturated sediment. Such features, however, can also be formed independently of linear tectonic fracture zones; they have been reported after many earthquakes where no surface fracturing was evident.

A dust blow, formed by the extrusion of dry silt, clay, and sand, was found within the fracture zone about 800 feet southeast of F27. The dust-blow deposit formed a mound about 6 inches in diameter and half an inch high; this mound has a crater about half an inch deep that has a central orifice about an inch long and half an inch wide.

In two areas of flat to gently sloping (5°) ground, dislodged boulders, cobbles, and pebbles were noted within the main fracture zone or within a few feet of it. Most of the dislodged stones were shifted only slightly from their earlier positions (as shown by impressions in soil and grass), but a few were moved entirely out of their former sites to places several inches away. Some of the stones left skid marks (fig. 14*E*), others that moved under apparently identical conditions did not.

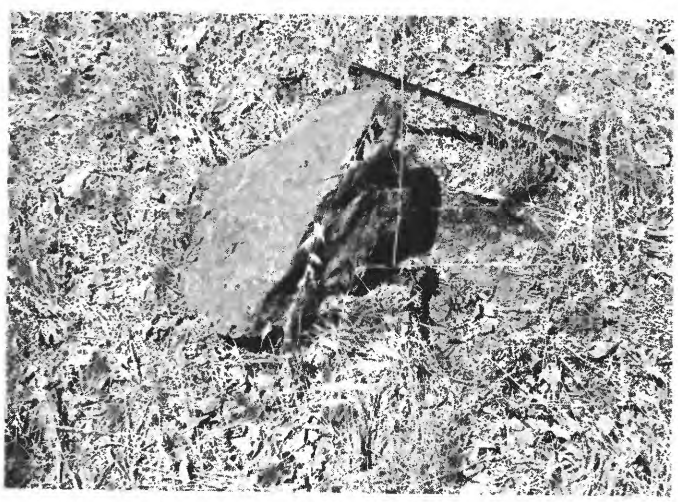
One of the areas of disturbed stones lies along the fracture zone between locality F8 and the road to Turkey Flat. The other lies along the fracture zone about 1 mile southeast of Highway 46. They were noted independently by Robert D. Brown (Turkey Flat road area) on July 6 and J. G. Vedder (1 mile south of Highway 46) on June 29 and 30. The area near the Turkey Flat road was revisited and photographed on July 14, but by then only the impressions of relatively large stones, that is, cobbles and boulders, were clearly discernible. We cannot entirely rule out the possibility that the stones were dislodged by means other than the earthquakes. Conceivably, dislodgement could have been caused by humans, by grazing cattle, or by wild animals seeking food. The last two possibilities seem to us unlikely because no recent hoofprints were observed, dry grass near the stones was untrampled, and the former sites of the stones were undisturbed at the margins (small animals grubbing for worms or insects would have disturbed the margins). Persons visiting the locality near the Turkey Flat road

A

B

C

D



E

FIGURE 14.—Features associated with tectonic fracture zones. *A*. Debris slide at intersection of main fracture zone (arrows) with left bank of Cholame Creek, locality F14. Note other debris slides upstream along creek bed. *B*. Steel-stake and barbed-wire fence at locality F31. Extension resulting from strike slip has tightened top strand of wire pulling one stake out of alinement. *C*. Sand flow north of locality F25 formed by the extrusion of water saturated sand and silt. Orifice for flow indicated by arrow. *D*. Oak tree, split vertically by tectonic fracture visible in left foreground. Handle of knife is 3 inches long. *E*. Dislodged angular cobble at locality F8, showing original "nest" in which cobble rested and skid mark formed during movement.

after the earthquake may have accidentally moved the stones by walking on them, but the locality south of Highway 46 was in undisturbed dry grass that normally shows footprint impressions for many days. Since the grass was undisturbed, dislodging of the stones by humans seems to be ruled out, at least at this locality.

SIGNIFICANCE OF SURFACE TECTONIC FRACTURES

Faulting, accompanying the Parkfield-Cholame earthquakes of June 27–29, resulted in surface fracture along a 23½-mile segment of the main trace of the San Andreas fault. Surface fractures also formed, with less continuity, along a nearby subordinate fault within the San Andreas fault zone. The recent fractures closely followed earlier well-defined fault traces which were recognized as early as 1908 and which have been the site of repeated and well-documented earth movements for more than 100 years. A much longer history of movement is afforded by geologic evidence.

The sense of movement along both fracture zones was right lateral; that is, objects northeast of each fracture zone shifted a few inches toward the southeast relative to a point on the southwest side of each fracture zone. Both the sense of movement and the amount are commensurate with long-term directions and rates of movement along the San Andreas fault, in this area and elsewhere.

The earthquakes of June 27–29 and their accompanying tectonic fracture zones attest to continuing tectonic movement along the San Andreas fault. This movement, manifested throughout the San Andreas fault zone either by slow tectonic creep or by episodic displacements accompanying earthquake activity, or by both, shows no sign of abating. All of the available evidence indicates that it will continue in the future, both in the Parkfield-Cholame area and elsewhere along the San Andreas fault. Although the time, place, and magnitude of specific earthquakes cannot yet be predicted, more earthquakes will occur along the San Andreas fault, and if tectonic fracture zones accompany them, these fractures will in many places follow earlier fault traces. These earlier fault traces can be easily delineated along much of the San Andreas fault zone, and damage and loss from earthquakes can be at least partly reduced by avoiding construction on active, or recently active but dormant, strands of the fault.

In the Parkfield-Cholame area most of the damage resulted from seismic shock or ground waves, and only a little resulted directly from tectonic fracturing. Damage attributable to tectonic fracture was confined almost entirely to roads and highways although a few earth dams along the fracture zone were slightly damaged and pipelines for oil, water, and gas were disrupted or broken. Every road crossed by the fracture zone was cracked, some of them seriously. The relatively slight damage from tectonic fracture is largely a function of the low population density in this area although the narrowness of the fracture zone also tended to minimize damage. In heavily populated areas, such as that part of the San Francisco peninsula along the San Andreas fault or that part of the East Bay area along the Hayward fault, a fracture zone of comparable size would almost certainly have caused more extensive damage, particularly to building foundations, underground utility lines (water, gas, electricity, telephone, and telegraph), sewer lines, and streets. Moreover, relative ground displacements slightly larger than those (2–4 inches) associated with the Parkfield-Cholame fracture zones would probably result in damage to utility lines suspended above ground.

Several interesting relationships are apparent from this study of surface fracturing, and although these are not yet fully understood, they suggest avenues of future investigation. Perhaps foremost of these is the association of extensive tectonic fracturing with earthquakes of moderate magnitude. Surface tectonic fracture zones, comparable in length to those in the Parkfield-Cholame area, have been reported for many earthquakes with magnitudes greater than 6.0 on the Richter scale (Tocher, 1958, p. 149–150; Otsuka, 1964, p. 19–22; Allen and others, 1965, p. 766–769), but are relatively uncommon for smaller earthquakes. Seismologists in Japan and in the United States have observed that for most earthquakes the length of the fracture zones (or "earthquake faults") increases with increasing energy, expressed as magnitude, and several workers have attempted to quantify this relationship. Otsuka (1964), however, suggested that the length of surface fracturing is not a simple function of energy or magnitude but that it depends also on other variables, particularly focal depth. Thus, moderate earthquakes with relatively shallow focal depths may produce longer zones of surface fracture than deep earthquakes of greater magnitude. Preliminary seismological analyses show that focal depths for the Parkfield-Cholame earthquakes are, indeed, shallower than those reported for most earthquakes; studies of Parkfield-Cholame aftershock sequences indicate that many aftershocks originate 1–10 kilometers from the surface (Jerry Eaton, oral commun., Sept. 8, 1966). Although the length of the fracture zones in the Parkfield-Cholame area may be attributable largely to shallow focal depths, additional data on similar earthquakes with extensive surface fracture are needed to evaluate this suggestion. Evaluation is greatly hampered by the lack of reliable data on focal depths.

The genesis of tectonic fracture zones and the relation of surface fractures to declining earthquake activity are also significant, for they provide a key to a better understanding of the strain release and deformation following important earthquakes. A few observations suggest that different parts of the two mapped fracture zones were formed at different times; it is clear, however, that once formed they did not remain static but underwent continued deformation. In the Parkfield-Cholame area, accurate mapping of the fracture zones was completed about 2 weeks after the first earthquake, or nearly 4 weeks after Allen and Smith (1966, p. 966) observed fractures on the Turkey Flat road; the zones as mapped thus represent a synthesis of tectonic deformation during a period of at least a month. For those parts of the fracture zone that were recognized immediately after the earthquake, repeated observations, photographs, and quadrilateral measurements provide a good index of the rates and patterns of progressive deformation. More expeditious mapping of the entire fracture zone would have provided more sites for such observations and consequently a better basis for relating postearthquake movements to aftershocks and to regional long-term creep rates.

Dislodged stones at two localities along the main tectonic fracture zone are suggestive of relatively high acceleration locally although this evidence must be interpreted with caution. Cloud (1966, p. 971) reports a recorded acceleration of 0.5 g. Conceivably, an acceleration of 0.5 g coupled with ground-wave effects could have dislodged the stones, most of which had a relatively high center of gravity and appear to have been toppled rather than lifted bodily from their former sites.

RATES AND PATTERNS OF PROGRESSIVE DEFORMATION

By Robert E. Wallace and Edward F. Roth

During the first day following the major pair of earthquakes of June 27, it became apparent that displacements first observed were enlarging and that progressive deformation was taking place. To measure the rate of deformation at different places along the fracture zones, 10 quadrilaterals of survey markers were installed on June 30 and the following days by E. F. Roth, who also carried out the repeated measurements of the quadrilaterals. Several hundred photographs were taken from the air and ground to document both the geometry and rates of deformation; in addition, a search was made to find historic evidence of displacement during past decades so that longer term rates could be compared with shorter term rates.

DEFORMATION RELATED TO 1966 EARTHQUAKES

DIMENSIONAL CHANGES OF QUADRILATERALS

Bench marks were installed at nine localities by driving 5-foot copper-weld rods into the ground, crimping brass bench-mark tables to the top, and surrounding the uppermost part of each rod with concrete. Most of the bench marks were arranged in the form of quadrilaterals of from 20 to 180 feet on a side straddling the fracture zone. At one locality (QAB) a larger quadrilateral QB, measuring about 130 feet on a side, was placed around a smaller quadrilateral QA, and one side (B4–B6) was extended to a length of 260 feet (B3–B7).

The data obtained permit only approximations of strain rates and patterns because clearly points have, to some degree, moved randomly, owing to inhomogeneities, such as irregular fractures, pressure ridges, or desiccation cracks in the vicinity of individual bench marks. Emphasis was placed on measuring diagonals of the quadrilaterals to obtain an estimate of the amount and rate of strike slip, but the data also permit some conclusions about areal contraction and enlargement.

The model of simple shear illustrated in figure 15 was used in calculating an approximation of the strike-slip component. In this model, AB is the quadrilateral dimension measured (see fig. 15), and point B is assumed to move to B' along the heavy arrow, thereby increasing the length AB to AB' by an amount CB'. Considering the overall dimensions, angles ACB and ABC both approach 90° (see enlarged insert), and AB virtually equals AC; thus the component of strike slip represented by lengthening CB' is BB', and $BB'=CB'/\cos\theta$.

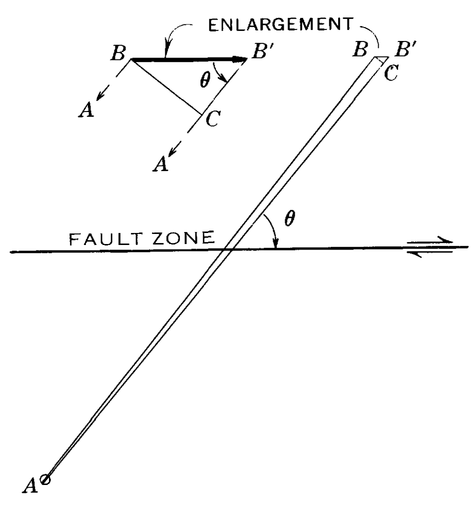


FIGURE 15.—Geometry for determining strike-slip component from dimensional changes of quadrilateral.

Repeated measurements of the dimensions of the quadrilaterals were made using an invar tape under a standard measured tension. Measurements were read to one-thirty-secondth of an inch. Location of the quadrilaterals are shown by symbols QA to QJ (fig. 2).

Quadrilaterals QA and QB

Measurements of quadrilaterals QA and QB (fig. 16) show continuing deformation up to the last time recorded here although the rate has decreased. (See also fig. 17 for map of fracture zone at this locality.) By

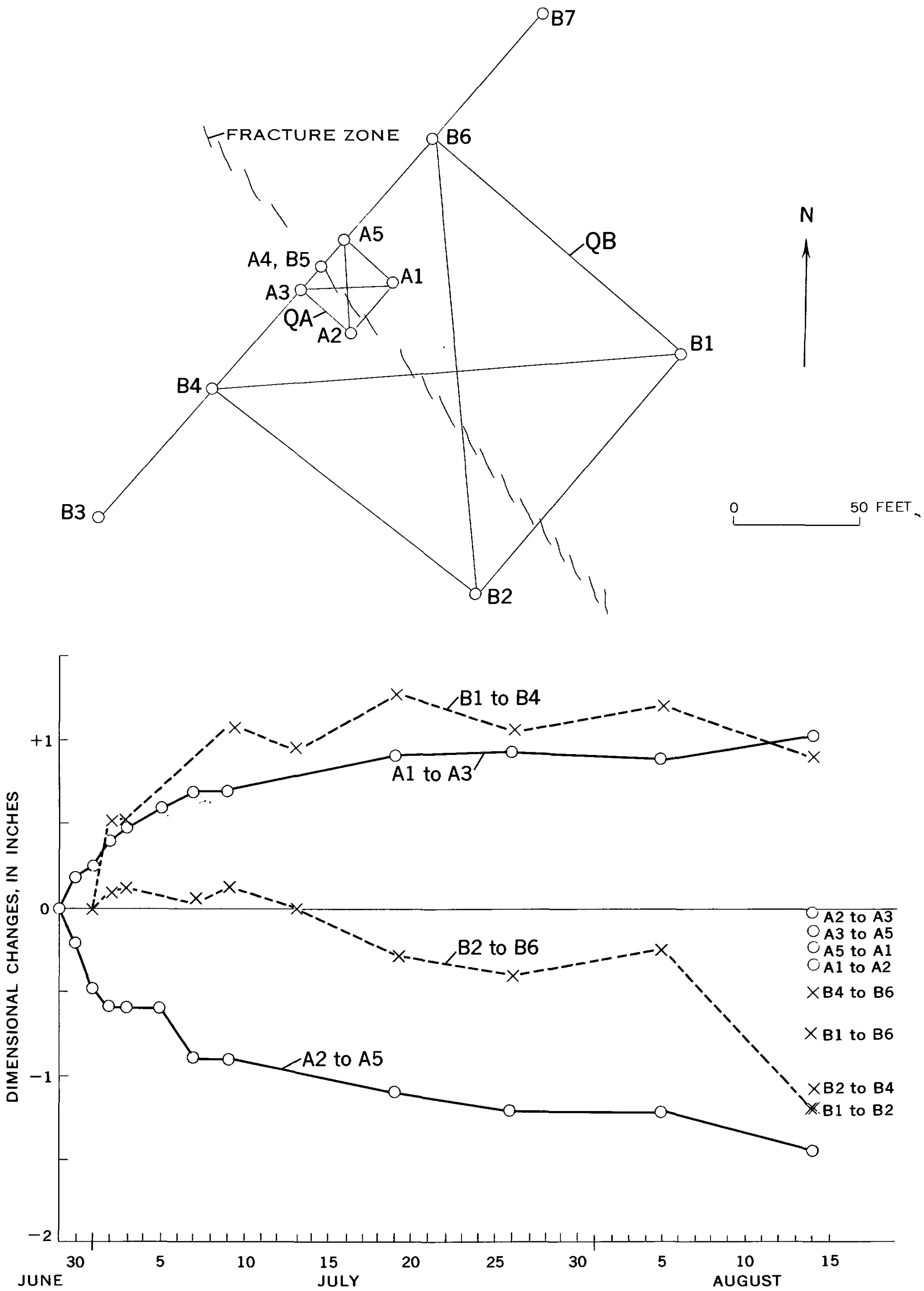


FIGURE 16.—Plan of quadrilaterals QA and QB and graph of dimensional changes with time. See figure 17 for detailed map of fractures.

August 14 only the two diagonals B1–B4 and A1–A3 showed extension; the remaining two diagonals and eight sides all showed shortening.

The extension of B1–B4 and A1–A3 and the shortening of B2–B6 and A2–A5 is consistent with overall right-lateral strike slip on the fracture zone. The total changes in the diagonals of both the small and large quadrilaterals by August 14 were virtually equal. This fact would indicate that the change resulted from strain within the small quadrilateral, but this conclusion is contradicted by the different amounts of shortening of sides of the two quadrilaterals, the sides of the larger quadrilateral showing the most shortening. Shortening of all the sides and diagonals except A1–A3 and B1–B4 implies an overall contraction of the area, or compression, on which is superimposed the strike slip.

Diagonal B2–B6 appears to have lengthened during the period July 2 to July 14 although the amount was only slightly more than the estimated limit of accuracy; later this diagonal shortened, and this fact suggests that areal expansion was followed by areal contraction. Such a strain history parallels that represented by Robert D. Brown's observation that the en echelon fractures in the northern two-thirds of the main fracture zone appeared to be primarily tension fractures during the period June 29 to July 15, when he examined them, although strike slip was apparent on many fractures at later dates. Unfortunately, the record of the dimensions of the sides of the quadrilaterals is not complete enough to evaluate the overall dimensional changes thoroughly. Nonetheless, between July 8 and 14, B1–B2 and B4–B6 appear to have increased in length, while B2–B4 and B1–B6 shortened (not shown on graph), and this fact provides additional suggestion of some expansion across the fault before July 14.

Unlike quadrilateral B, the diagonals of quadrilateral A shortened and lengthened, respectively, at approximately equal rates.

An approximation of strike slip suggested by the lengthening of B1–B4, after correcting for shortening of B1–B2 and B2–B4, is 3.4 inches. An amount almost equal to this may have taken place before measurements were started because estimates based on fracture dimensions (fig. 17) suggest 6 or 7 inches of strike slip at this locality.

Quadrilateral QD

Measurements of quadrilateral QD (fig. 18) show relatively little change in the length of the diagonals during the period July 6 to July 30; however, on August 5, following the aftershock of August 3, D1–D3, which would be expected to increase in length during right-lateral strike-slip strain, did indeed shown an extension of about 0.5 inch. Similarly, during the period July 28 to August 3, two marks across fractures on the road about 40 feet south of the quadrilateral were offset by 0.15 and 0.2 inch, although one mark had been offset about 0.1 inch between July 24 and 28. If all the dimensions of the quadrilateral are considered, however, no clear pattern of strike slip is required; rather, the movement of the points with respect to each other might be considered random, perhaps because of the nearness of D1 and D4 to fractures. One anomaly seems difficult to explain, that is, how the length of D3–D4 could have shortened by almost 0.5 inch while an open fracture 0.6 inch wide apparently was unchanged between the two points and at right angles to the side.

At locality (F20) near quadrilateral QD, nails were placed as leveling points along the center of the Cholame-Parkfield road across the main fracture zone. The profile on August 5 (fig. 19) shows that the southeast side is about 0.8 foot higher than the northwest side. Successive measurements made between July 19 and August 5 showed that the southeast side rose as much as 0.06 foot relative to the northwesternmost point as shown in figure 20. Figure 20 also shows that both northwest and southeast of the fracture zone, relative rates and amounts of uplift were greatest about 50–100 feet from the fracture zone, reflecting the growth of broad upwarps a few hundred feet wide bordering the fracture zone. Such upwarped or uplifted blocks bordering the fault are a common feature as geomorphically displayed at many localities along the San Andeas fault. Within a few feet of the fracture zone, a relatively downdropped or grabenlike depression developed during the period of measurements.

A comparison of vertical displacement (fig. 20) and horizontal displacements at this locality (F20) reveals that vertical displacement is as great as horizontal displacement during the period in which measurements were made and possibly was greater than the horizontal displacement. Apparently strike slip, which reaches a maximum of about 6 or 7 inches at locality F23 a mile southeast, dies out toward locality F20; as the trend of the fracture zone bends from N. 40° W. to N. 10° W. toward the en echelon segment to the north, vertical displacement becomes more important.

