DISPLACEMENTS ON THE IMPERIAL, SUPERSTITION HILLS, AND SAN ANDREAS FAULTS TRIGGERED BY THE BORREGO MOUNTAIN EARTHQUAKE[1]

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ABSTRACT

The Borrego Mountain earthquake of April 9, 1968, triggered small but consistent surface displacements on three faults far outside the source area and zone of aftershock activity. Right-lateral displacement of 1–2½ cm occurred along 22, 23, and 30 km of the Imperial, Superstition Hills, and San Andreas (Banning–Mission Creek) faults, respectively, at distances of 70, 45, and 50 km from the epicenter. Although these displacements were not noticed until 4 days after the earthquake, their association with the earthquake is suggested by the freshness of the resultant en echelon cracks at that time and by the absence of creep along most of these faults during the year before or the year after the event. Dynamic strain associated with the shaking is a more likely cause of the distant displacements than is the static strain associated with the faulting at Borrego Mountain because (1) the dynamic strain was much larger and (2) the static strain at the San Andreas fault was in the wrong sense for the observed displacement. The principal surface displacements on the Imperial fault took place within 4 days of the earthquake and may have occurred simultaneously with the passage of the seismic waves, but the possibility of delayed propagation to the surface is indicated by a 1971 event on the Imperial fault in which the surface displacement followed the triggering earthquake by 3–6 days. All three of the distant faults are "active" in that they show evidence of repeated Quaternary movement, and surface displacements occurred only along those segments where the fault trace is well delineated in surface exposures, at least in uncultivated areas. This is the first documented example of fault displacement triggered by seismic shaking far from the source area, although such displacement has probably gone undetected many previous times here and in similar tectonic environmments. This phenomenon forces us to be much more conservative in estimating the probabilities of damage from surface displacements along active faults in seismic regions.

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INTRODUCTION

The Borrego Mountain earthquake of April 9, 1968 (magnitude 6.4) was associated not only with a conspicuous surface break in its source region along the Coyote Creek fault (Clark, "Surface Rupture Along the Coyote Creek Fault," this volume), but also with displacements far outside the epicentral region along three major faults in the Imperial Valley region to the east and southeast of the epicenter (fig. 52). The Imperial, Superstition Hills, and San Andreas[2] faults broke along segments at least 22, 23, and 30 km long, respectively, at distances of 70, 45, and 50 km from the epicenter. Remeasurements of several small-scale geodetic networks that had been established before the earthquake, as well as observations of en echelon cracking, showed that right-lateral displacements of 1–2½ cm had occurred on these three distant faults. This is the first documented case of an earthquake apparently causing fault displacements well outside the epicentral region. A similar phenomenon may have occurred along a segment of the Garlock fault as a result of the 1952 Kern County earthquake on the White Wolf fault (Buwalda and St. Amand, 1955, p. 53), but the Garlock fault is relatively close to the White Wolf fault and was almost within the zone of aftershock activity.

This paper presents evidence that the displacements on the Imperial, Superstition Hills, and San

[2]The branch of the San Andreas fault system northeast of the Salton Sea has sometimes been called the Banning–Mission Creek fault because it represents the combined Banning and Mission Creek faults southeast of their point of coalescence near Indio and because of this fault's debatable continuity with the San Andreas fault farther north. The name San Andreas is used in this report for the sake of brevity and in keeping with usage by Dibblee (1954) and Hope (1969).

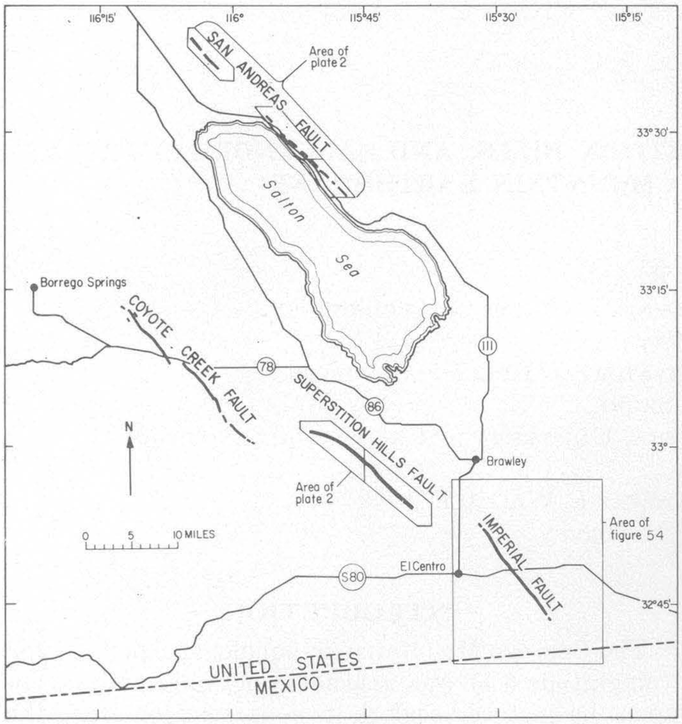

FIGURE 52. — Index map showing relation of the Coyote Creek fault (locus of the 1968 Borrego Mountain earthquake) to the three distant faults, the San Andreas, Superstition Hills, and Imperial, upon which triggered movements occurred. Heavy lines represent approximate segments which broke at that time.

Andreas faults were in fact triggered by the seismic shaking of the distant Borrego Mountain earthquake, that these displacements were not associated with normal aftershocks, and that they were not caused by the change in the regional static strain field that resulted from the fault displacements of the Borrego Mountain earthquake.

ACKNOWLEDGMENTS

Participation in this study by the California Institute of Technology was supported by National Science Foundation Grants GA–1087 and GA–12863. Mr. James Hileman assisted in the interpretation of the data from the small geodetic networks, Dr. Walter Arabasz studied the microearthquakes that followed the main shock, and Dr. R. D. Nason first observed the cracks at Highway 80 that stimulated the subsequent investigations. The authors appreciate the critical comments of R. V. Sharp.

OBSERVATIONS

IMPERIAL FAULT

Although a number of auxiliary faults near Borrego Mountain were examined for possible surface displacements on the day after the April 9 earthquake, the Imperial fault, 70 km distant, was not visited until April 13. At that time, Wyss and R. D. Nason noticed fresh en echelon cracks along the trace of the fault at Highway 80[3] (fig. 53) suggesting at least one-third centimeter of right-lateral displacement. It was this discovery that then stimulated the careful examination of other distant faults and led to the subsequent documentation of surface displacements on the Superstition Hills and San Andreas faults, as well as at other localities along the Imperial fault.

Because of the unusual fault displacement along the Imperial fault in March 1966 (Brune and Allen, 1967a) and the suspicion that creep might be occurring along this and related faults, Brune and Allen in 1966 and 1967 established a series of small geo-