A comparison of level surveys made in 1942 and 1961 indicates subsidence of Cholame Valley northwest of locality F20. Although bench marks 1142, 1141, and 1138 along the Cholame to Parkfield road (see Cholame Valley and Cholame 1:24,000-scale quadrangle topographic maps) southwest of locality F20 did not change altitude between 1942 and 1961, northwest of locality F20 bench marks 1154, 1177, and 1202 subsided approximately 2.4, 1.4, and 1.1 feet, respectively. The apparent coincidence of the boundary of the area of

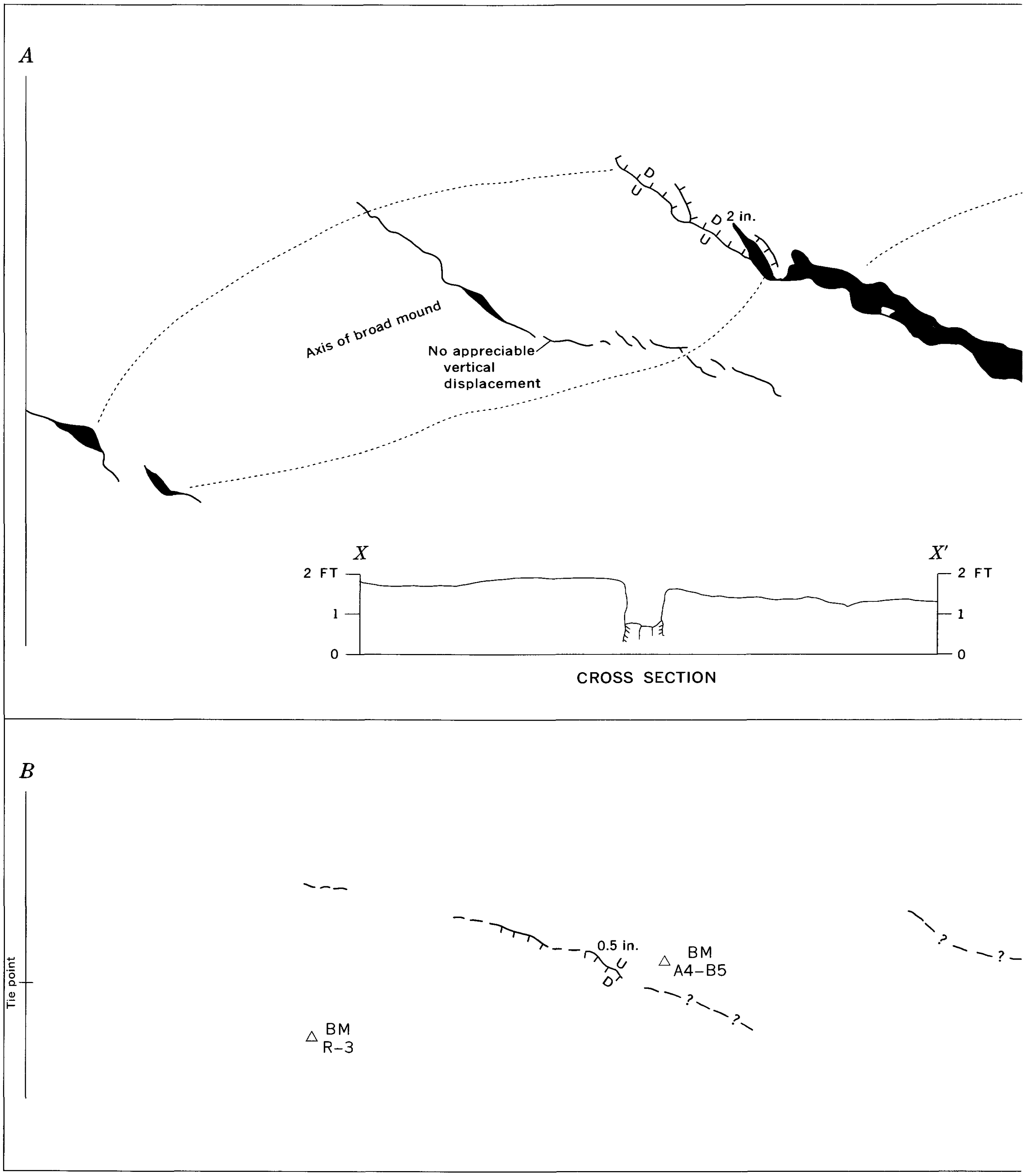
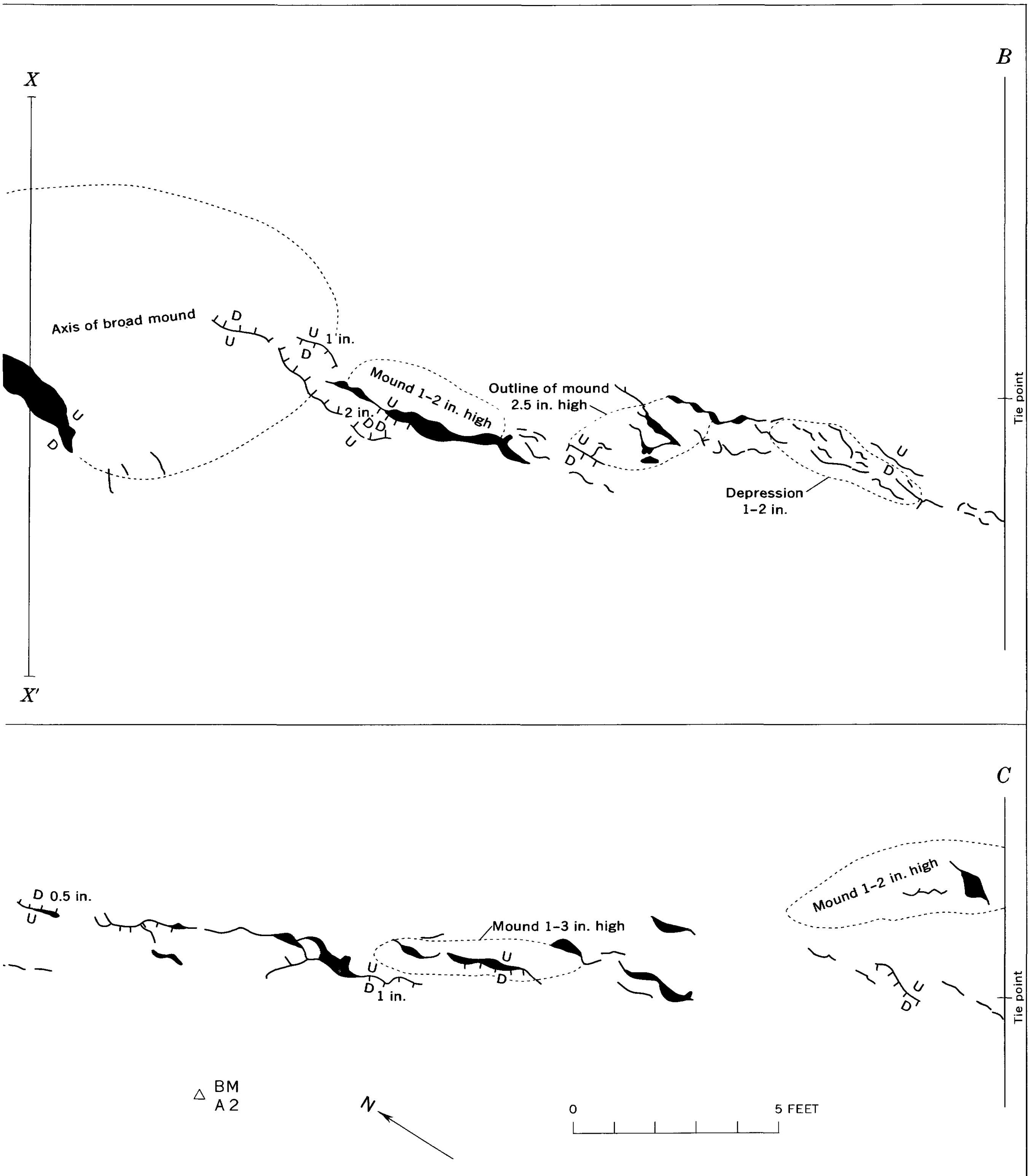


FIGURE 17.—Detailed map of tectonic fracture zone at quadrilaterals QA and QB. Bench marks A4, B5, and A2 mark quadrilateral downthrown side of fractures with vertical displacement.



reference points shown in figure 16. Dark areas indicate open fractures; dashes show mound outlines; hachures indicate the (For map sections *C* and *D* see p. 28–29.)

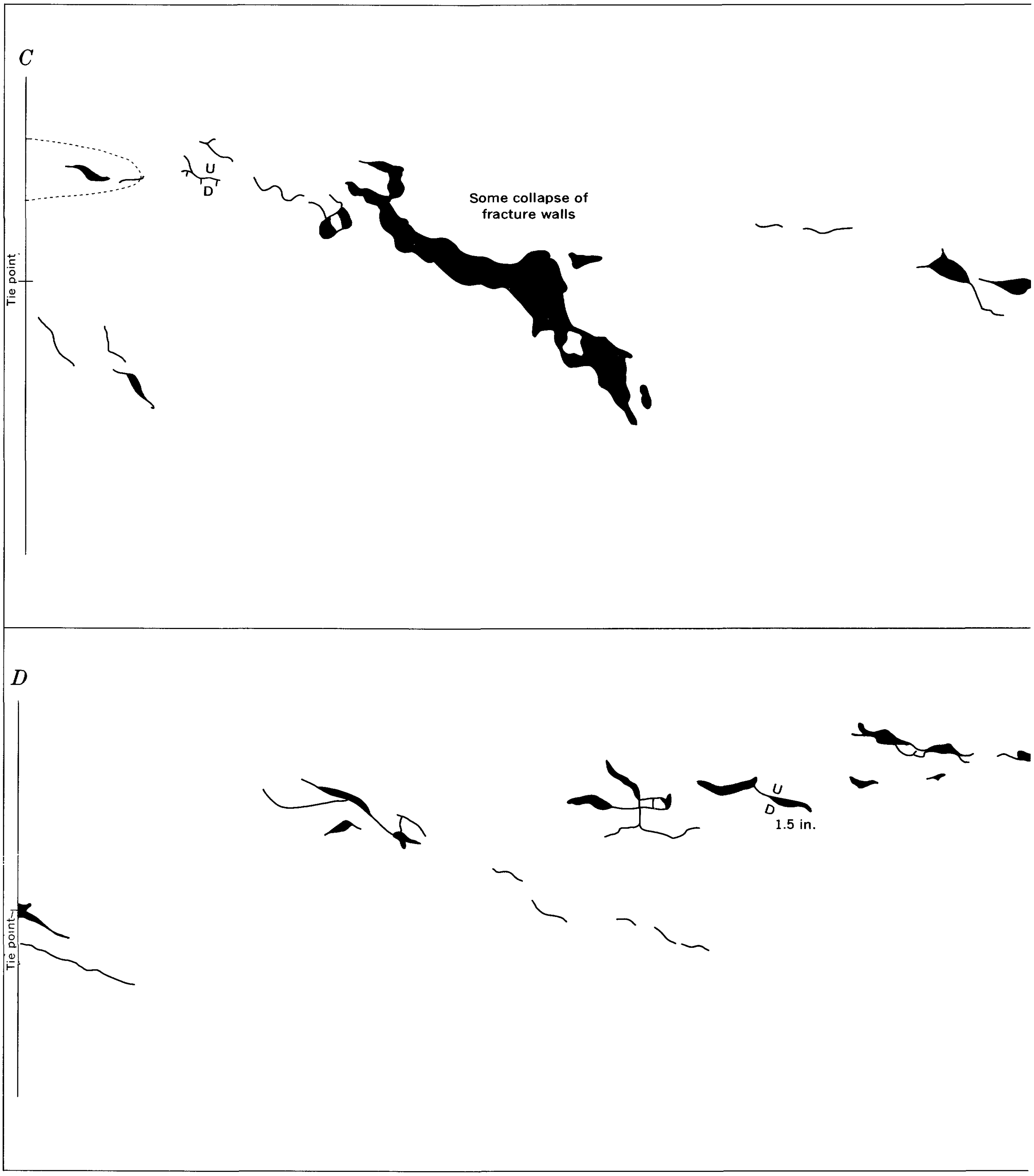
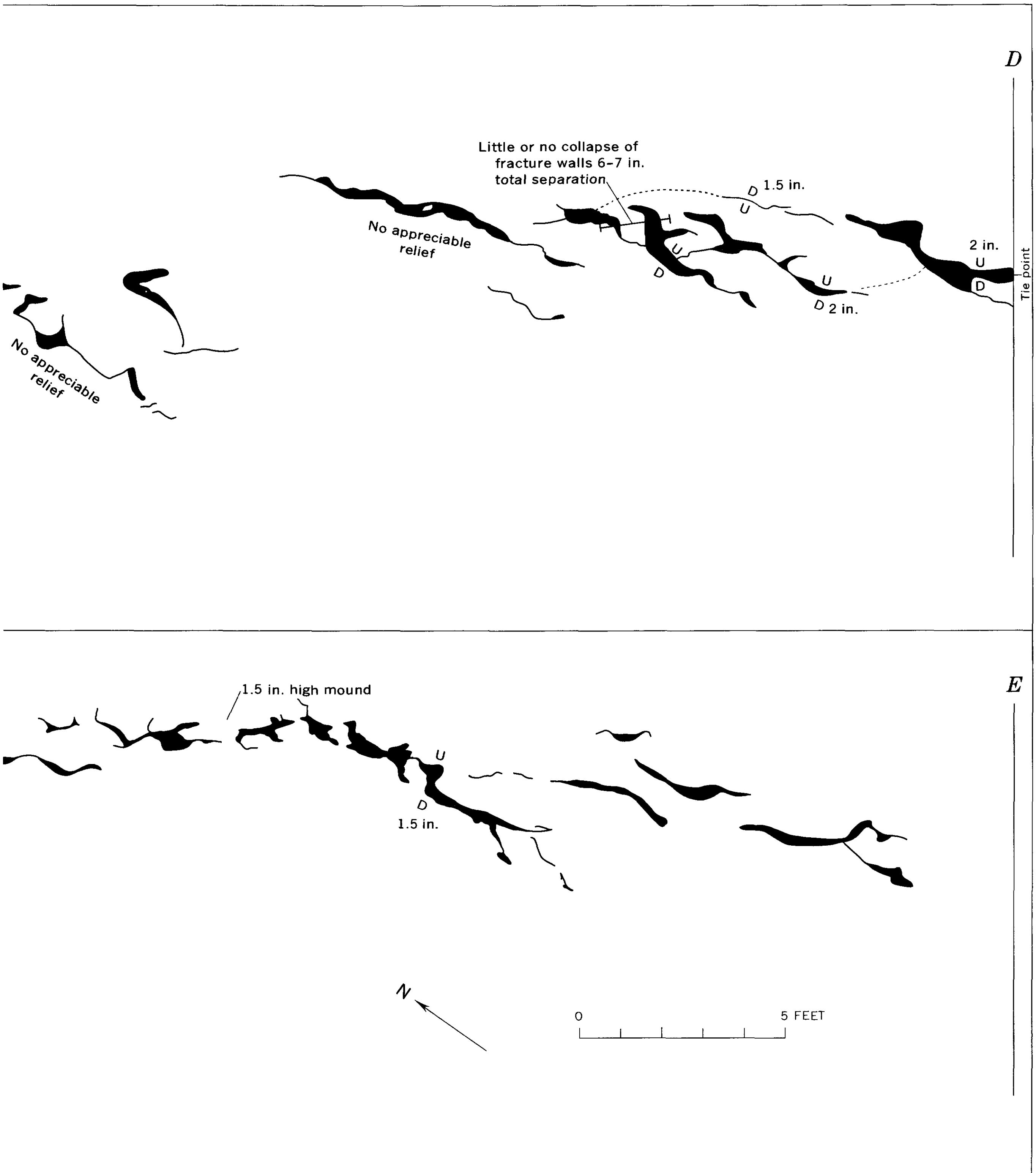


FIGURE 17.—(See p. 26–27



for map sections *A* and *B*.)

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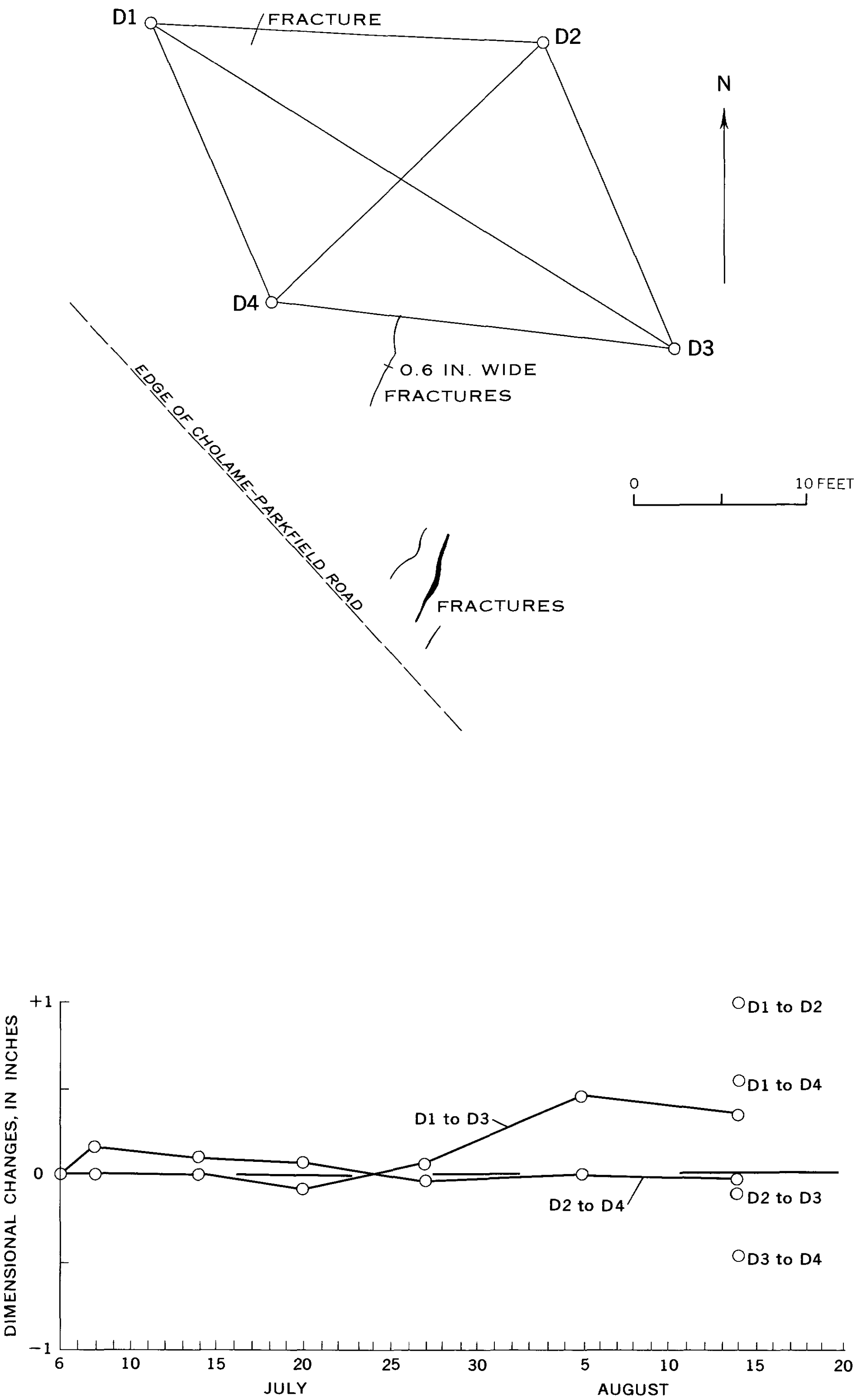


FIGURE 18.—Plan of quadrilateral QD (showing fractures in ground) and graph of dimensional changes with time.

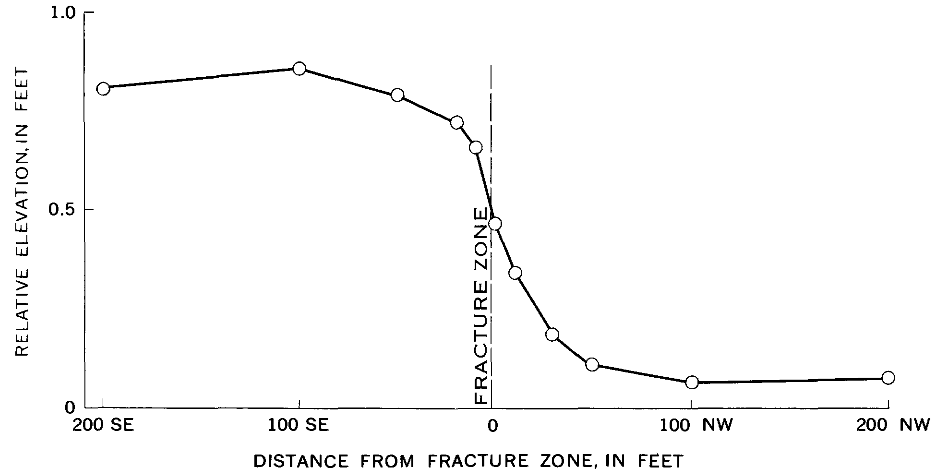


FIGURE 19.—Profile along Cholame-Parkfield road where fracture zone crosses 3.2 miles northwest of Highway 46, showing relative elevation August 5, 1966. Compare with figure 20.

subsidence with the segment of the San Andreas fault that crosses Cholame Valley suggests that the subsidence is in part tectonic, and the relative sense of vertical displacement is indeed the same as measured following the 1966 earthquakes. A subsidence of 2.4 feet between 1942 and 1961, however, seems unusually large to ascribe entirely to tectonism, and very likely the largest part of the subsidence relates to water pumping. Available well records do not provide satisfactory evidence. Perhaps the fault also indirectly influences differential subsidence by its effects on ground-water flow and distribution.

The problem of linkage of en echelon fractures has attracted attention over the years; for example, McKinstry (1948, p. 314) diagrams nine different types of linkages. The pattern displayed here appears to be one in which two en echelon fault segments displaying principally strike slip are linked by a structure in which vertical displacement is important. Figure 21 illustrates a model in which vertical displacement represented by normal faulting could accommodate tensional stresses across the north-trending segment which links the two northwest-trending segments. The greater thickness of alluvium in the valley under which the north-trending segment passes also may modify the style of strain at the ground surface; for example, the vertical displacement may be in part accommodated by a sharp monoclinal flexure at the surface even though faulting may exist at depth.

Quadrilateral QF

Measurements of quadrilateral QF (fig. 22) show continuing deformation up to the last time recorded here. Of the six dimensions measured, only two, F1-F3 and F1–F2, showed extension. The pattern of strain is consistent with right-lateral strike slip accompanied by shortening both across and parallel to the fault. The en echelon fracture pattern accompanied by low mounds or pressure ridges also reflects this general pattern of strain. The strike-slip component of strain was about 0.4 inch during the period of measurement.

Quadrilateral QJ

Measurements of quadrilateral QJ, the farthest north of the quadrilaterals installed (fig. 23), show strain consistent with strike slip. The two sides subparallel to the fracture zone remained almost constant in length, but the diagonals shortened and lengthened. More shortening of J2–J4 than lengthening of J1–J3 implies overall areal contraction, but the lengthening of J4–J3 as compared to the near constancy of J1–J2 suggests some random movement. The strike-slip component is of the order of 0.25 inch for the 18-day period.

Quadrilateral QI

Quadrilateral QI was installed July 14, relatively late in the sequence of events. The data (fig. 24) are included even though the significance of the results is somewhat questionable; this was the only quadrilateral installed on the southwest fracture zone. The fractures here indicate that strike slip was much less than on the main fracture zone, and indeed the three sets of measurements on the quadrilateral require no strike slip. Both diagonals of the quadrilateral shortened between July 14 and 20, suggesting areal contraction, then remained constant between July 20 and August 5.

Measurements of quadrilaterals QC, QE, QG, and QH are not reported upon because for various reasons these were found to be unsatisfactory for the purpose intended. Their localities are shown in figure 2, how-

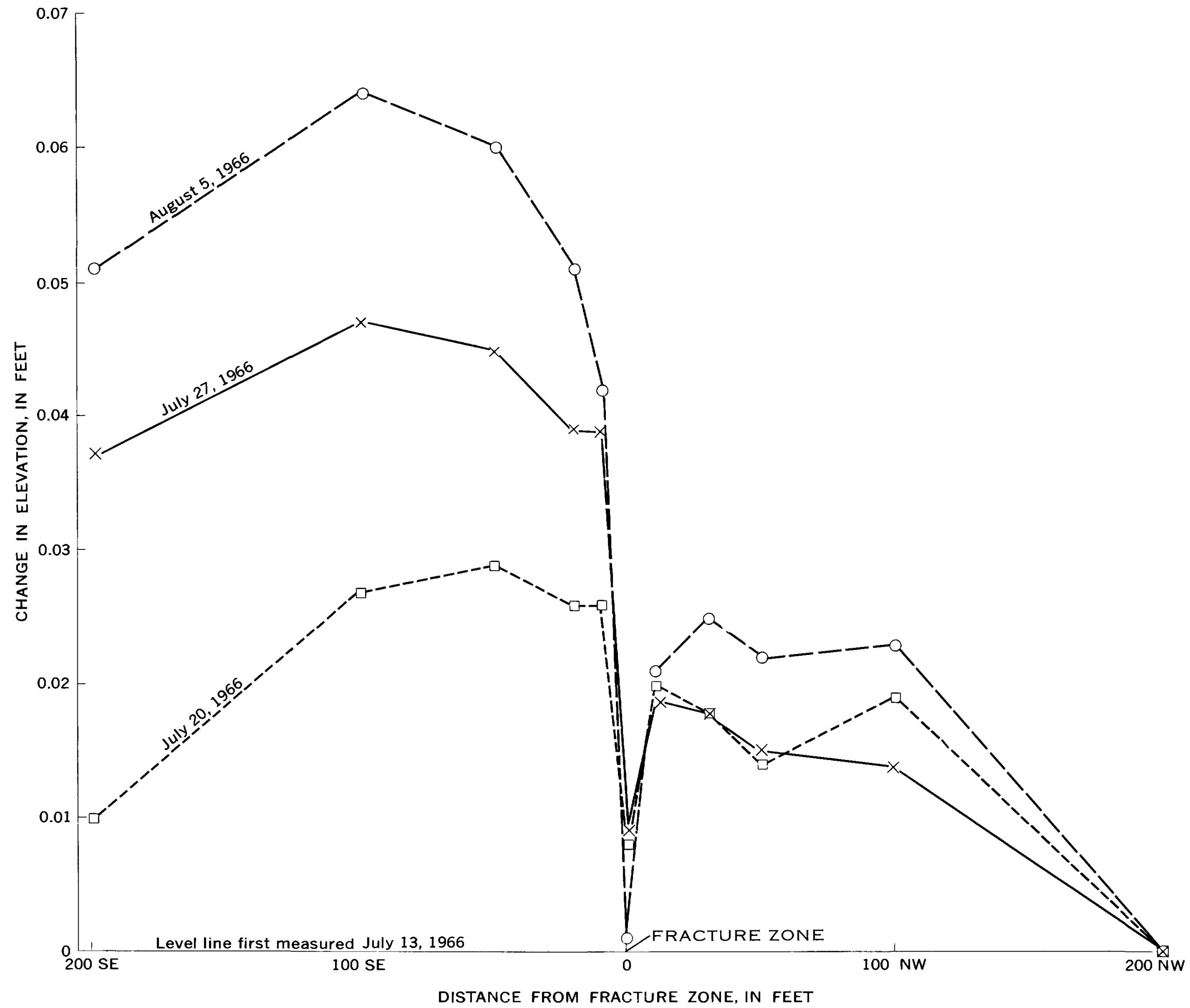


FIGURE 20.—Relative change in elevation with time of points along centerline of Cholame-Parkfield road where fracture zone crosses 3.2 miles northwest of Highway 46. Northwesternmost point arbitrarily considered constant.

ever, to serve as reference points to the exact location of the fracture zone.

DISPLACEMENTS MEASURED ON ROADS

The white centerline of Highway 46, 0.85 mile northeast of Cholame, was displaced in a right-lateral sense 1.8 inches by 7:00 a.m. (P.d.t.) on June 28 (Allen and Smith, 1966); the displacement increased during succeeding hours and days as shown on the graph (fig. 25) and in the photographs (fig. 26 *A*, *B*). The white line was painted June 6, 1966, and as far as can be determined, no fracture had formed before the earthquakes of June 27. After the original white line deteriorated near the fracture, new reference lines were painted (spray painted around a rectangular card of known dimensions) across the fracture on July 21. These lines remained undisplaced during the period July 21–28, but on August 3, 1½ hours after the aftershock of 5:39 a.m. (P.d.t.) (magnitude 3.4), the lines were checked and several were found to be displaced 0.1 inch. Very possibly the displacement was associated with the aftershock.

On July 21 other marks were painted across fractures in pavements at localities F27, F20, F10, and 200 feet southeast of F9. Of these, only one mark at locality F20 showed displacement, about 0.2 inch, on July 28; however, by 7:00 a.m. August 3, following the strong aftershock, displacements were registered at all local-

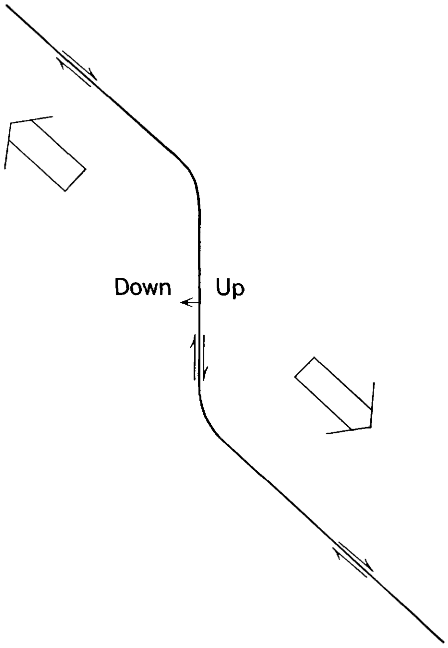


FIGURE 21.—Diagram of suggested linkage between two en echelon segments of San Andreas fault.

ities (although not all reference marks at each locality were displaced, as some were on minor fractures), and at locality F11 the displacement measured 0.4 inch. By afternoon of August 4, the 0.4-inch displacement had increased to 0.5 inch. These measurements, although somewhat crude, add to the evidence of progressive displacement, somewhat slow and sporadic between seismic events and greatly accelerated during earthquakes, even those of relatively small magnitude.

Figure 27 shows a diagram of fractures at locality F25 on Highway 46 as they were mapped at 4:00 p.m. June 28 and new fractures that formed between that time and July 21.

En echelon fractures may not have formed at locality F20 on the Cholame-Parkfield road 3.2 miles north of Highway 46 until the night of June 30, according to Julius Schlocker and Reuben Kachadoorian. Similarly, on June 28 fractures were looked for in the soil near a group of three pipelines 0.2 mile south of Highway 46 but were not identified, very likely because of interfering desiccation cracks; however, by June 30 en echelon fractures were very clearly defined, despite the desiccation cracks.

PROGRESSIVE DEVELOPMENT OF EN ECHELON CRACKS AND MOLE TRACKS

During the field examinations following the main earthquakes, it was apparent that numerous new tectonic fractures were forming, old ones were widening, and relative vertical displacements of several inches were developing.

Figure 28 shows two photographs of an area at locality F23, one taken at 7:00 p.m. June 28, the other on July 21. Note the much wider crack and greater microrelief on July 21. The relief is shown more clearly in figure 29 and is diagrammed in figure 17. No more than an inch or two relief was present on June 28, whereas relief of as much as 10 inches was recorded on July 21. On June 28 the "scissors" movement was clearly displayed on numerous fractures, but mounds or pressure ridges which make up the mole tracks were not obvious; however, a few days later mole tracks were very conspicuous. Figure 30 shows relief of about 0.5 foot, which developed near locality F23, in part after June 28.

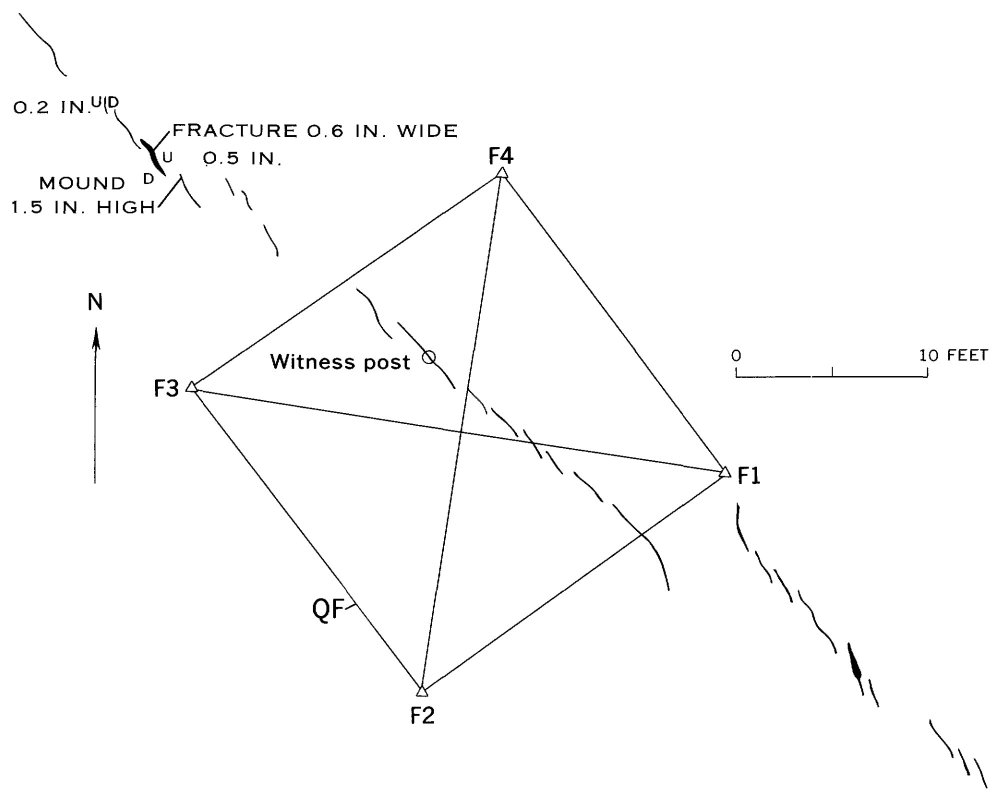
On June 28 many of the individual fractures of the en echelon system at Highway 46 and at locality F23 showed the steplike pattern of alternating open and tight fracture segments (fig. 12) clearly representing right-lateral strain. Robert D. Brown, however, reports that during the period June 29 to July 15 in the segment of the main fracture zone north of locality F18, most of the fractures showed separation normal to their trends. In early August many of these same fractures displayed a significant amount of right-lateral strike slip, indicating that original tension fractures had been progressively modified by strike-slip strain.

HISTORIC DEFORMATION PRIOR TO 1966

Displacement that took place before the 1966 earthquakes have been noted at various places in the area. Two fences and one bridge which cross the main fracture zone show clear evidence of strike-slip displacements considerably greater than any that has occurred since June 27. Three fences, two built in 1959 and one early in 1966, show misalinements virtually equal to strike slip represented by separation along fractures produced during the months following the June 1966 earthquakes.

On table 3, data related to the misalinement of the fences and the bridge are given. Since each misalinement can only be approximated because of irregularities and original misalinements, a maximum and minimum are given, and even these limits are somewhat subjective. Strike slip produced during the recent earthquakes was estimated from the strike-slip component of separation of walls of fractures in soil near the structure.

A fence of wooden posts and barbed wire, the Claassen fence, trends approximately east across the main fracture zone (strike N. 40° W.) in the SW¼ sec. 26, T. 22 S., R. 13 E., Stockdale Mountain 7½-minute



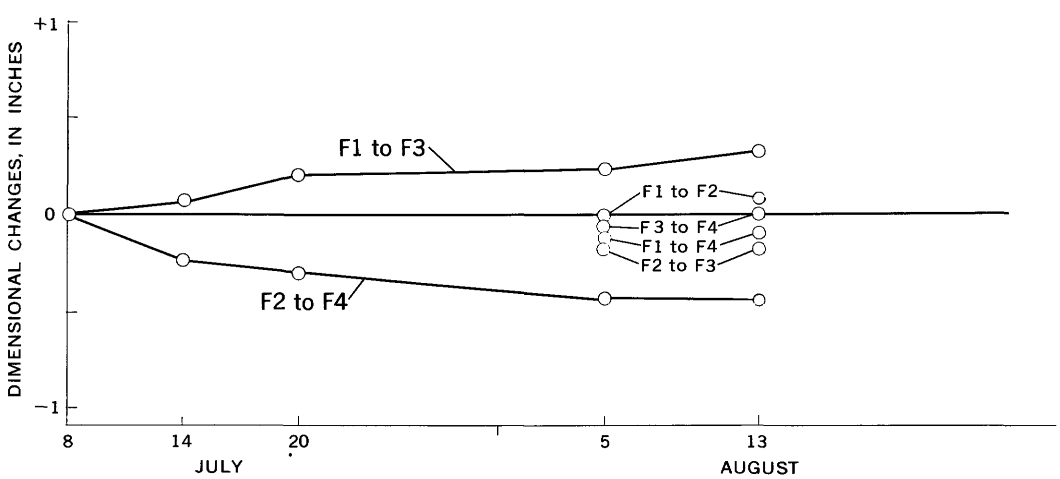


FIGURE 22.—Plan of quadrilateral QF (showing fracture pattern) and graph of dimensional changes with time.

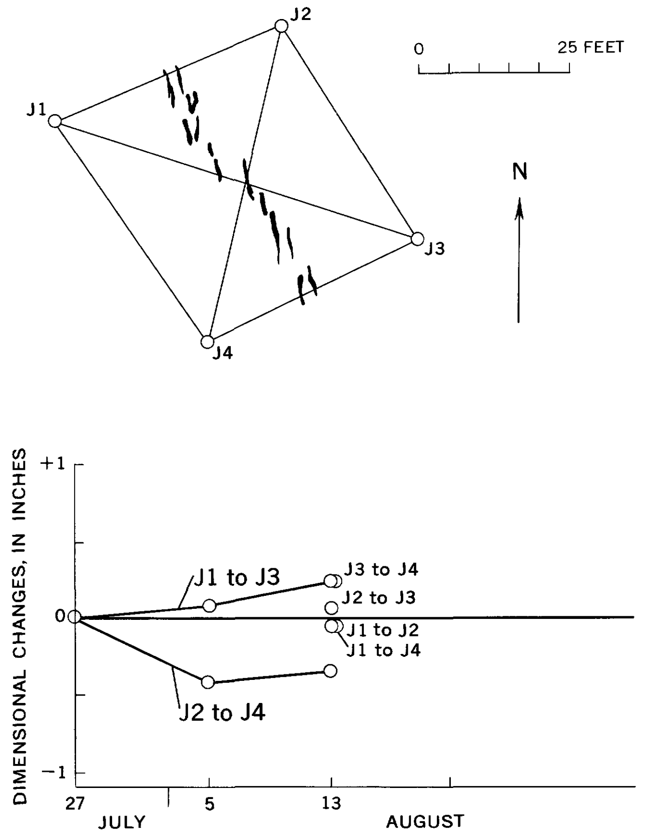


FIGURE 23.—Plan of quadrilateral QJ and graph of dimensional changes with time.

quadrangle. A photograph (fig. 31) shows the misalinement and the topography over which the fence is built. Strike slip appears to have been confined to a zone no more than 20 feet wide, probably less, although posts on the steep slope just east of the fault are tilted and shifted slightly by downhill movement of soil. Arthur Claassen states that he rebuilt this fence about 20 years ago and, although uncertain of the exact date, knows that it was soon after World War II.

TABLE 3.—*Data related to misalinement of fences and bridges*

	Date installed	Maximum and minimum estimated misalinement (inches)	Strike slip represented	1966 strike slip estimated from ground fractures (inches)	Minimum and maximum rates of strike slip indicated (inches per century)
Highway 46 fences	1959	5–7	5–7	4.6	------------
Turkey Flat Road fence	1966	1.5–2.5	1.5–2.5	2.5	------------
Claassen fence	1946	12–18	16–24	2	80–120
Parkfield bridge	1932	17–18	22.5–24	2.5	66–71
Cholame Ranch fence	1908	18–25	18–25	7	31–43

Significantly, the fence is misalined by at least 10 inches more than the strike slip accompanying the recent earthquakes, and yet no earthquake greater than magnitude 5 has occurred in the area since the fence was built. Perhaps tectonic creep or slippage accounts for the discrepancy or perhaps unreported surface fractures accompanied the small earthquakes of November 16, 1956, October 10, 1958, and July 31, 1961 (McEvilly, 1966).

A fence of wooden posts and barbed wire trends N. 45° E. across the fracture zone at locality F23, 1.9 miles northwest of Highway 46 (fig. 32). This fence shows fairly good alinement east of the fault trace but west of the trace has a slightly arcuate bend within the first 50–60 feet. Most of the present misalinement is between two fence posts, and the maximum and minimum misalinements given in table 3 represent misalinements of segments immediately adjacent to the fault trace and segments farther from the trace, respectively. Mr. Howard V. Jack reported that this fence was built in 1908, the year before he came to the Cholame Ranch, and that the fence had not been realined since. There is evidence of repair, however, and another man on the Cholame Ranch believed that the fence was repaired or rebuilt in the early 1920's. It is difficult to imagine that a fence would not need considerable work in a 60-year period. The present misalinement of 18 inches within about 20 feet of the fracture zone may not represent the entire displacement since 1908, and if the fence was repaired at the fracture zone, the maximum of 25 inches, representing misalinement of segments farther from the trace, may be the more meaningful figure.

Fences along the highway right-of-way both north and south of Highway 46 were completed in October 1959 according to Mr. W. A. Saunders of the San Luis Obispo County Highway Department. Present misalinement of these fences matches, as nearly as can be measured, the amount of strike slip represented by fractures in the ground and highway, about 5 inches.

A fence on the north side of Turkey Flat road 1.7 miles southeast of Parkfield that was realined early in 1966, according to Mr. Robert Durham, shows a misalinement about equal to the strike slip represented by ground fractures, approximately 2.5 inches.

The bridge over Little Cholame Creek 0.3 mile south of Parkfield shows pronounced misalinement of the girders immediately under the deck although the deck itself is only slightly bowed in plan (figs. 33*A*, 42). Figure 33*A* shows a diagrammatic plan of the steel I-beam girder supporting the north side of the bridge deck. The girders between bents 2 and 3 and bents 3 and 4 from the west end, both sections of which lie over the fracture zone, are decidedly misalined, although the eastern three sections (bents 4–7) are fairly well alined. The present concrete deck was poured directly over the misalined girders so that the top part of the I-beam is

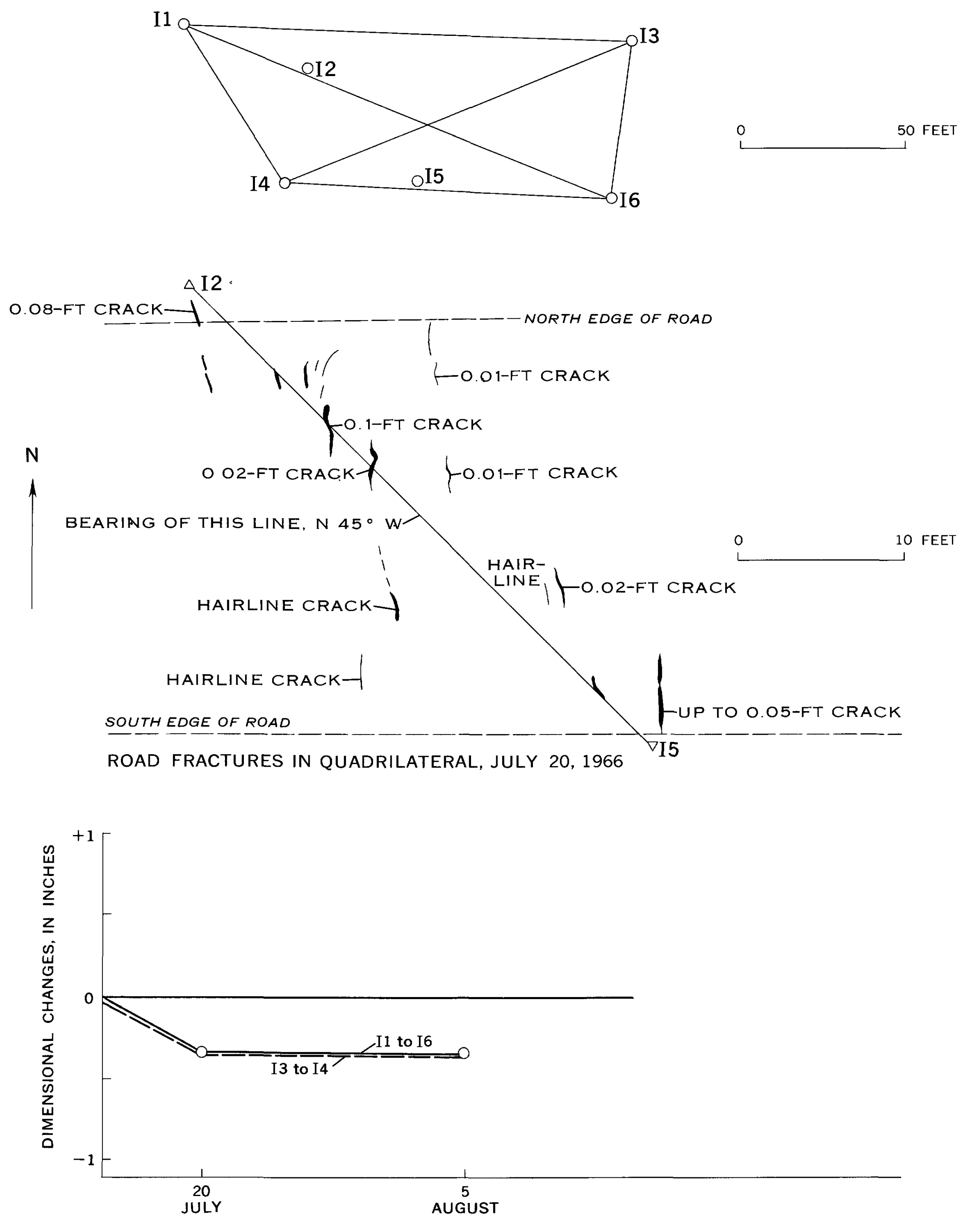


FIGURE 24.—Plan of quadrilateral QI and graph of dimensional changes with time.

now encased in concrete (fig. 33*B*). No chipping or cracking of the concrete at the junction with the **I**-beam was noted, indicating that the principal misalinement of the **I**-beam came about before the deck was poured.

According to Mr. Graebe of the Monterey County Road Department, this bridge was built in 1932 and was redecked in 1960. The misalinement thus represents displacements between 1932 and 1960, and much of this misalinement, although possibly not all, resulted during the 1934 earthquake, for residents of Parkfield report that considerable damage was done to the bridge in the earthquake of 1934. Strain produced during the recent earthquakes seems limited to possible slight bowing of the deck, twisting of some bents, and a maximum

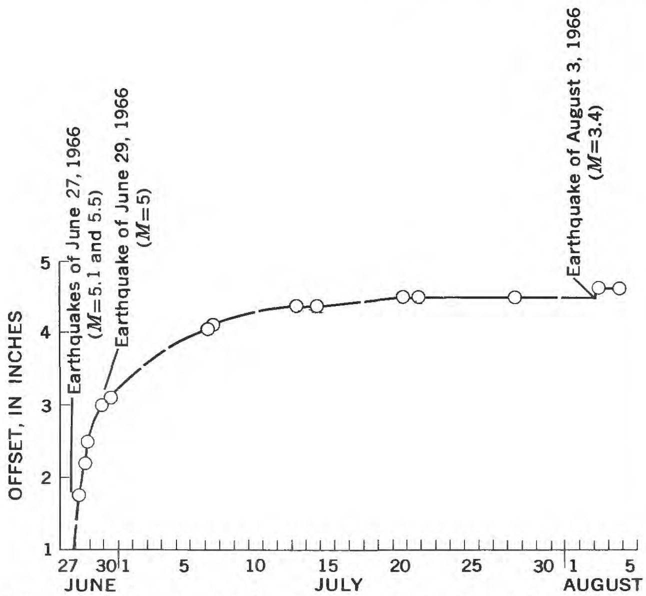


FIGURE 25.—Graph of offset of center white line on Highway 46, 0.85 mile northeast of Cholame. M=magnitude.

extension of the span of 7.9 inches as measured by maximum partings of 3 and 2.5 inches at the west and east abutments, respectively, and 2.4 inches at the center expansion joint.

Although a clear history of fault movement cannot be determined from the offset of these structures, an order of magnitude of the rate nevertheless can be suggested. The range in rates is between 31 and 120 inches per century. By a subjective evaluation of the numerous variables in the evidence observed, the upper limit for the Cholame Ranch fence and the lower limit for the Claassen Ranch fence probably can be considered a more realistic set of limits, that is, between 43 and 80 inches per century. To compare these rates with those interpreted for longer periods of geologic time, it can be pointed out that 60 inches per century is equivalent to about 1 mile in 100,000 years, 10 miles in 1,000,000 years, and 100 miles in 10,000,000 (early Pliocene). The rate suggested by the history here thus is consistent with hundreds of miles of strike slip during the Tertiary Period.

PRECURSORY EVENTS

Allen and Smith (1966) report that on the Taylor Ranch 1 mile southeast of Parkfield very fresh-appearing en echelon cracks were noted on June 16, 1966 (fig. 34), and that the Cholame-Parkfield road about 2.4 miles southeast of Parkfield had required repair several times during the preceding 2 or 3 years at the point where the fault trace crosses.

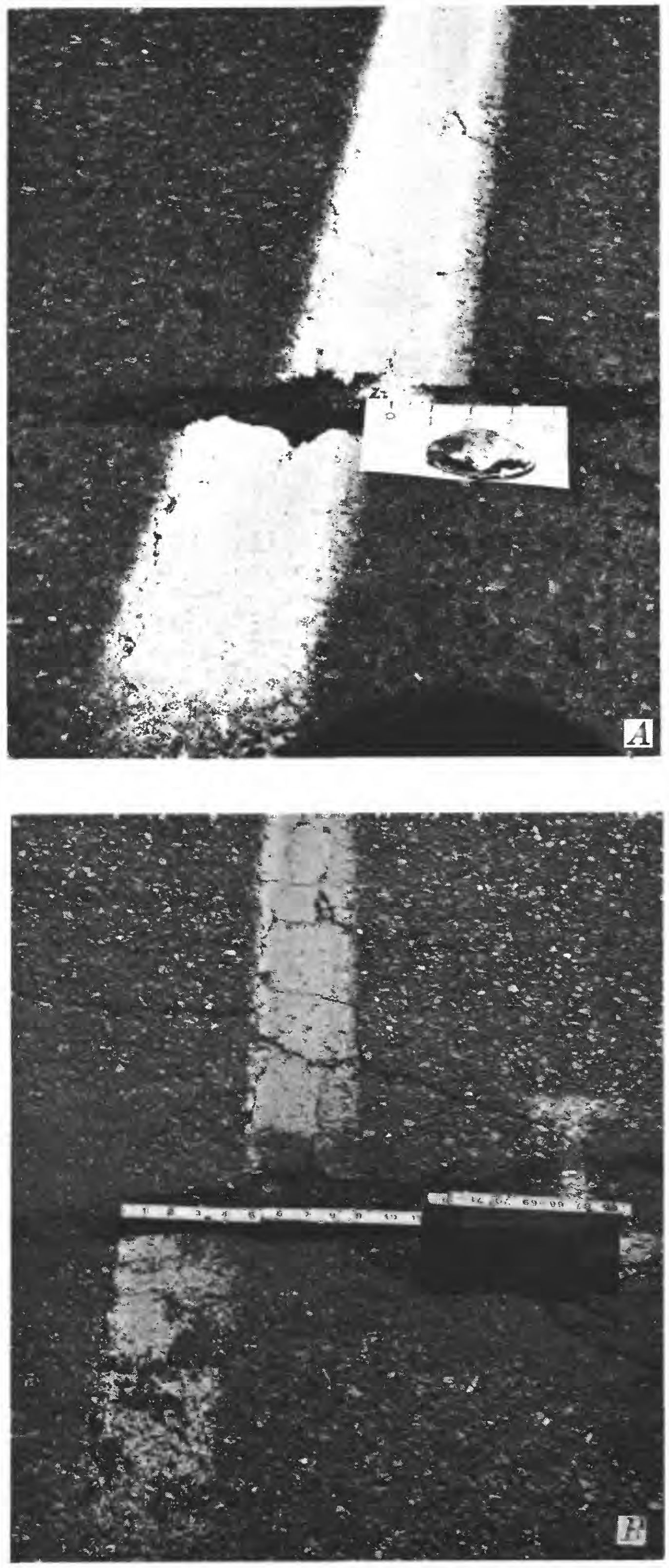


FIGURE 26.—White centerline on Highway 46, 0.85 mile northeast of Cholame showing offsets along a fracture in the San Andreas fault zone. *A*. 4:00 p.m. June 28. *B*. 8:00 a.m. August 4.

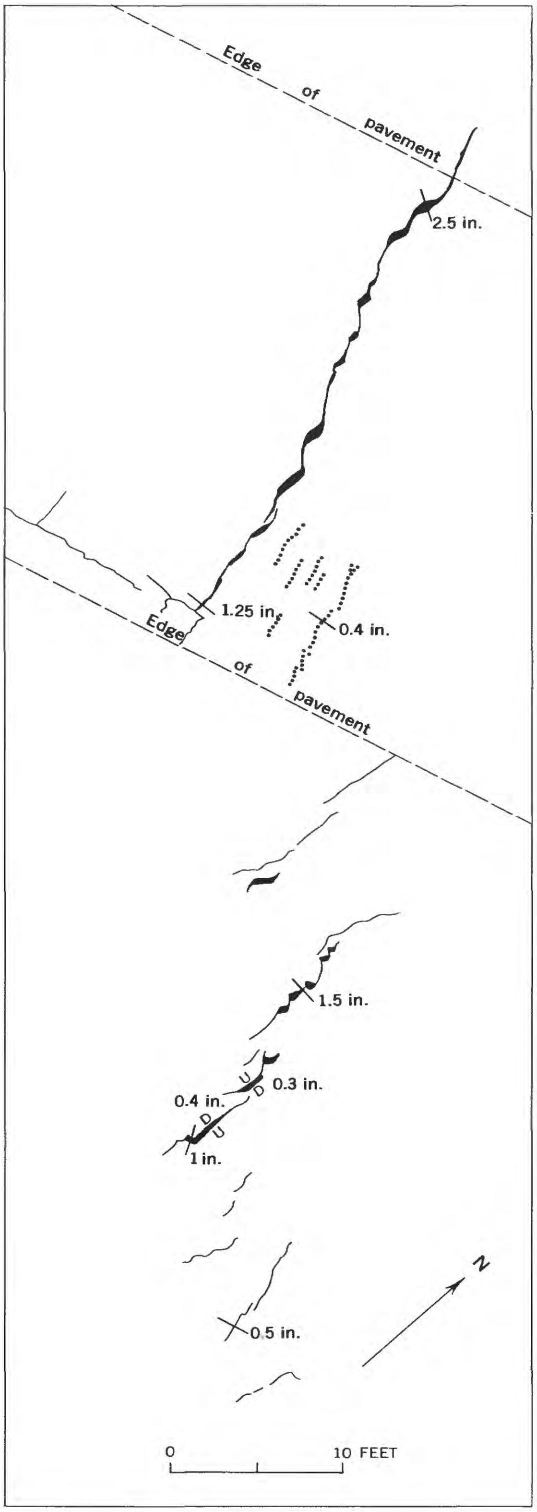


FIGURE 27.—Map of fractures in Highway 46, 0.85 mile northeast of Cholame. Solid mapped June 28; dotted mapped July 21. Numbers indicate width of fracture in orientation shown. U, upthrown side; D, downthrown side.

FIGURE 28.—Growth of a fracture at locality F23 between June 28, 7:00 p.m. (*A*) and July 21 (*B*).

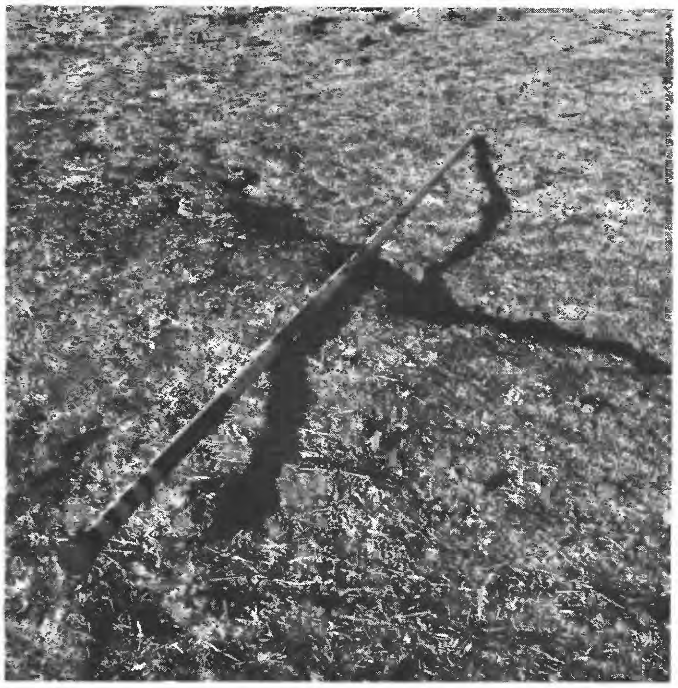


FIGURE 29.—Fracture (also shown in fig. 28) showing relief. Photograph taken July 21, 1966.

FIGURE 30.—Relief across fracture zone, view looking northeast near locality F23.

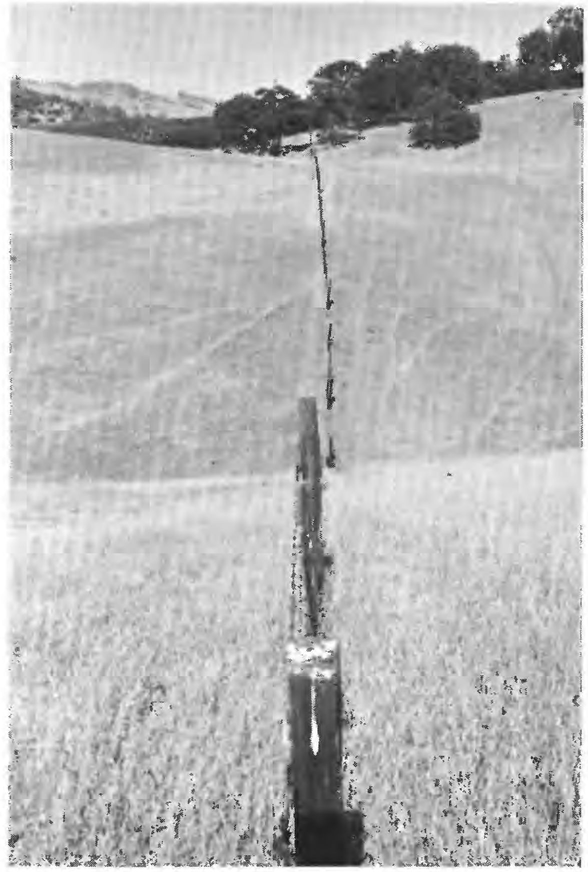


FIGURE 31.—View looking east along Claassen fence.

Another piece of evidence, although questionably related to tectonic strain, bears reporting. An irrigation pipe (fig. 48*B*) broke about 9 hours before the earthquakes of June 27. The details are reported in the section on "Engineering geology aspects." We have formulated no certain interpretation of the cause of the break, but its proximity to the fracture zone—although all sections of the pipe affected lie east of the zone—and the precursory timing make the event of particular interest. If the break was a result of strain in the block immediately east of the fracture zone, it produced no obvious effects in the ground surface. At several places along the east side of the main fracture zone, however, as at locality F23, a broad arch 50 or more feet wide represents distinct tectonic strain, possibly including shortening in plan. Progressive shortening of the sides of quadrilaterals, for example, of QA and QB (fig. 16), following the earthquakes

FIGURE 32.—View looking west along fence at locality F23.

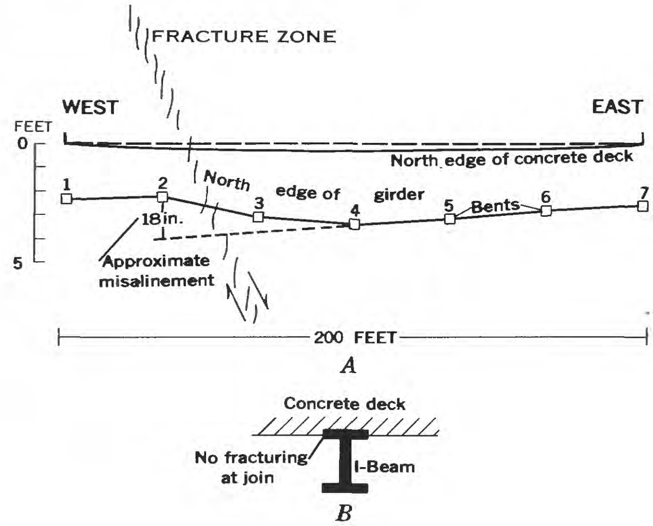


FIGURE 33.—Diagrammatic plan showing misalinement of I-beam girder at Parkfield bridge (*A*) and cross section (*B*) of I-beam showing no fracturing at joint between deck and beam.

may represent this same type of strain. This type of strain also may account for the slack developed in telephone wires between two poles lying 10 and 115 feet, respectively, east of the fracture zone along the south side of Highway 46. We do not know when the slack developed, but it was repaired on June 28.

ENGINEERING GEOLOGY ASPECTS

By R. F. YERKES and R. O. CASTLE

The Parkfield-Cholame earthquakes of June 1966 (table 1) were felt over an area extending from Santa Cruz (116 miles northwest of the epicentral area) to Oxnard (140 miles southeast) and the foothills of the Sierra Nevada (92 miles northeast) (McEvilly, 1966, p. 969), but the known permanent (as contrasted with transitory) effects of the earthquakes were confined to the narrow alluviated Cholame Valley and adjoining areas. Despite the restricted distribution of permanent effects, the earthquakes are of particular significance to engineering geology in two important respects:

1. The three largest shocks of this sequence, which had provisional Richter magnitudes of 5.1, 5.5, and 5.0 (McEvilly, 1966), were accompanied by the formation of two narrow subparallel zones of en echelon tectonic surface fractures, one at least 23½ miles long that developed along preexisting faults of the San Andreas zone. Moreover, creep and similar forms of movement continued along the zones for at least 7 weeks following the June earthquakes. Such extensive tectonic fracturing of the ground surface is not known to have accompanied earthquakes of such small magnitude but rather has been associated with earthquakes of Richter magnitude about 7, as based on pre-1955 records for California north of lat 35°30′ and for Nevada (Tocher, 1958, fig. 2, p. 150; see also Allen and others, 1965).

2. Terrain and structural effects of the earthquakes indicate Modified Mercalli intensities as high as VIII as noted by McEvilly (1966, p. 969) and locally perhaps IX. Preliminary evaluation of the records from 16 seismoscopes and 5 strong-motion seismographs (one on State Highway 46 within 250 ft of the main fracture zone) indicate that the earthquakes produced a short-duration horizontal acceleration of 0.5g (Cloud, 1966). Correlation of the records of these instruments with those of timed instruments placed nearby indicate that this acceleration is best attributed to the magnitude 5.5 shock of 9:26 p.m. P.d.t. on June 27. As in tectonic fracturing of the ground surface, epicentral intensities and accelerations of this degree have commonly been correlated with earthquakes of magnitude about 7, whereas only much smaller accelerations and intensities, 0.07g and VI–VII, have been correlated

FIGURE 34.—Fractures along trace of San Andreas fault 1 mile south of Parkfield. Photograph taken June 16, 1966, by Dr. Keichi Kasahara of the Earthquake Research Institute, University of Tokyo during Second United States–Japan Conference on Research for Earthquake Prediction.

with earthquakes of magnitude 5.5 (Gutenberg and Richter 956, p. 132).

This report describes and illustrates those effects of the June earthquakes that are significant to engineering geology and relates them to the geologic environment. Partial support for the investigation was provided by the Division of Reactor Development and Technology, Atomic Energy Commission.

The investigation, which began on July 7, 10 days after the main shocks of June 27, focused on effects to terrain and manmade structures. All bridges of Highway 46 east of Paso Robles were systematically examined eastward to the Kern County boundary 8 miles east of Cholame. Spot checks were made and interviews were conducted with local residents along the main roads. From Highway 46 the observations were extended northwestward along Cholame Valley and Little Cholame Valley to about 4 miles northwest of Parkfield and also southeastward along the San Andreas fault zone for about 8 miles. Most of the investigation was concentrated in the Little Cholame Valley–Cholame Valley area between Parkfield and Cholame (fig. 35).

The conclusions based on this investigation are tentative in that (1) it was not feasible to systematically survey all outlying areas, especially the more hilly areas east of the San Andreas fault zone, and (2) evaluation of earthquake intensity is based in part on effects to manmade structures, which are few and which are concentrated in or near alluviated areas generally near the fault zone.

EFFECTS

The effects associated with the Parkfield-Cholame earthquakes are classified by origin as direct or primary (due directly to fault movement) and indirect or secondary (due to shaking during the passage of seismic waves). They are also classified by object affected, such as terrain, manmade structures, loose objects (free, or partially free, to move relative to the ground), and miscellany. The classification (fig. 35) is adapted from Richter (1958, p. 81). Most of the significant nonterrain effects are attributed, on the basis of eyewitness descriptions, to the second major shock of June 27, 1966 (9:26 p.m. P.d.t.; magnitude 5.5); the first major shock (9:09 p.m. P.d.t. June 27; magnitude 5.1) caused only mild alarm and no known damage.

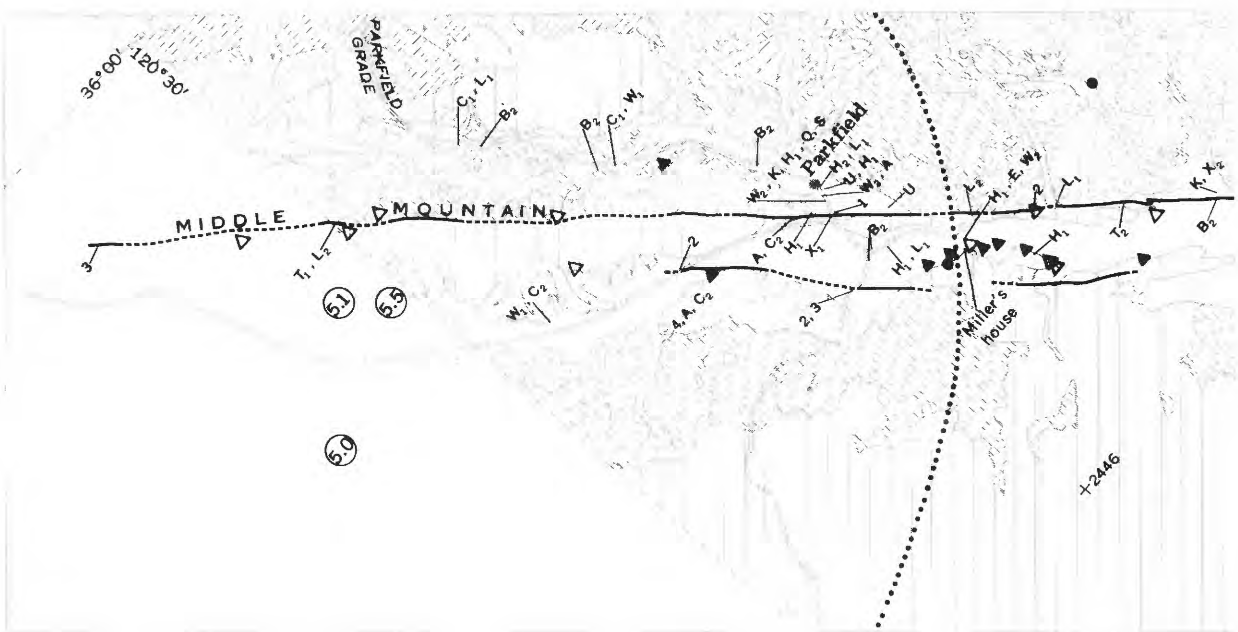
PRIMARY EFFECTS ON TERRAIN

The most spectacular and significant effects on terrain are the two zones of well-defined en echelon tectonic fractures and intervening pressure ridges or mounds that mark the traces of right-lateral strike-slip movement. The main fracture zone extends from the epicentral area northwest of Parkfield for 23½ miles southeastward to beyond Cholame (fig. 35); the southwest fracture zone is less than 1 mile southwest of the longer zone and extends about 5.5 miles southeastward from the latitude of Parkfield.

SECONDARY EFFECTS ON TERRAIN

Secondary effects on terrain, attributed to seismic shaking, consist chiefly of slope failures of several types: soil falls, block glides, debris slides, and slumps (classification and terminology after Varnes, 1958). Most of the slope failures are small in size, and a few large reactivated slumps moved only slightly. Some slumps affected manmade structures, and a few small slope failures locally dammed small dry drainages.

All but one of the known slope failures are concentrated in an elongate band about 2 miles wide that



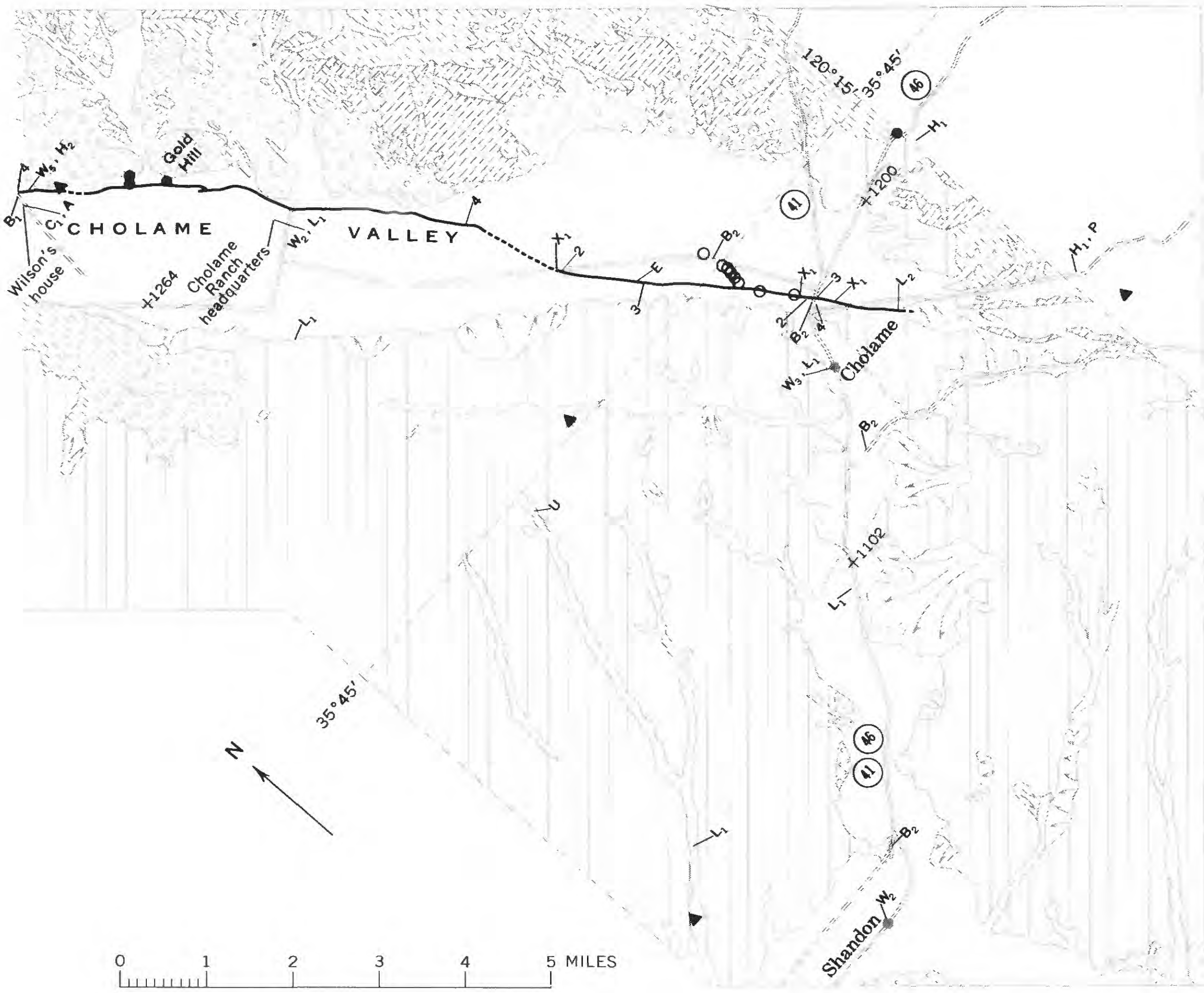
ENGINEERING GEOLOGY EFFECTS OF THE PARKFIELD-CHOLAME EARTHQUAKES OF JUNE 1966 [Classification of effects modified from Richter (1958, p. 81)]						
Effects:	Direct or primary effects (Due to fault movement)		Indirect or secondary effects (Due to passage of elastic waves)			
	Map key		Map key	Permanent effects	Map key	Transitory effects
Terrain		Fractures and offsets		Slope failures[1]		
		Pressure ridges (Extensively developed along fracture zones; see Brown and Vedder, this report).	●	Soil falls		
			○	Block glides		
			▲	Debris slides		
			△	Slumps (chiefly reactivated)		
			X_1	Deposits of sand, silt, or dust ejected by fluids		
Manmade structures		Deformed by bending, twisting, or rending:		Damaged by shaking:		
				Chimneys:		
	1	Bridges	C_1	Collapsed or toppled[2]		
	2	Roads	C_2	Cracked or separated from building		
	3	Fences		Walls (masonry):		
	4	Pipelines, canals, dam	W_1	Disrupted by extension[2]		
			W_2	Cracked		
				Walls (wood frame):		
			W_3	Separated at joins with annexes[2]		
			W_5	Siding detached—nails pulled out during rocking of frame		
			K	Concrete slab shifted or cracked		
			B_1	Bridges: Swaybraces of bents buckled, partial bearing failure		
			B_2	Abutments cracked or displaced; fill buckled or settled at aprons;[3] concrete deck spalled		
			A	Anchored fixtures pulled or snapped from fittings (water heaters, toilets, bell post)		
			U	Unanchored building or water storage tank shifted or toppled during collapse of support		
Loose objects			S	Automobiles shifted laterally	Q	Anchored objects swung or whipped (flagstaffs, chandeliers)
			H_1	Heavy objects shifted or projected (furniture, water heaters, monuments)		
			H_2	Heavy objects overturned (water heaters, stacked goods)		
			L_1	Light objects shifted, projected, or overturned (lamps, shelf goods, pictures)		
			L_2	Light objects displaced (cobbles, boulders)		
Miscellaneous	T_1	Tree split by fracturing	E	Wires parted (overhead, fence, or guy)	P	People had difficulty standing or walking
			T_2	Large tree broken off near ground level	X_2	Seiche in small reservoir

[1] Classification and terminology after Varnes (1958); slope failures in turn damaged manmade structures (roads, earthfill dam, swimming pool) by cracking or disruption; they also produced cracks and other effects similar to those produced by fault movement

[2] Damage impairs utility or safety of structure

[3] Locally includes minor damage to fill at aprons by slope failure

Figure 35.—Distribution and types of effects that accompanied the Parkfield-Cholame



EXPLANATION*

Trace of fracture zone formed during June and July 1966. Dashed where poorly formed or concealed. Mapped by R. D. Brown, Jr. and J. G. Vedder

5.5

Preliminary instrumental epicenter of main shock sequence of June 27-28, 1966, after McEvilly, (1966). Figure gives magnitude; inferred location error shown by dotted arc

+2446

Spot altitude, in feet above mean sea level

*Geologic units are explained in figure 3

earthquakes of June 27–28, and selected geologic features of the Cholame Valley region.

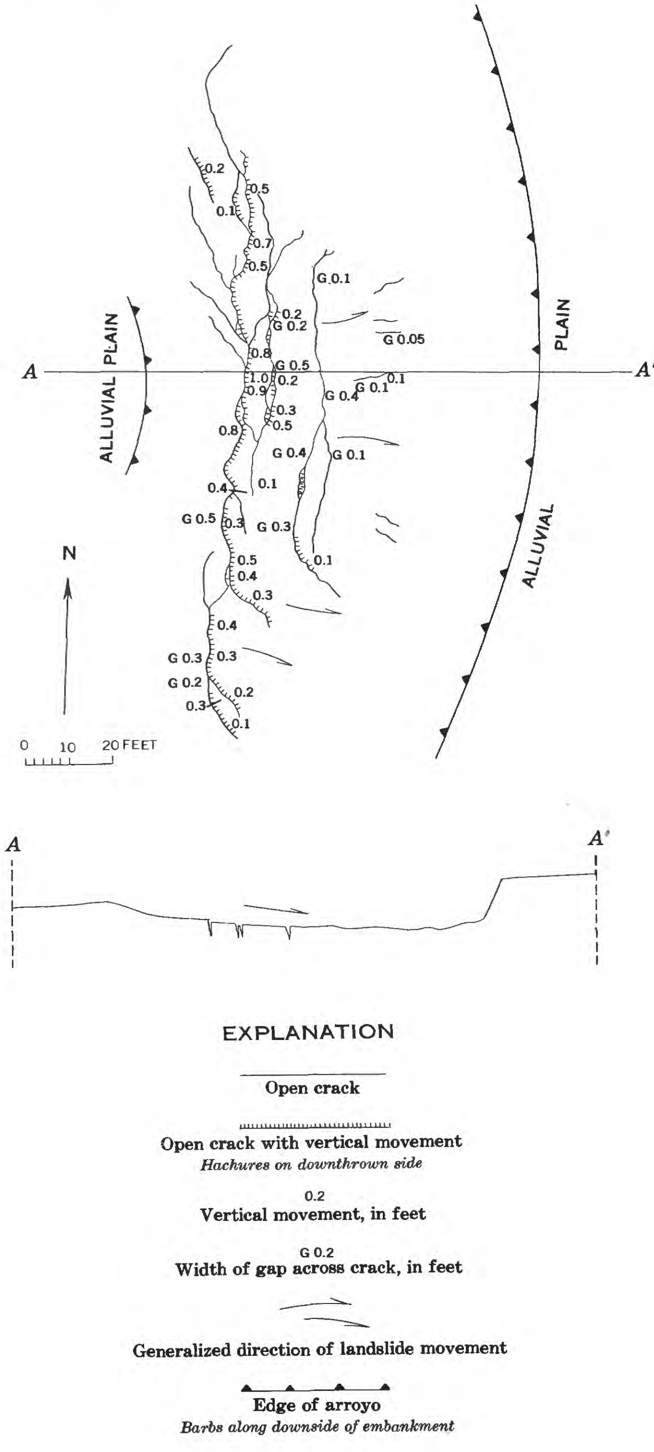
A

parallels the fracture zones. One of the most extensive debris slides occurred in semiconsolidated material of the Paso Robles Formation along a roadcut 3.7 miles southeast of Highway 46 along the trend of the fault zone; the roadcut is about 10 feet high and slopes at about 45°. The main fracture zone trends along the crest of Middle Mountain northwest of Parkfield, and the slopes of the ridge bear evidence of many preexisting slope failures, chiefly large slumps. Numerous fresh headwall fissures near the ridge crest indicate that many of these slumps were slightly reactivated during the earthquakes; dust clouds that were sighted over this area during the daylight hours of June 29 suggest that some failures accompanied the earthquakes of that day. One isolated slope failure, a small debris slide, occurred in a cut along McMillan Canyon road, 2.5 miles northwest of Shandon and 6.8 miles southwest of the main fracture zone; the cut slopes at about 70°, is about 8 feet high, and is underlain by semiconsolidated material of the Paso Robles Formation.

Block glides

Small block glides occurred on 5°–10° slopes at the inside of almost every meander of Cholame Creek, which is incised to depths as great as 9 feet (fig. 36), in the area just north of State Highway 46. These slopes are underlain by clayey soil above and fine-grained well-sorted sand and clayey silt below. Although the ground surface was dry and cracked, material from 3 to 4 inches below the surface was damp, and standing water locally occurs along scour channels in this part of the creek; it was not determined to what extent moisture content of the soil contributed to these failures.

Small dry soil falls, chiefly along steep banks in clayey soils, occurred along many drainages of the area.



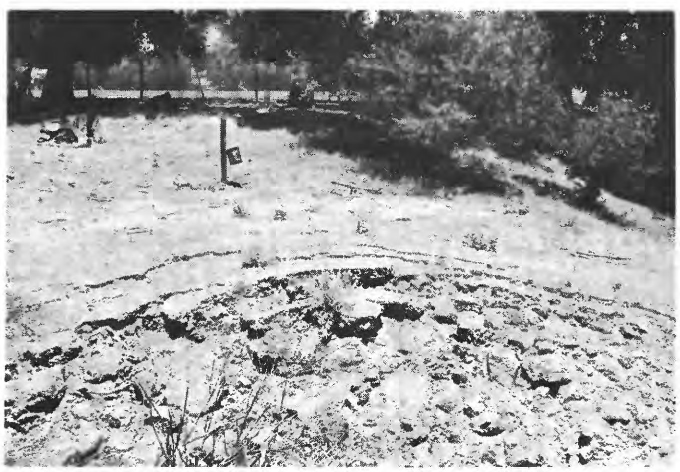
B

FIGURE 36.—Block glide inside of meander, west side of Cholame Creek just east of Parkfield road, 2 miles north of Cholame. *A*. View southward. *B*. Sketch map, by M. G. Bonilla and R. F. Yerkes, July 6, 1966.

Debris slides

Debris slides occurred in gently dipping, clayey, silty, or sandy semiconsolidated sedimentary rocks of the Paso Robles Formation, as well as in soils developed on these materials. Most such slides in the Paso Robles are in steep roadcuts or streamcuts 15–40 feet high that had original slopes of 70°–75° (fig. 37).

A



B

FIGURE 37.—Debris slides. *A*. Slide and toppled tree in Paso Robles Formation along west cut of road just northwest of Parkfield cemetery, half a mile southeast of Miller's house, and about midway between the fracture zones. Original cut slope was about 15 feet high at an angle of 70°–75°. *B*. Headwall fissures of small debris slide in alluvial deposits along north bank of Cholame Creek, near north end of southwest fracture zone.

Slumps

Natural slopes as low as 20°, generally underlain by dry soil and clayey silt or mudstone of the Paso Robles Formation, locally failed through slight reactivation of preexisting slumps. These failures were characterized by linear-to-arcuate slightly open headwall fissures (tension cracks due to lateral spreading toward an unconfined face) as long as 12 feet; the downslope blocks commonly dropped 1–2 inches across the fissures. Fissures of this type were traced completely across the crest of a long west-trending ridge between the fracture zones about 1 mile southeast of the Miller house; they also outline the margins of an extensive preexisting landslide more than 1,500 feet long (fig. 38). A slump about 600 feet in diameter, along the east bank of Cholame Creek about 1 mile northwest of Gold Hill and immediately east of the main fracture zone, was reactivated. Large arcuate fissures, with vertical separation of as much as 1.5 feet, opened at the heads of many lobes of this slump (fig. 39), and a pressure ridge about 6 inches high formed in the alluvial gravels of the stream bottom about 20 feet away from and opposite the toe of the failure.

Structural damage associated with slope failures occurred where structures had been placed across the margins of slumps that were slightly reactivated, chiefly in the area between the fracture zones just south and southeast of Parkfield. Headwall fissures extended more than 225 feet along the margin of a reactivated slump near the Miller house, intersecting and cracking a swimming pool (fig. 40). These fissures trend subparallel to the north bank of Cholame Creek between 20 and 40 feet away from the top of the bank; vertical separation across the fissures was about half an inch and wall separation about an inch. The slump movement also snapped strands of a barbed-wire fence that crosses the fissure at right angles.

Other secondary effects on terrain include a dry ejection deposit of dust and silt near the main fracture zone just south of Highway 46 (fig. 41) and small silt or sand deposits formed during ejection of water at several known localities along the main fracture zone: on the west bank of Cholame Creek just north of Highway 46 (fig. 14*C*) immediately east of the Cholame-Parkfield road about 3.3 miles northwest of Highway 46, and in Little Cholame Creek just north of the Parkfield bridge. In addition to the fluid-ejection deposits, several water spouts were reported to have occurred along Cholame Creek in the area between the two fault zones. Although these were not verified during the field investigation, the report can be credited in view of the known ejection deposits.

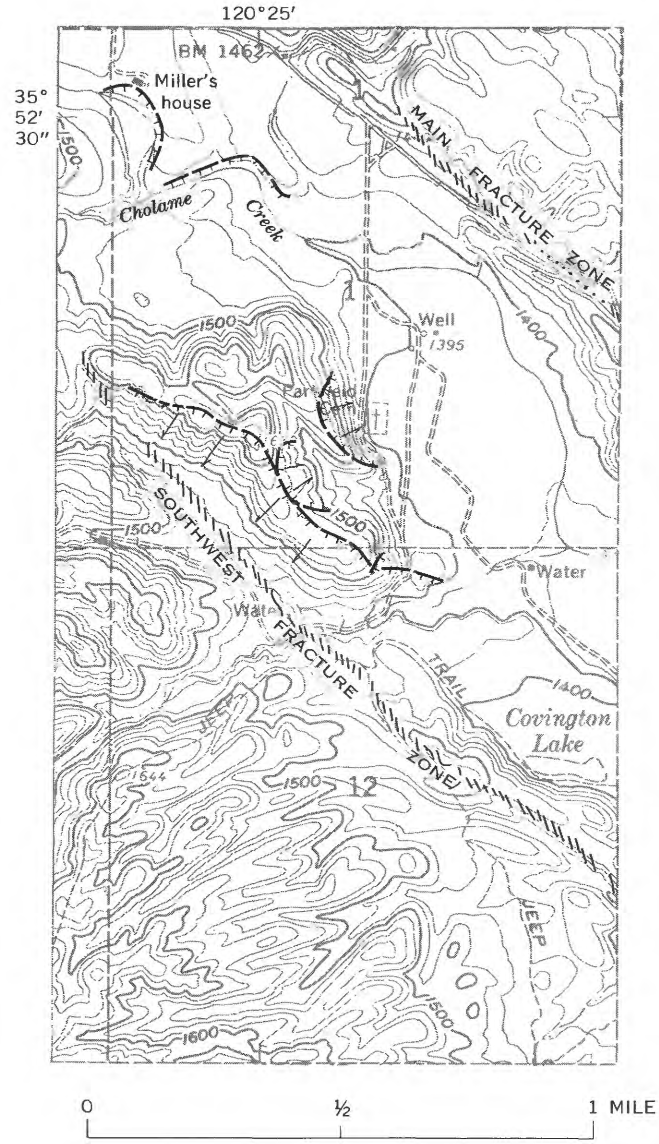


FIGURE 38.—Area between fracture zones about 2 miles south of Parkfield, showing distribution of fresh fissures at heads of new debris slides in alluvial deposits along Cholame Creek and at heads of slightly reactivated slumps in the Paso Robles Formation southwest of the creek. Mapped during July 1966; base from Cholame Hills and Parkfield 1:24,000 topographic quadrangles; area in northeast corner of T. 24 S., R. 14 E., Mount Diablo base and meridian; contour interval is 20 feet.

FIGURE 39.—View southward of new fissures within a large reactivated slump in alluvial deposits on east wall of Cholame Creek, about 1¼ miles northwest of Gold Hill. The main fracture zone is exposed near the toe of the slide in stream gravels at upper right.

FIGURE 40.—View northwest of swimming pool at Miller's house; pool was cracked along headwall fissure (more than 225 ft long) of slump in alluvial deposits. Slump was slightly reactivated during earthquakes of June 27. The major crack is continuous from slab in left foreground through pool to pool wall in background. See also figure 39.

PRIMARY EFFECTS ON MANMADE STRUCTURES

Primary effects on manmade structures consist of minor bending, twisting, or partial rending of structures or features that were affected by movement along the fracture zones: one bridge, several roads, fences, pipelines, a concrete canal, and an earthfill dam, all in the Cholame Valley area.

The Monterey County road bridge across Little Cholame Creek just south of Parkfield was slightly deformed by movement along the main fracture zone during the June 1966 earthquake. The bridge is about 200 feet long in east-west dimension and consists of a two-segment, flat concrete deck that rests on three steel I-beam girders. The girders are in turn supported by seven equally spaced bents, each of which consists of three steel piers that are secured by X-sway-braces.

The main fracture zone trends N. 52° W. between bents 2 and 3 as numbered from the west end of the

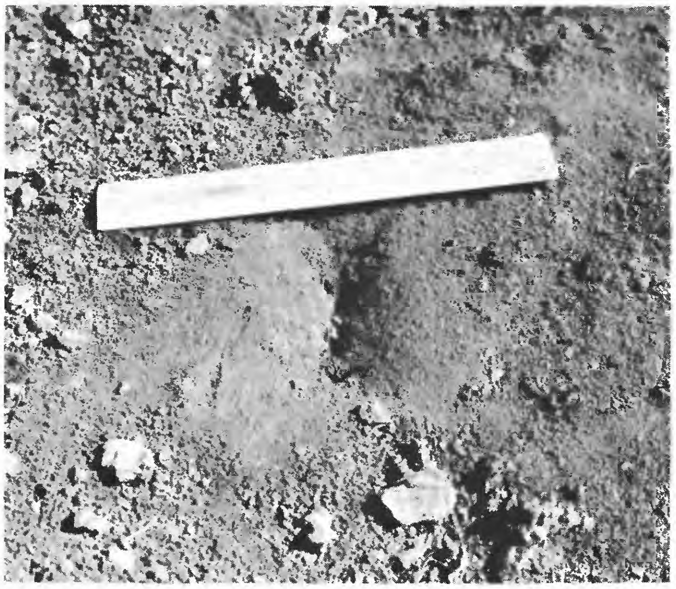


FIGURE 41.—Deposit of dust and silt ejected by air near main fracture zone south of Highway 46. Scale about 7 inches long. Photograph by Reuben Kachadoorian. See also figure 14C.

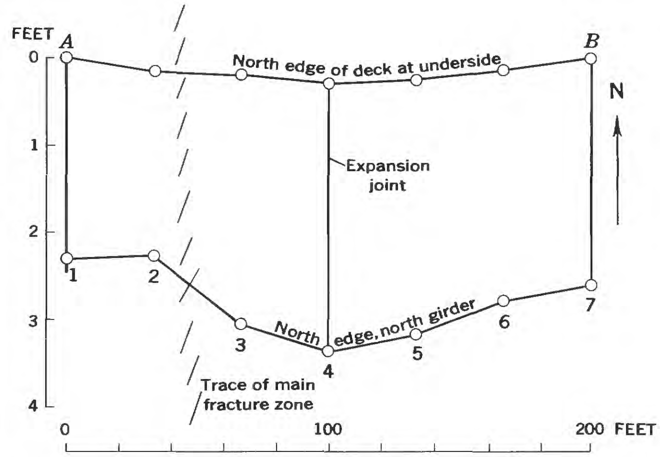


FIGURE 42.—Deformation of Monterey County road bridge (No. 438) over Little Cholame Creek just south of Parkfield. Configuration of north edge of concrete deck as measured at underside, and configuration of northernmost of three steel I-beam girders that support deck. Configurations based on measurements made by E. F. Roth in July and August 1966, at points opposite each of seven steel piers (numbered from west to east) that support the girder, with reference to a string that was tightly stretched between points *A* and *B* at lower edge of deck. Note great exaggeration (33⅓ ×) of north-south scale.

bridge (fig. 42). The steel bents on either side of the fracture zone are twisted out of plumb as much as 3° in a manner consistent with right-lateral offset of the ground in which they were set. The northernmost of the steel girders that support the deck is now out of alinement by 0.9 foot with reference to the north edge of the deck, and the deck itself is out of alinement by about 0.3 foot (fig. 42). Discussion with J. A. Graebe of the Monterey County Road Department indicates that the steel substructure of the bridge was built true and plumb in 1932 and that the original timber deck was replaced in 1960 by the present concrete deck on girders that were then about 1 foot out of alinement and were not realined. Most of the misalinement of the girders is here attributed to deformation between 1932 and 1960, some of which may have resulted from the Parkfield earthquake of 1934. The misalinement of the concrete deck is attributed to post-1960 deformation, some of which probably accompanied the June 1966 earthquakes: after the earthquakes the damp clayey alluvium around the base of the steel piers on either side of the fracture zone was freshly molded and segments of the deck were separated at expansion joints a total of 7.9 inches—3 inches at the west end, 2.4 inches at the center joint, and 2.5 inches at the east end. The molding of the soil was not symmetrical, as would occur during swaying of the bridge; rather, it indicates compression of the soil on the north side of piers east of the fault and tension on the south side. These relations were reversed at piers just west of the fault. The molding is thus consistent with right-lateral movement of the ground beneath the piers.

The fracture zones intersect paved or unpaved public roads at about ten localities in the Cholame Valley area. At each locality the fractures are well defined; many of them show right-lateral offset, and a few show vertical separation. Wallace and Roth (this report, p. 37) describe the cumulative right-lateral offset (4.7 in. by Aug. 4) of the centerline stripe of Highway 46, all the 4.7 inches being associated with the June 1966 earthquakes and subsequent creep. At six localities, barbed-wire cattle fences that cross the fracture zones are offset in a right-lateral sense and are extended by ground movement, some of which predates the June 1966 earthquakes.

Two buried pipelines were disrupted at or near the fracture zones during the night of June 27. A Union Oil Co. pipeline just south of Highway 46 was ruptured about 400 feet west of the main fracture zone, and although considerable oil was lost by leakage, the pipeline did not separate. A 2-inch private water service line on the southwest fracture zone near its north end separated, and service was lost during the 9:26 p.m. earthquake of June 27. The damage to both of these pipelines was repaired immediately.

A 4-foot-wide by 3-foot-deep concrete-lined irrigation canal in Cholame Valley 2.3 miles southeast of Cholame Ranch headquarters is intersected by the main fracture zone. When observed on July 13, the canal was cracked in several places near the intersection, but the age of the cracks could not be determined. One relatively fresh crack was open about an inch, and a right-lateral separation of the walls of about a quarter of an inch was indicated. The canal reportedly was in service during the day of June 27, but during the night developed leaks that destroyed its utility.

An unpacked earth embankment 4–6 feet wide and about 4 feet high forms a small circular irrigation reservoir about 40 feet in diameter, just west of Parkfield and on the main fracture zone. En echelon fractures of the zone were observed in the embankment, which did not fail; however, possible cracks in the floor of the reservoir may have caused leakage, as the water level was rather low when observed early in July.

It is noteworthy that the effects of subsurface movement were transmitted to the surface through, and expressed equally well in, dry semiconsolidated clastic material of the Paso Robles Formation, dry unconsolidated clayey soils, dry unconsolidated gravelly alluvium, and damp clayey alluvial sand. Fractures were also transmitted into and through loose earth embankments and artificially piled gravel (the latter near the east bank of Cholame Creek just southeast of Cholame Ranch headquarters).

SECONDARY EFFECTS ON MANMADE STRUCTURES

Most of the known secondary effects on structures occurred in alluviated areas within about half a mile of the fracture zones; the remainder are in the alluviated valley area between Cholame and Whitley Gardens, 12 miles southwest of Cholame (at one locality, not shown on map, a modern chimney was cracked in this alluviated valley 20 miles southwest of Cholame), and in the Choice Valley area within 7 miles of the southeast end of the main fracture zone and along its trend. Among the 50 or so houses and associated buildings in the Parkfield-Cholame area, structures and equipment that will require repair to restore their utility or safety include:

1. Five chimneys that were damaged. Two that were not reinforced collapsed completely in a manner suggestive of projection, and three were sheared at the top of the reinforcing near the roof line; the upper segments rotated or toppled (fig. 43).

2. Five unreinforced masonry walls that opened and extended (fig. 44) or the facing separated at the junction of wall and facing.

3. Wood walls and floors of two buildings, one in Parkfield and one in Cholame, that separated and opened at building joins.

4. One heavy unanchored building and two large water-storage tanks that shifted or toppled during collapse of supports.

FIGURE 43.—Selected examples of damaged chimneys. *A*. Half a mile northeast of main fracture zone and 2½ miles northwest of Parkfield. The 8-foot-long segment separated at the eaveline and toppled northeastward, directly away from the main fracture zone. *B*. Less than 0.1 mile west of the main fracture zone and about half a mile west of Parkfield. Upper part of chimney separated and rotated clockwise.

FIGURE 44.—Broken and expanded unreinforced adobe brick wall attached to frame house, on the Paso Robles Formation 1.2 miles southwest of main fracture zone and 3.5 miles northwest of Parkfield. Wall trends east-west. *A*. General view. *B*. Detailed view; scale is about 6 inches long.

In addition to the damage that requires repair, considerable minor damage occurred in the town of Parkfield, at the Miller house, the Wilson house, Cholame Ranch headquarters, and in the Shandon and Whitley Gardens areas; such damage included cracking of chimneys, concrete slabs, and plaster on adobe or wood-frame walls, or shifting of attached equipment and furniture. A Monterey County road bridge, which trends north-south across Cholame Creek near the Wilson house, swayed vigorously during the earthquake, as indicated by freshly buckled swaybraces on the steel bents and partial bearing failures where the swaybraces join the steel piers (fig. 45). The south end of the east abutment of the Highway 46 bridge across Cholame Creek near the main fracture zone was cracked and the parts separated slightly (fig. 46). Freshly patched pavement at the apron-abutment joins of most bridges in the Cholame Valley area indicate that the supporting fill was compacted and settled during the shaking.

Most of the structures that were damaged by shaking during the June earthquakes are on unconsolidated or slightly consolidated alluvial deposits or fill. Very few and only unreinforced structures (fig. 43) were damaged where built on more consolidated deposits, such as those of the Paso Robles Formation. Permanent effects due to shaking showed an apparent selective orientation in that unreinforced walls opened or extended along east-west trends, a bridge oriented north-south was damaged by lateral swaying, and bridges with east-west orientation were damaged by pounding at the abutments.

EFFECTS ON LOOSE OBJECTS

Loose objects (those free, or partially free, to move relative to the ground) are classified as heavy (furniture, water heaters, stone monuments) or light (lamps, shelf goods, pictures). Heavy objects were commonly shifted, and some overturned or projected, in alluviated areas within half a mile of the fracture zones.

At the Parkfield cemetery 1 mile southeast of the Miller house and between the two fracture zones, all but 1 of about 12 columnar stone monuments were toppled, and several were separated from their base or projected as much as 12 inches, uniformly east-northeastward to eastward toward the main fracture zone. A single monument in the small cemetery 0.1 mile west of Parkfield, on the opposite, or east side of the main fracture zone, was toppled in the same manner.

An unfloored barn immediately southwest of the main fracture zone and about midway along its length near the Wilson house contained an elongate stack of heavy boxes of wire; the stack was not in contact with the building. The stack tumbled northeastward during the earthquake, directly toward the fracture zone and parallel to the long dimension of the stack (fig. 47*A*). Near the same locality, a heavy wood box of hardware was projected southeastward about 4 feet from its

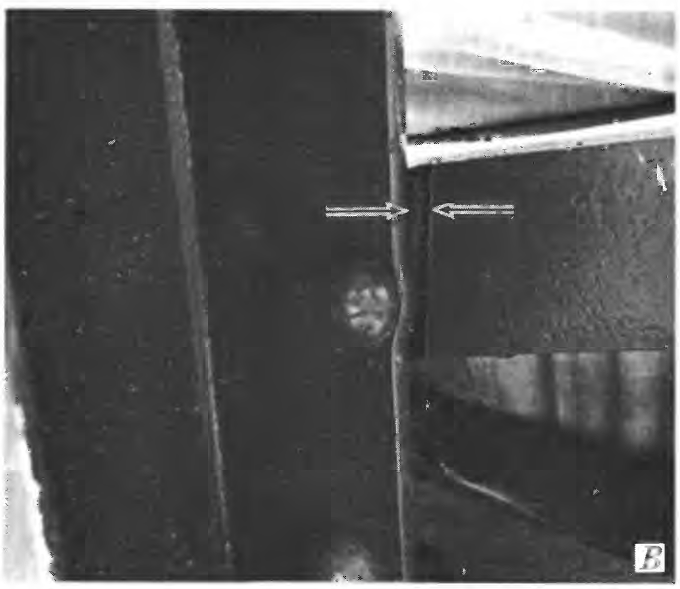


FIGURE 45.—Deformation of Monterey County road bridge (No. 444) over Cholame Creek, just southwest of the main fracture zone and about 0.1 mile northwest of Wilson's house. *A*. Buckled swaybraces, viewed southeastward at right angles to length of bridge. *B*. Freshly scraped paint (between arrows) and partial bearing failure (at rivet near center) between vertical steel pier (at left) and steel swaybrace.

FIGURE 46.—Damaged concrete bridge abutment, at east end of Highway 46 bridge over Cholame Creek, about 0.1 mile west of main fracture zone. Abutment is freshly cracked and slightly separated at crack. Scale is about 7 inches long.

initial position inside a second wooden box that had rested on top of an upright empty steel drum (fig. 47*B*). The drum and empty box were overturned along the line the box of hardware was projected; however, the drum and empty box were neither projected nor separated from each other.

Two automobiles parked at the California Division of Forestry station in Parkfield, about 1,100 feet northeast of the main fracture zone, were shifted laterally southward about 1.5 feet in such a manner as to leave no clear tracks on the unpaved surface. A concrete slab at the same station was shifted northward about half an inch.

Heavy furniture was reportedly shifted about 6 inches in directions normal to the trend of the San Andreas fault zone at two localities in the Choice Valley area, 7 miles and 13.6 miles beyond the southeast end of the main fracture zone.

Light objects were shifted, projected, or overturned at many localities within 1.5 miles of the fracture zones and as far southwest as Whitley Gardens, which is on the southwesterly continuation of Cholame Creek, 12½ miles southwest of Cholame and 13½ miles southwest of the main fracture zone.

MISCELLANEOUS EFFECTS

Miscellaneous effects include fractured or broken trees, parted wires, a seiche reported in a small reservoir, and rupture of an irrigation pipeline that occurred about 9 hours before the earthquakes.

A B

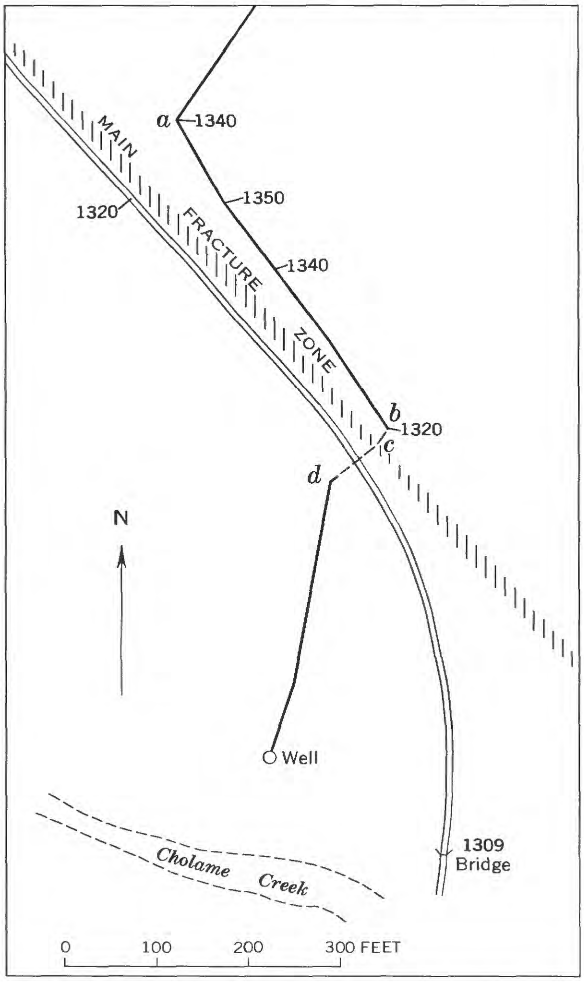
FIGURE 47.—Collapsed or projected heavy objects, just southwest of the main fracture zone near Wilson's house. *A*. Collapsed stack of 120-pound boxes that rest on wood pallet set on dirt floor of barn. Stack was not in contact with walls before earthquakes and collapsed directly toward the main fracture zone, which is about 200 feet to northeast. *B*. Heavy box of hardware at lower left was projected southeastward from within empty box still in contact with empty overturned steel drum. Drum was upright, with nested boxes resting on top, before earthquakes.

Overhead and guy wires were reportedly slackened or parted at several localities along the main fracture zone, particularly in the areas near the Wilson house and just south of Highway 46. A low-amplitude seiche reportedly occurred in a small reservoir that is about half a mile northwest of the Wilson house and about a tenth of a mile east of the main fracture zone; neither the height nor the period of the seiche could be determined.

An irrigation pipeline that crosses the main fracture zone near the Wilson house was in use on June 27 but was ruptured and separated about 9 hours before the sequence of main shocks. The rupture occurred near an elbow that connects a 400-foot-long exposed segment of pipe that is parallel to and about 20 feet east of the main fracture zone with a short segment that is buried where it crosses the fracture zone and the Parkfield road (fig. 48). The rupture was caused by about 2 feet of southeastward shifting of the long segment of the pipe parallel to its trend and relative to the elbow, which is constrained by the rigid support of the buried segment. The cause of the shifting has not been determined, but two possibly contributory factors should be noted: (1) The long segment drops in latitude between 20–30 feet from northwest to southeast along its length, and (2) according to Allen and Smith (1966), en echelon fractures existed along the trend of the main fracture zone about 1.8 miles southeast of Parkfield on June 16, 11 days before the main shocks. Furthermore, broad arches 50 feet or more wide have been documented at several localities east of the main fracture zone; such arching may have been accompanied by horizontal shortening of the ground surface (p. 32). Shifting of the pipeline is tentatively attributed to preearthquake deformation of the ground surface near the main fracture zone; the shifting cannot be attributed solely to gravitational movement during foreshocks, as the first recorded foreshock occurred at 6:00 p.m. on June 27 (McEvilly, 1966, p. 967).

INFERRED INTENSITY

An intensity of VIII to IX (Modified Mercalli) was attained during at least the second main shock of June 27, 1966 (9:26 p.m. P.d.t.; magnitude 5.5, acceleration 0.5g) in a narrow band 1–2 miles wide, that extended along the length of the main fracture zone. Intensity IX may be indicated by the local ejection of sand, mud, and water near the fracture zones (see the Modified Mercalli scale, 1956 revision, in Richter, 1958, p. 137–138), but an intensity of VIII is indicated by most effects, such as slope failures in dry semiconsolidated material, breaking of trees, movement of unanchored heavy objects and buildings, overturning and projection of stone monuments and chimneys, and damage to masonry. The duration of strong ground motion (acceleration 0.1g or greater), which is probably as significant as maximum acceleration in producing permanent effects, lasted about 6 seconds, as based on



A

B

FIGURE 48.—Irrigation pipeline that crosses the main fracture zone and Monterey County road between Cholame and Parkfield, about 0.1 mile northwest of Wilson's house. *A*. Plan view of pipeline. Pipe is buried between points *c* and *d* where it crosses the fracture zone and the road, and exposed elsewhere. The pipeline ruptured and separated near elbow (*b*) about 9 hours before main earthquakes of June 27, owing to 1–2 feet of southeastward movement of long segment (*a–b*) relative to buried segment (*c–d*). Figures show approximate spot altitudes in feet as interpolated from Cholame Hills 1:24,000 topographic quadrangle; plot traced directly from vertical aerial photograph. *B*. View eastward of part near elbow (arrow corresponds to point *b* of map) that ruptured.

the records of strong-motion instruments. An intensity of VIII corresponds to an epicentral acceleration of about 0.4g (see Gutenberg and Richter, 1956), in reasonable agreement with the acceleration (.05g) recorded for this shock at the south end of the main fracture zone (Cloud, 1966). Intensities and accelerations of this degree have in the past been correlated with shocks of magnitude about 7; in contrast, a shock of magnitude 5.5 has commonly been correlated with accelerations of about 0.07g and intensities of VI to VII (Gutenberg and Richter, 1956, fig. 6, p. 132). The 1960 Agadir, Morocco, earthquake constitutes at least one other known exception to this empirical relationship between intensity and magnitude in that intensities up to XI (Modified Mercalli) there accompanied an earthquake of magnitude 5.75. This association was attributed in part to very shallow focal depth (2–3 km) (Comm. Structural Steel Producers, 1962, p. 27–28).

CONCLUSIONS AND IMPLICATIONS

The main shock of 9:26 p.m. P.d.t., June 27, 1966, was particularly well recorded and was associated with surprisingly intense effects for a shock of only moderate magnitude (5.5):

1. A zone of en echelon tectonic fractures at least 23½ miles long closely followed earlier well-defined fault traces that have been the loci of repeated and well-documented earth movement for more than 100 years (Brown and Vedder, this report, p. 9).

2. A right-lateral offset of about 1.8 inches (Highway 46) occurred near the south end of the main fracture

zone, the end opposite the epicentral area (Wallace and Roth, this report, p. 23; Allen and Smith, 1966).

3. A short-duration horizontal acceleration of 0.5g was measured near the south end of the main fracture zone.

4. Intensity VIII to IX effects were noted in a narrow band along the fracture zones; such intensities correlate reasonably well with the measured acceleration.

These effects commonly accompany shocks of magnitude about 7, at least 100 times greater in energy release than a shock of magnitude 5.5 (Tocher, 1958, fig. 2, p. 150; Gutenberg and Richter, 1956, p. 136). This occurrence of relatively high-intensity effects with moderate magnitude may represent a common but previously unrecognized association, or it may represent an unusual association. The association certainly indicates that the potential destructiveness of earthquakes of moderate magnitude should be reappraised, especially for seismically senstive structures in alluviated areas near faults of the San Andreas type. The entire sequence of earthquakes, moreover, was accompanied by creep and ground movement that continued along the main fracture zone for at least 7 weeks following the main shock.

No serious damage and only modest damage requiring repair resulted from either the direct or indirect effects of the June earthquakes, a fortunate circumstance that can be attributed to (1) the narrowness of the zones of damaging effects, and (2) the sparseness of manmade structures. Had this particular combination of effects (surface fracturing and high acceleration and intensities in a zone 23½ miles long combined with unconsolidated or slightly consolidated ground, especially if saturated) occurred in a more densely populated area, widespread damage and locally major damage could have occurred.

WATER-RESOURCES ASPECTS

By A. O. Waananen and R. W. Page

Seismic shocks associated with the Parkfield-Cholame earthquakes of June 27, 1966, caused noticeable fluctuations in the stages of streams and reservoirs and in ground-water levels over an area extending a considerable distance from the Cholame Valley. Preliminary evidence, however, indicates few, if any, significant effects on the water resources of the region. Several features of water quality, including toxicity, reportedly caused by the earthquakes, were found on investigation to be coincidental.

The effects of earthquakes on water resources may be grouped into (1) water-level fluctuations caused by seismic shock, (2) changes in ground-water levels, spring flows, or base flow of streams, as a result of compaction, slides, and related tectonic fracturing of the earth's surface, (3) changes in quality of water, including the silting or roiling of water in wells, and (4) other physical effects. Some of these effects are immediate; others may develop slowly and not become fully evident for some time.

The Arvin-Tehachapi earthquake of July 21, 1952, for example, as reported by Briggs and Troxell (1955), caused a substantial, though temporary, increase in flow in many streams and springs in the area affected, some of which was still evident as late as June 1953. An increase in nominal low flow from 17 to 37 cubic feet per second in Sespe Creek near Fillmore over a 10-day period and a threefold to fourfold increase in the discharge of a small spring on the Juan Y Lolita Rancho in the Santa Ynez Mountains represent the more spectacular effects. Yet many other streams and springs in the same area showed no significant changes, and a few showed declines in yields. The increases were attributed to disturbances of unconsolidated materials in the spring discharge areas, with resultant clearing of existing outlets and opening of new ones.

Davis, Worts, and Wilson (1955) reported that the Arvin-Tehachapi earthquake caused water-level fluctuations in wells over an area extending from Durham in Butte County to Oceanside in San Diego County. Water-level graphs for 55 wells showed fluctuations that reached a maximum range of 7.34 feet in a well 5.6 miles north of Arvin in Kern County and about 20 miles northeast of the epicenter. In eight of these wells, the fluctuations exceeded 3 feet. Many records, especially those from wells near the epicenter, showed a small residual displacement of water level from the preearthquake levels. Water-surface fluctuations in wells penetrating unconfined aquifers were of small amplitude, but those in wells penetrating partially confined or confined aquifers were many times greater, and much greater than comparable ground motion. The water-surface movement in the partially confined and confined aquifers seemed to be related to the compressibility and elasticity of the aquifer materials, as well as to the degree of confinement of the aquifer or the distance of the well from the epicenter.

WATER-SURFACE FLUCTUATIONS IN JUNE 1966

The principal effect of the June 27, 1966, earthquakes relating to water-resources aspects was the abrupt and pronounced fluctuation of water level recorded on many water-stage recorders. Such a record is common on analog-type recorders in areas affected by earthquakes. At times of large shocks, the recorder traces show vertical lines caused by movement of the recorder float as a result of wave action in the gage well induced by the shocks. There is a rough relation between the severity of the shock, amplitude of the fluctuations, and distance from the epicenter.

Recorders at a few streamflow-measurement stations in the Salinas, Santa Maria, Santa Ynez, and Ventura River basins and in coastal basins near Santa Barbara showed the influence of the earthquakes. One of these stations is on Cholame Creek near Shandon (fig. 49, gaging station 6), only a few miles west of the quake area. Two distinct shocks were recorded at some stations June 27, at times corresponding to the shocks at 9:09 and 9:26 p.m. P.d.t., the second shock being more pronounced. The time scales on the water-stage recorders (2.4 in. per day) preclude close fixing of the shock times as shown on the charts.

The location of gaging stations that showed the shock effects is shown in figure 49. Pertinent data on the range of the fluctuations and the net change in stage are given in table 4. Many streams were dry, but some of the gage wells contained water; in a few places, the wells were dry, but ground motion caused by the shocks produced discernible traces on the recorder charts.

Parts of recorder charts showing the fluctuations at three selected stations on June 27, 1966, are reproduced in figure 50. The Cholame Creek record illustrates a sequence of shocks extending over a period of nearly 20 minutes. Those for Estrella River near Estrella and Salinas Reservoir near Pozo clearly show the two principal shocks.

The record for the Salinas Reservoir (fig. 49, gaging station 9) does not show significant periodic water-level oscillations (seiches). This is in sharp contrast to the response of this reservoir to the Alaskan earthquake of March 27, 1964, when seiche-caused water-level fluctuations had an initial range of 0.42 foot and continued for nearly 6 hours. The Salinas Reservoir record may not be representative of the full magnitude of the lake-level fluctuations, because the recorder is installed in a stilling (gage) well that purposely has a small inlet capacity for damping of local wave action; the well, however, may be reasonably responsive to seiches that have longer periods.

TABLE 4.—*Fluctuations recorded at gaging stations, June 27*

[Net change in water stage is 0.00 ft at all stations]

Map No. (fig. 49)	Stream or reservoir and station	Fluctuations in gage well (double amplitude, in feet)	
		9:09 p.m. shock	9:26 p.m. shock
1	Salinas River near Spreckels	0.01	--------
2	Arroyo Seco near Soledad	.005	0.02
3	Los Gatos Creek above Nunez Canyon, near Coalinga.	.01	.02
4	Nacimiento River near Bradley	.02	.04
5	Estrella River near Estrella	.02	.08
6	Cholame Creek near Shandon	([a])	[a] .11
7	Huerhuero Creek near Creston	--------	.02
8	Jack Creek near Templeton	--------	.02
9	Salinas Reservoir near Pozo	.03	.18
10	Toro Creek near Pozo	--------	.05
11	Foxen Creek near Sisquoc	--------	.04
12	Santa Cruz Creek near Santa Ynez.	--------	.01
13	Santa Ynez River at narrows, near Lompoc.	--------	.01
14	Santa Ynez River at barrier, near Surf.	--------	.03
15	Atascadero Creek near Goleta	--------	.03
16	Santa Ana Creek near Oak View	--------	.005
17	Matilija Creek at Matilija Hot Springs.	--------	.02

[a] Continuing oscillation.

FLUCTUATIONS IN GROUND-WATER LEVELS

The Geological Survey has no ground-water observation wells in the Parkfield-Cholame area. Water-level recorders on wells and compaction recorders and tiltmeters maintained for subsidence studies in the San Joaquin Valley, however, showed definite seismic effects, with amplitudes of the fluctuations considerably greater than those at the stream-gaging stations. Data for selected wells are shown in table 5, and the location of the wells is shown in figure 49. A part of the recorder chart for well 23S/25E-17Q3, near Pixley in Tulare County, shown in figure 50, illustrates a direct response to the seismic shock. The net changes in water level shown in table 5 are approximate because of short recorder time scales and appreciable daily water-level fluctuations.

Compaction recorders in Fresno, Tulare, and Kern Counties, installed at or near observation-well sites (fig. 49), showed movements at the approximate time of the principal shock on June 27. These movements seem to be attributable to the earthquake. A tiltmeter installed near Mettler in Kern County, about 24 miles south of Bakersfield, also reflected the major shocks.

Yerkes and Castle, in their discussion of engineering geology aspects (p. 41), comment on secondary terrain effects, such as slope failures, including soil falls, block glides, debris slides, and slumps. The Parkfield-Cholame earthquake occurred in a region where many of the streams are ephemeral and at a time when most of the streams were dry and water tables were low. Under different hydrologic conditions, slope failures, such as those reported, might have affected stream flow or the discharge of ground water by temporarily detaining the water in impoundments caused by debris. And changes

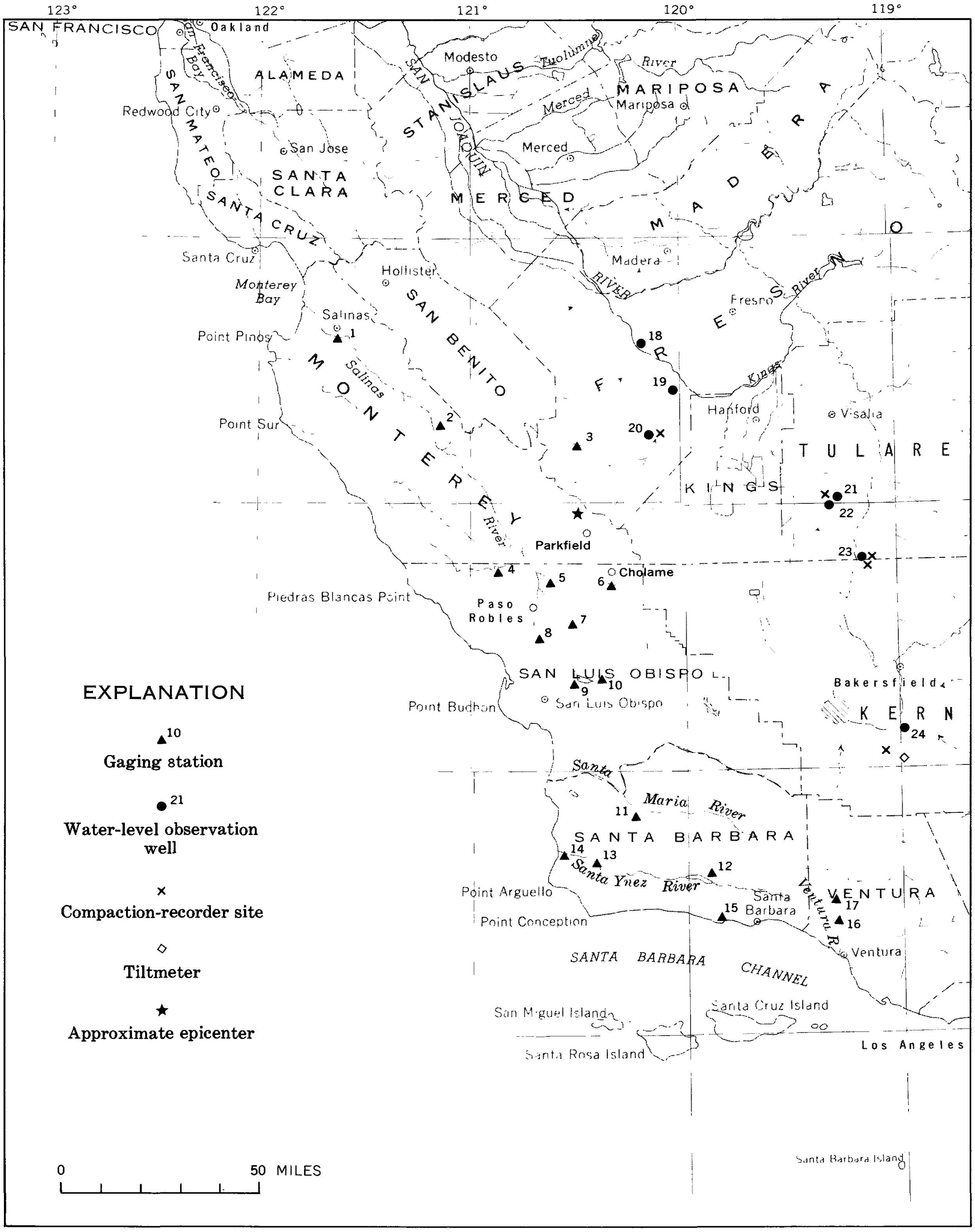


FIGURE 49.—Selected gaging stations, observation wells, and compaction-recorder sites that showed effects of Parkfield-Cholame earthquakes, June 27, 1966. Gaging stations and observation wells are given in tables 4 and 5, respectively.

TABLE 5.—*Fluctuations of water level in observation wells, June 27*

Map No. (fig. 49)	Well	Location [1]			County	Area	Depth of well [2] (feet)	Water-bearing material	Depth to water below land surface (feet)	Double amplitude [3] (feet)	Net change [4] (feet)
		Sec.	T. (S.)	R. (E.)							
18	15S/16E-20R1	20	15	16	Fresno	San Joaquin	356.0	Alluvium	79.28	[5] 0.08	−0.02
19	17S/17E-21N2	21	17	17	do	Five Points	908.0	do	303.10	.70	
20	19S/16E-23P2	23	19	16	do	Huron	2,200	do	570.80	.25	−.25
21	23S/25E-16N4	16	23	25	Tulare	Pixley	250	do	95.66	[5] .08	
22	23S/25E-17Q3	17	23	25	do	do	355.0	do	100.86	.94	.00
23	24S/26E-34F1	34	24	26	do	Richgrove	1,510.0	do	272.88	.15	.00
24	32S/28E-20Q1	20	32	28	Kern	Conner	970.0	do	222.85	.40	−.35

[1] All locations are referenced to Mount Diablo base line and meridian.
[2] Well depths given in feet and tenths of a foot were measured below land-surface datum by Geological Survey.
[3] Recorder time scale precludes close fixing of time of occurrence.
[4] Approximate water-level offset before and after shock.
[5] Unconfined aquifer.

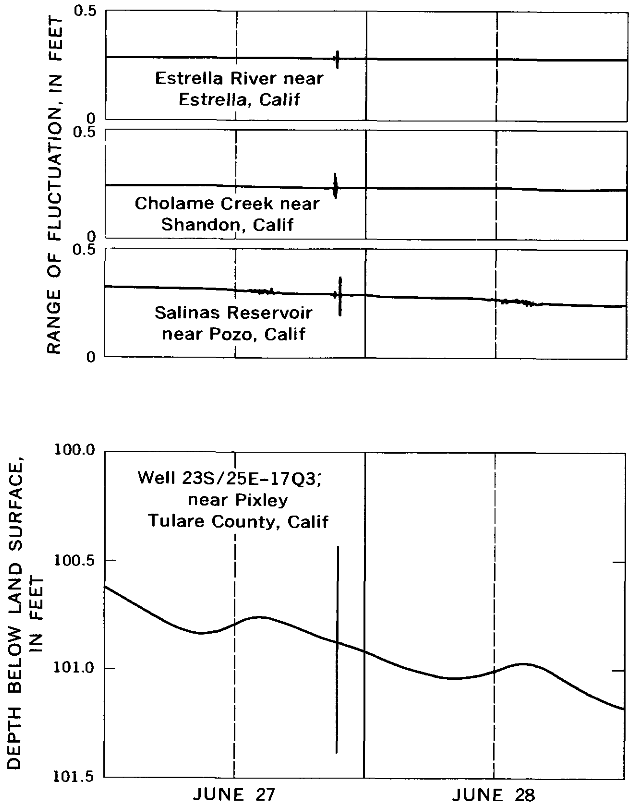


FIGURE 50.—Fluctuations recorded at gaging stations and an observation well during Parkfield-Cholame earthquakes, June 27–28, 1966.

in spring flows could have resulted from compaction or fracturing of soil materials.

Detailed examination of recorder charts and further appraisal of water-level and discharge records may provide more complete identification of the areal extent of the earthquake influences and possible postquake changes. Generally, however, these may be minor.

EFFECT ON QUALITY OF WATER

As is common after earthquakes of appreciable magnitude, investigators received various reports of water problems attributed to the Parkfield-Cholame event. Some of these reports referred to problems in water quality that included possible toxic concentrations of arsenic in areas of the San Joaquin Valley, such as Lemoore, Avenal, and Allensworth. A reported fish kill near Lemoore Naval Air Station, about 35 miles south of Fresno, for example, was thought by some to have been caused by abnormal arsenic concentrations associated with quake effects. Inquiry indicated, however, that the kill actually resulted from reduction of dissolved-oxygen content of the water by algae blooms during hot cloudy days. Arsenic is known to occur in undesirable concentration in the water-bearing deposits above the Corcoran Clay Member of the Tulare Formation in the Allensworth area in Tulare County, 40 miles northwest of Bakersfield, but no evidence is available to indicate any change in concentration as a result of the earthquake. A routine chemical analysis of water from the Avenal High School well, about 55 miles southwest of Fresno, sampled by the California Department of Water Resources on June 17, 1966, showed only 0.01 part per million of arsenic, and this constituent has not been a problem in Avenal.

An unusual feature of the Parkfield-Cholame earthquake, with respect to water quality, was the absence of reports of muddied water in wells. Commonly, major earthquakes are followed by temporary turbidity of water in wells and springs where the aquifer contains a silt or clay fraction, some of which is freed by the earth tremors and clouds the water for a time.

CONCLUSIONS

The foregoing summary indicates that the Parkfield-Cholame earthquakes of June 27, 1966, had very little effect on the water resources. The principal effect was seismographic, as shown by the charts from recorders at gaging stations and ground-water observation wells in the area affected by the quakes. There were no indications of early significant effects on the base flow of streams, water levels in wells, discharge of springs, or quality of water.

INSTRUMENTAL SEISMIC STUDIES

By Jerry P. Eaton

U.S. Geological Survey instrumental seismic studies in the Parkfield-Cholame area consist of three related parts that were undertaken as pilot studies in a program designed to develop improved tools and concepts for investigating the properties and behavior of the San Andreas fault. These studies include

1. The long-term monitoring of the seismic background on the San Andreas fault in Cholame Valley by means of a short-period Benioff seismograph station at Gold Hill.
2. The investigation of the geometry of the zone of aftershocks of the June 27 earthquakes by means of a small portable cluster of short-period, primarily vertical-component, seismographs.
3. The seismic refraction calibration of the region enclosing the aftershock source by means of three short reversed refraction profiles and a "calibration shot" near the epicenter of the main June 27 earthquake.

This brief report outlines the work that has been completed and presents some preliminary results obtained from analysis of records from Gold Hill and the portable cluster.

RESULTS FROM THE GOLD HILL SEISMOGRAPH

With support from ARPA (Advanced Research Projects Agency), a Long Range Seismic Measurements "van" was installed at Gold Hill during October 1965, to record seismic waves from an underground nuclear explosion on Amchitka Island (the "Longshot" experiment). Gold Hill, a sliver of crystalline rock in the San Andreas rift zone on the northeast side of Cholame Valley (fig. 53), was suggested as a seismograph site by J. G. Vedder. This site was selected because it promised to be a quiet one, it filled a gap between the two California local earthquake networks (University of California at Berkeley in the north, and California Institute of Technology in the south), and it permitted the monitoring of small earthquakes on the San Andreas in a region where U.S. Geological Survey geologists were undertaking detailed studies of geologically recent movements along the fault.

For reasons of economy, only the 3-component short-period Benioff seismograph system was installed. When the 35-mm film records from all three components are enlarged 15 times in the film viewer, they provide ground displacement magnifications of about 200,000, and more than 600,000 (peak magnification) for waves with frequencies of 1 and 3 cps (cycles per second), respectively. The vertical component is also recorded at 1 mm/sec on a "Helicorder" monitor with ground displacement magnifications of about 75,000 and 240,000 (peak magnification) for waves with frequencies of 1 cps and 3 cps, respectively.

The Gold Hill records of the June 27 earthquakes and their aftershocks are of particular interest for several reasons:

1. Gold Hill was the nearest seismograph to the epicentral tract and augmented the Berkeley network so as to surround the epicenter of the main shock. Gold Hill data on the foreshocks, the main shock, and the principal aftershocks have already been utilized in Berkeley's epicenter determinations.
2. The surface faulting associated with the earthquakes followed the western flank of Gold Hill within 1,500 feet of the seismometer pits.
3. Continuous records of background seismic activity along the future fault break were obtained for a period of 8 months before rupture; the foreshocks, the main shock, and all the aftershocks were recorded by the same instruments at the same gain levels.
4. By the very low sensitivity direct seismic response of the radio-time-trace galvanometer and by the inertial offset of the film recorder drum (also visible as an offset in the radio time trace), the onset of varying levels of very strong motion at the Gold Hill van, 500 feet from the surface fault trace, can be detected and timed.

PREEARTHQUAKE SEISMIC ACTIVITY

The level of local seismic activity at Gold Hill from November 1965 through June 26, 1966, was extremely low: only 52 events with $S—P$ intervals less than 4 seconds (epicentral distances less than about 30 km) were detected during the entire 34-week interval. Monthly totals were

November	8	March	1
December	1	April	18
January	6	May	11
February	4	June	3

Although these figures represented a considerable increase over previous months, the modest April and May totals did not single out the Parkfield-Cholame region for special attention before June 27.

RELATIONS BETWEEN FORESHOCKS, MAIN SHOCK, AND AFTERSHOCKS

Examination of the Gold Hill records and comparison of P arrival times at that station with those at Priest, the Berkeley station just east of the San Andreas fault 44.3 km northwest of Gold Hill, clearly indicate that the largest earthquake of the sequence, magnitude 5.5 at 04:26 Z on June 28 (Greenwich), was the one that accompanied breakage (or at least sudden movement) along the fault past Gold Hill. The first foreshock, of magnitude 3.1, was recorded at Gold Hill at 01:00:35.6 Z (June 28), 1.3 seconds earlier than at Priest. It was followed at 01:14:59.2 Z by a much smaller shock that recorded 0.8 second earlier at Gold Hill than at Priest. The third event of the sequence was the largest foreshock, with a magnitude of 5.1; it was recorded at Gold Hill at 04:09:00.4 Z, 1.2 seconds earlier than at Priest. The sole aftershock of this quake that was detected at Gold Hill was recorded at 04:18:38.2 Z, 1.1 seconds earlier than at Priest. Its magnitude was 2.6. The main earthquake, with a magnitude of 5.5, was recorded at Gold Hill at 04:26:17.4 Z, 1.6 seconds earlier than at Priest.

The instrumental epicenters of all these earthquakes lie near the San Andreas fault northwest of Parkfield, at least 17 km northwest of Gold Hill. During the interval between the largest foreshock, whose magnitude approached that of the main shock, at 04:09 and the main shock at 04:26, no aftershock sequence was observable. When the Gold Hill trace quieted down so that it could be seen 9 minutes after the 04:26 earthquake, however, a strong aftershock sequence was in progress. During the first hour about four aftershocks per minute could be identified on the vertical component short-period Benioff film record. The first of these for which *P* could be timed arrived at Gold Hill 6.3 seconds earlier than at Priest. The frequency of aftershocks declined gradually from its maximum. Differences in *P* arrival times (Priest–Gold Hill) ranged from 0.8 second to more than 7 seconds, indicating that the aftershocks were originating all along the zone from somewhat northwest of the epicenter of the main shock to at least as far southeastward as Gold Hill. Aftershocks with *S* minus *P* intervals smaller than 1 second occurred throughout the sequence beginning with the main shock at 04:26. Thus, the aftershock sequence began at the time of the main shock, and the essential characteristics of the sequence that are indicative of the spatial distribution of individual aftershocks in relation to Gold Hill were established at the same time.

Assuming that the main earthquake, together with its foreshocks and aftershocks occurred on the San Andreas fault between Gold Hill and Priest at a depth not greater than a few kilometers, we can use differences in *P* arrival times at Gold Hill and Priest to determine the approximate location of each quake. For such earthquakes the distance from Gold Hill to the epicenter is approximately $L_{(km)}=22.2-3\ \delta\ T$, where a crustal *P*-wave speed of 6 km/sec has been assumed and $\delta\ T$ is the arrival time of *P* at Priest minus that at Gold Hill. Systematic errors in this simplified epicenter determination procedure result in calculated values for L that are somewhat too large for most earthquakes, especially for earthquakes that originate near Gold Hill. Data required for calculating L, and values of L, for all the foreshocks, the main earthquake, and the principal aftershocks recorded during the first 2 hours of the swarm are presented in table 6. The restriction of the epicenters of the foreshocks and the main earthquake to a small part of the fault between 17 and 20 km northwest of Gold Hill and the scatter of aftershock epicenters along the fault from that region to at least as far southeastward as Gold Hill are clearly indicated. Similar data on a calibration shot near the fault 21.4 km (the calculated value of L is 20.4 km) northwest of Gold Hill are also presented in table 6.

TABLE 6.—*Comparison of Gold Hill and Priest* P-*wave arrival times*

Gold Hill	Priest minus Gold Hill [1] (seconds)	Distance from Gold Hill to epicenter (kilometers)	Magnitude [1]
P arrival times June 28 (Greenwich)			
01:00:35.6	+1.3	18.3	3.1
01:14:59.2	+0.8	19.8	-----
04:09:00.4	+1.2	18.6	5.1
04:18:38.2	+1.1	18.9	2.6
04:26:17.4	+1.6	17.4	5.5
04:35:00.8	+6.3	3.3	3.0
04:42:35.2	+6.8	1.8	1.9
05:01:01.2	+6.0	4.2	3.1
05:03:47.3	+4.2	9.6	1.9
05:09:54.4	[2] +7.7	-----	2.0
05:12:45.6	+3.1	12.9	2.4
05:29:18.2	+2.9	13.5	1.6
05:37:06.6	+5.2	6.6	2.0
05:40:23.1	+2.2	15.6	2.2
06:32:22.0	+1.5	17.7	3.4
06:35:13.2	+6.7	2.1	2.5
06:39:33.9	+3.9	10.5	1.7
07:33:55.4	+3.9	10.5	2.2
Calibration shot September 15 (Greenwich)			
12:00:05.0	+0.6	20.4	[3] 2,600

[1] Magnitudes and Priest arrival times were provided by Prof. T. V. McEvilly, University of California at Berkeley.
[2] Epicenter is southeast of Gold Hill and cannot be determined by this technique.
[3] Charge (pounds).

FREQUENCY OF AFTERSHOCKS

To provide uniform treatment of the entire aftershock sequence, an attempt was made to count all discernible aftershocks on the Helicorder monitor of the vertical-component Benioff seismograph at Gold Hill. Starting 12 hours after the main shock, this task was relatively simple: total aftershock counts were made directly on the monitor for each record interval (usually about 24 hr), and the average rate of occurrence of aftershocks during each interval was computed. The power supply for the Helicorder was out of operation for several hours after the main shock; so, hourly totals of aftershocks were determined from the film record of the vertical-component Benioff seismograph for the first 12 hours. The rate of occurrence of aftershocks determined from the film record for each of these hourly intervals was adjusted to that expected on the Helicorder by comparing the total number of events on the two records between 07:55 Z and 16:25 Z, June 28, when both recorders were in operation.

Figure 51 and table 7 show the frequency of aftershocks as a function of time as recorded at Gold Hill. Investigators in Japan (Mogi, 1962) have found that the frequency of aftershocks as a function of time, for several Japanese earthquakes, can be adequately represented by a pair of empirical relationships:

$$R(t)=R_o t^{-h},\ 0<t<100 \text{ days};$$

$$R(t)=N_o e^{-pt},\ t>100 \text{ days};$$

where $R(t)$ is the frequency of aftershocks at time t after the main shock and R_o, N_o, h, and p are constants.

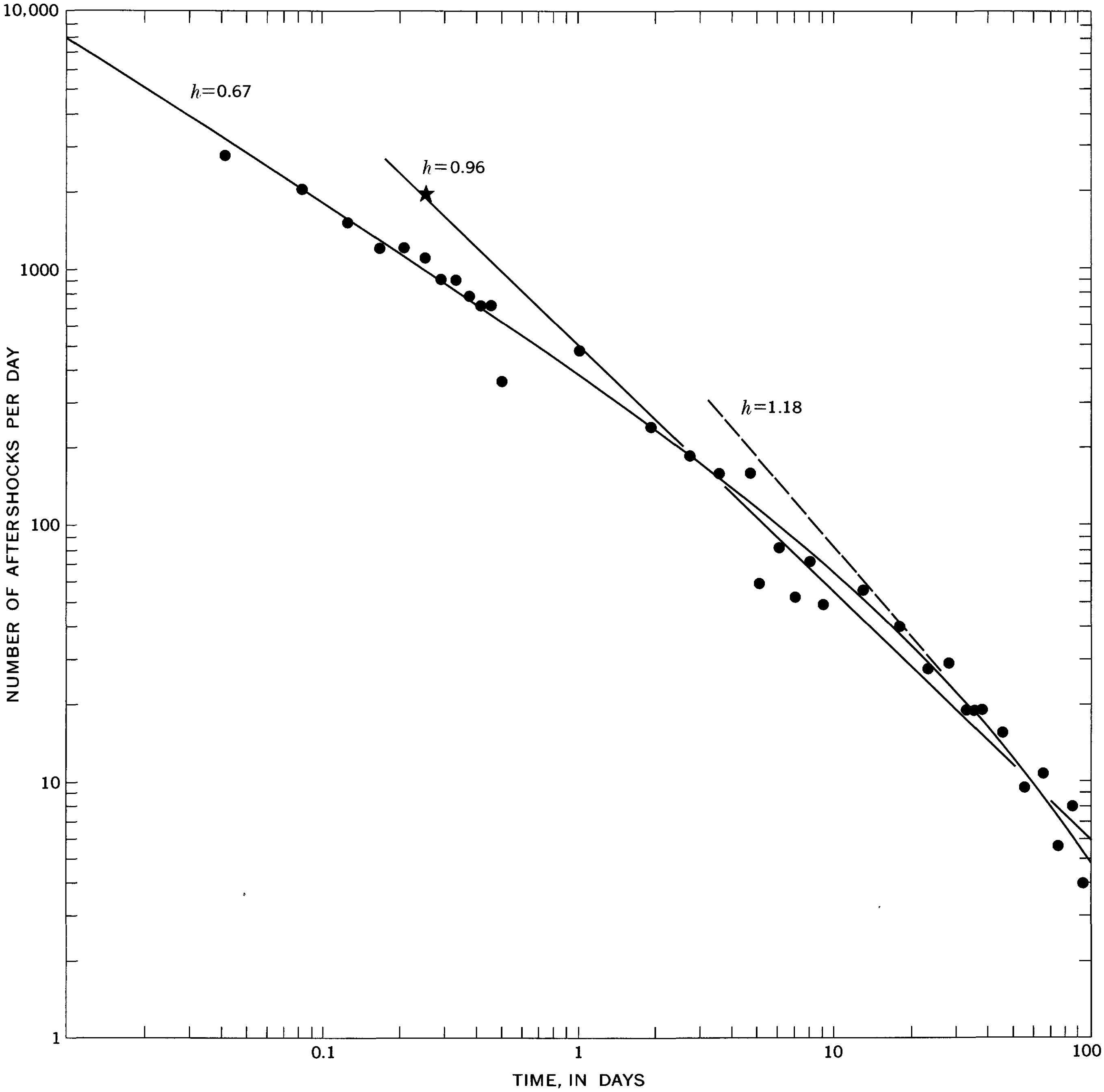


FIGURE 51.—Frequency of aftershocks at Gold Hill as a function of time for 96 days after the main shock. Solid circles represent hourly averages for the first 12 hours, daily averages for the next 5 days, 5-day averages for the next 30 days, and 10-day averages thereafter. The star represents events during the first 12 hours when they are lumped into a single interval. The h's refer to the rate of decay of the aftershock sequence according to the empirical equation $R(t)=R_o t^{-h}$.

TABLE 7.—*Frequency of aftershocks recorded at Gold Hill*

Interval	*Rate (quakes per day)*
June 28,* 05:00 to 06:00	2,760
06:00 to 07:00	2,064
07:00 to 08:00	1,511
08:00 to 09:00	1,200
09:00 to 10:00	1,224
10:00 to 11:00	1,104
11:00 to 12:00	912
12:00 to 13:00	912
13:00 to 14:00	774
14:00 to 15:00	720
15:00 to 16:00	720
16:00 to 17:00	360
June 28, 17:00 to June 29, 16:00	480
June 29, 16:00 to June 30, 12:00	241
June 30, 12:00 to July 1, 05:00	186
July 1, 05:00 to July 2, 04:00	160
July 2, 04:00 to July 2, 17:00	159
July 2, 17:00 to July 3, 18:00	59
July 3, 18:00 to July 4, 16:00	81
July 4, 16:00 to July 5, 16:00	52
July 5, 16:00 to July 6, 17:00	72
July 6, 17:00 to July 7, 17:00	49
July 7, 17:00 to July 8, 22:00	45
July 8, 22:00 to July 14, 01:00	56
July 14, 01:00 to July 19, 00:00	40
July 19, 00:00 to July 24, 00:00	25
July 24, 00:00 to July 28, 15:00	27
July 28, 15:00 to Aug. 2, 16:00	19
Aug. 2, 16:00 to Aug. 7, 14:00	19
Aug. 7, 14:00 to Aug. 17, 12:00	16
Aug. 17, 12:00 to Aug. 27, 13:00	10
Aug. 27, 13:00 to Sept. 6, 16:00	11
Sept. 6, 16:00 to Sept. 16, 19:00	6
Sept. 16, 19:00 to Sept. 26, 16:00	8
Sept. 26, 16:00 to Oct. 2, 16:00	4

*1,186 per day 05:00 to 17:00.

The first equation implies a linear relationship between log R and log t; the second, between log R and t. On a plot of log R versus log t, data from the first 100 days of the aftershock sequences of the Tottori (1943) and Tokachi (1952) earthquakes are adequately fit by straight lines with h equal to 1.36 and 0.98, respectively (Mogi, 1962).

A similar plot of data for the Parkfield-Cholame earthquake (fig. 51) appears to be best fit by a curve that deflects downward with respect to a straight line as time increases. Tangents to this curve which fit the plotted points from 0 to 4+ days and from 10 to 96 days have h equal to 0.67 and 1.18, respectively. The apparent differences between these data and those reported by Mogi may result from differences in the time intervals over which aftershocks were counted for the purpose of determining the aftershock frequencies. For example, if aftershocks during the first 12 hours of the Parkfield-Cholame sequence were added together and plotted at t=0.27 day (star on fig. 51), it would be possible to fit all the data fairly well with a straight line with h=0.96.

Possibly a better method of displaying aftershock sequences would be to plot curves showing cumulative total aftershock counts as a function of time. Necessary smoothing of the raw data could be accomplished in the process of abstracting information from the seismograms, for example, by recording the times at which the cumulative total of aftershocks reached prescribed values such as 100, 200, 300, and so forth. Frequency curves would be calculated readily from such a set of cumulative total versus time number pairs.

It appears, however, that the progressive increase in the rate of decay of the Parkfield-Cholame aftershock sequence is real; at least, there is a clear difference before and after t=10 days. This phenomenon may be related to the relatively large amount of postearthquake creep along the surface that slipped suddenly at the time of the main shock; the "sudden" redistribution of stress in the vicinity of the fault, usually held to be responsible for aftershock sequences, was effectively prolonged after the time of initial rupture by creep along the fault. In this view, the later part of the frequency versus time curve is tending toward a normal slope, and the early part is abnormal.

RECORD OF INTENSE GROUND MOTION

With the arrival of P waves from the main shock at 04:26:17.4, all regular seismic traces at Gold Hill were "blanked out" for nearly 10 minutes. The fourth channel on the 35-mm film recorder, which normally records the rectified audio signal from WWV to provide frequent chronometer corrections, responded to the intense motion of the ground at the recording site and wrote an interpretable record of it. Abnormal deflections of the radio trace appear to have resulted both from the direct seismic response of the recording galvanometer and from axial excursions of the recording drum, which is normally restrained by a friction clamp.

Immediately before the quake the radio trace was recording a slowly varying audio WWV "tone" punctuated by the 40-millisecond interruptions that mark individual seconds. These "second ticks" can be seen clearly in figure 52, a sketch of the critical part of the record, before and during the first few seconds of the earthquake. The actual times of several of the second marks are indicated on the sketch, where an irregular advance of the drum during the earthquake is evidenced by the uneven spacing of the second marks. The arrival of the P waves is marked by a slight widening of the trace at 04:26:17.4, and a moderate increase in shaking occurred about 1 second later. Still stronger longer period motion (possibly S) began just before 04:26:21. At about 04:26:22 the inertial forces acting

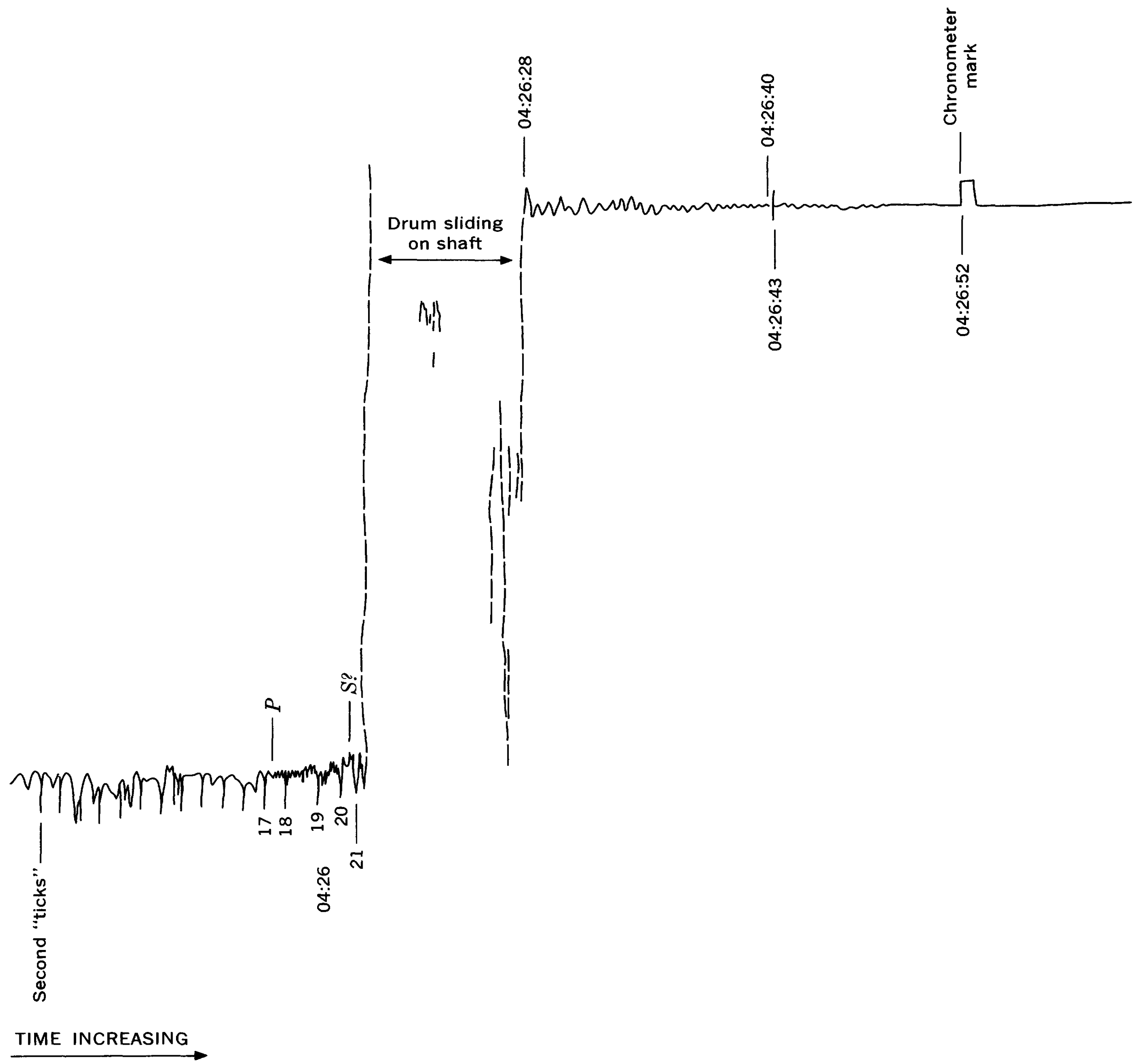


FIGURE 52.—Abnormal behavior of the radio time trace on the 35-mm film recorder produced by strong ground motion at the Gold Hill van. Indicated times are Greenwich. Dash lines indicate very faint parts of the trace that were written while the drum was sliding to and fro on its shaft.

on the drum overcame its frictional restraints, and the ground and recorder carriage moved to and fro beneath the drum for about 6 seconds. The slipping of the drum on the shaft was overcome by the friction clamp at about 04:26:28. For the next 20 seconds, a decaying train of waves with a period of about ½ second was recorded. Because the radio power was shut off when commercial power to the van was interrupted during the strong shaking, radio time marks are absent after 04:26:28.

The event, possibly related to the propagating end of the ruptured zone on the fault, that reached Gold Hill at 04:26:22 and caused the recording drum to slip on its shaft traveled from the focus at an average speed of 2.2 km/sec. This speed is significantly lower than that (3.3–3.5 km/sec) appropriate for S waves traveling through the upper part of the crystalline crust. The duration of shaking that was sufficiently intense to keep the drum in motion against its frictional restraints was only 6 seconds.

GEOMETRY OF THE AFTERSHOCK SOURCE REGION SOUTHEAST OF GOLD HILL

To study the relationship between the surface fault break and the aftershocks of the Parkfield-Cholame earthquake, a small cluster of portable seismographs was laid out around the part of the surface break that lies southeast of Gold Hill. Locations and periods of operation of individual stations are given in table 8. The basic cluster consisted of Gold Hill and eight portable stations in a 20-km-diameter pattern with five stations along the fault and two pairs of stations about 10 km from the fault on either side of it (fig. 53). During the last two weeks of the experiment, four additional portable stations were laid out to extend coverage northwestward along the fault (stations 9, 10, 12, and 13), and another was installed at Gold Hill to supplement the Benioff seismograph. At most stations, only a vertical-component seismograph was operated.

TABLE 8.—*U.S. Geological Survey seismograph stations in the Parkfield-Cholame area*

Station	Lat 35° N.	Long 120° W.	Height (feet)	Installed	Removed
Gold Hill	49.88′	21.18′	1,430	10– –65	--------
1	45.30′	18.70′	1,220	6-30-66	9-15-66
2	47.36′	21.44′	1,240	6-30-66	9-16-66
3	43.20′	16.85′	1,370	6-30-66	9-15-66
4	48.82′	16.07′	1,590	6-30-66	9-15-66
5	42.61′	22.72′	1,470	6-30-66	9-15-66
6	40.30′	12.65′	2,100	6-30-66	9-15-66
7	39.06′	19.22′	1,530	7- 9-66	9-15-66
8a	47.23′	11.06′	1,615	7- 9-66	8-14-66
8b	47.39′	10.55′	1,700	8-14-66	9-15-66
9	52.79′	24.72′	1,540	9- 1-66	9-16-66
10	49.47′	26.41′	2,120	9- 2-66	9-16-66
11 (tape)	49.88′	21.18′	1,430	9- 3-66	9-16-66
12	53.33′	20.55′	1,800	9- 5-66	9-16-66
13	55.09′	28.69′	1,980	9- 6-66	9-16-66

Overall system response increased 6 db (decibles) per octave with increasing frequency between the lower limit set by the 1-cps seismometer and the 17-cps upper limit set by the low-speed tape recorder. Amplifier gain levels were set so that the prevailing background noise produced about 10 percent modulation on the high-level tape channel. A second channel recorded with 30 db greater attenuation. Primary timing was provided by the continuous recording of WWVB, and a crystal chronometer supplemented WWVB during brief broadcast interruptions or receiver malfunctions. Events on the tape "playbacks" can be timed to within 0.01 second.

Complete analysis of data from the portable cluster will require some time; so a short time sample was analyzed in a preliminary effort to establish analytical procedures and to survey the kind and quality of results that can be obtained. All events discernible on the Gold Hill monitor record during the quiet hours of the night of July 16 and July 17 (about 04 : 00 Z to 13 : 00 Z on July 17) were played back for the other eight stations of the basic cluster. Of the 13 events selected in this manner (table 9), 3 lay so far northwest of the cluster that their foci could not be determined with accuracy, 2 lay only a few kilometers northwest of Gold Hill, and the remaining 8 lay very near or southeast of Gold Hill. This sample is not a uniform one of all events occurring throughout the aftershock source region because most of the small events of which it is composed would not have been detected at all if they had occurred near the northwest end of the zone of surface fracture.

TABLE 9.—*Aftershocks detected at Gold Hill between 04:00 Z and 13:00 Z July 17*

Origin time	Depth (kilometers)	Lat 35° N.	Long 120° W.	Average |ε| (seconds)
05:55:00	--------	NW of cluster		--------
07:12:03.55	6	49.5′	20.9′	0.06
07:25:21.20	1±	51.0′	22.7′	.09
08:23:54.8	1±	50.9′	22.0′	--------
08:43:46.37	6	45.7′	18.7′	.04
09:51:30.91	2	48.7′	20.3′	.04
10:19:41.32	4	49.9′	21.7′	.05
10:47:01.80	4	47.9′	19.5′	.07
10:50:31.85	12	49.8′	21.8′	.06
11:19:10.90	4	46.3′	10.9′	.06
12:19:29	--------	NW of cluster		--------
12:40:02	--------	NW of cluster		--------
12:46:35.5	1±	47.4′	19.2′	.06

To determine the foci of these aftershocks, a series of isochron charts constructed for quakes at various focal depths in a crustal model (fig. 54) established by refraction profiling between Camp Roberts (30 km west of Cholame) and San Francisco were used (Healy, 1963; Eaton, 1966). This method is based on that described by Riznichenko and others (Riznichenko, 1960). The epicenter and focal depths selected are those which yield the smallest *P*-wave arrival time residuals at available stations. For the events near or within the network, which were successfully located, average (absolute value) residuals ranged from 0.04 second to 0.09 second.

Epicenters and focal depths of the 10 "located" aftershocks in table 9 are indicated in figure 53. The epicenters lie very close to the trace of the main fracture zone, and there appears to be no sorting of earthquakes with respect to distance from the surface break as a function of focal depth. Thus, it seems that the aftershocks included in this small sample occurred on or very near a fault surface that extends vertically downward from the surface break to a depth of about 12 km.

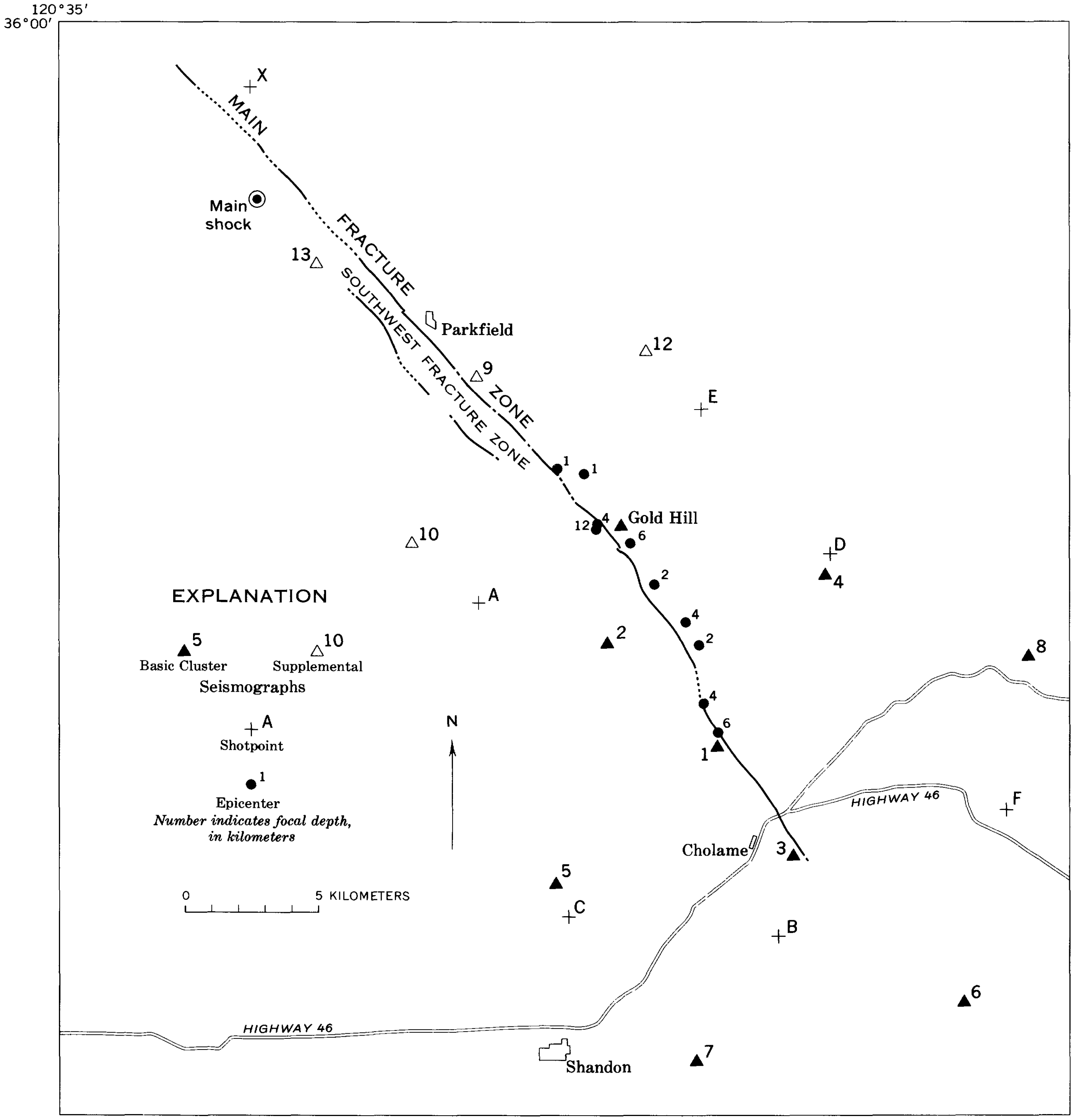


FIGURE 53.—Parkfield-Cholame region. U.S. Geological Survey seismograph stations, epicenters of July 17, 1966, aftershocks, refraction and calibration shot locations, and the surface fracture zones associated with the 1966 earthquake sequence (from fig. 2). The epicenter of the main shock was provided by Prof. T. V. McEvilly, University of California at Berkeley.

To indicate the sensitivity of the cluster to variations in focal depth, P-wave traveltime curves for earthquakes at various depths between 2 and 14 km are given in figure 54. Observed arrivals from four aftershocks with different focal depths are plotted in figure 54 for comparison. This comparison illustrates how the range in recording distance, and scatter in arrival times, of observations from individual earthquakes limit the precision with which focal depths can be determined. If ± 1 km precision is sought, some observations at epicentral distances as small as the focal depth are required.

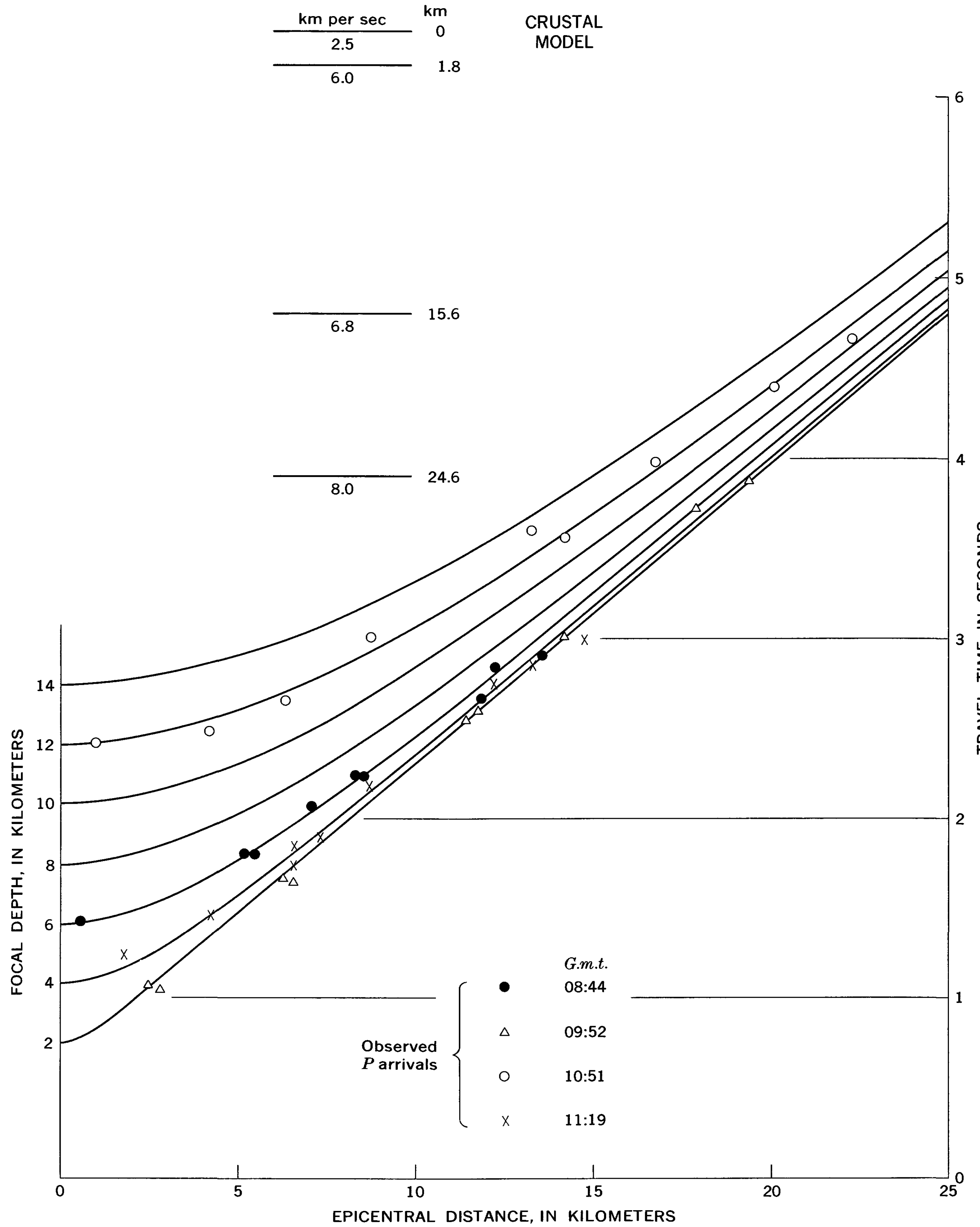


FIGURE 54.—Theoretical traveltime curves for earthquakes with focal depths from 2 to 14 km and the crustal model from which they were calculated. Observations from four July 17 aftershocks (see table 9) are plotted on the diagram for comparison with the theoretical curves.

SEISMIC-REFRACTION CALIBRATION OF THE CRUST IN THE AFTERSHOCK REGION

To approach maximum precision in locating aftershocks in three dimensions, more detailed information on crustal structure beneath the cluster is required. This need is particularly acute when the cluster is cut by a geologic discontinuity as profound as the San Andreas fault.

On September 13, 14, and 15, eight explosive charges ranging in weight from 310 to 2,600 pounds were detonated in drill holes to provide sources for three 20-km-long reversed seismic-refraction profiles and one calibration shot to help refine the epicenter assigned to the major earthquake. Essential data on the shots are given in table 10, and the shot points are plotted in figure 53. Nine mobile refraction units employing six vertical-component 1-cps seismometers at ½-km spacing and two horizontal-component 1-cps seismometers at one of the vertical locations, plus two shot-point units employing four vertical component 2-cps seismometers at ½-km spacing, were deployed along lines connecting pairs of shot points to record the refraction profiles. Profile A–B was designed to determine near-surface and upper-crust properties on the southwest side of the fault; and profile E–F was designed for the same purpose on the northeast side of the fault. A transverse profile between C and D was recorded to test for possible velocity perturbations in the rift zone itself. The 2,600-pound calibration shot (X) was detonated at a convenient location a few kilometers north of the instrumental epicenter of the main earthquake. The mobile refraction equipment was laid out between C and D to record it.

TABLE 10.—*U.S. Geological Survey calibration shots in the Parkfield-Cholame area*

Shot	Charge (pounds)	Lat 35° N.	Long 120° W.	Height (feet)	Detonation time	Date
A	540	48.30′	24.64′	2,140	04:00:00.35	9–13
B	540	41.61′	17.23′	1,550	04:29:59.79	9–13
C	540	41.99′	22.41′	1,380	03:59:59.00	9–15
D_1	310	49.27′	15.98′	1,660	05:59:5[illegible].86	9–14
D_2	1,020	49.27′	15.97′	1,660	04:30:30.28	9–15
E	540	52.23′	19.28′	1,640	03:59:59.82	9–14
F	540	44.14′	11.59′	1,560	04:29:59.88	9–14
X	2,600	58.64′	30.38′	2,030	04:59:59.82	9–15

Because all eight shots were recorded by the augmented cluster (Gold Hill plus portable stations at the 12 other sites), they should provide the data required for the calculation of individual station corrections that are needed for the further refinement of aftershock epicenters.

Work on the analysis of the refraction and calibration data is in progress.

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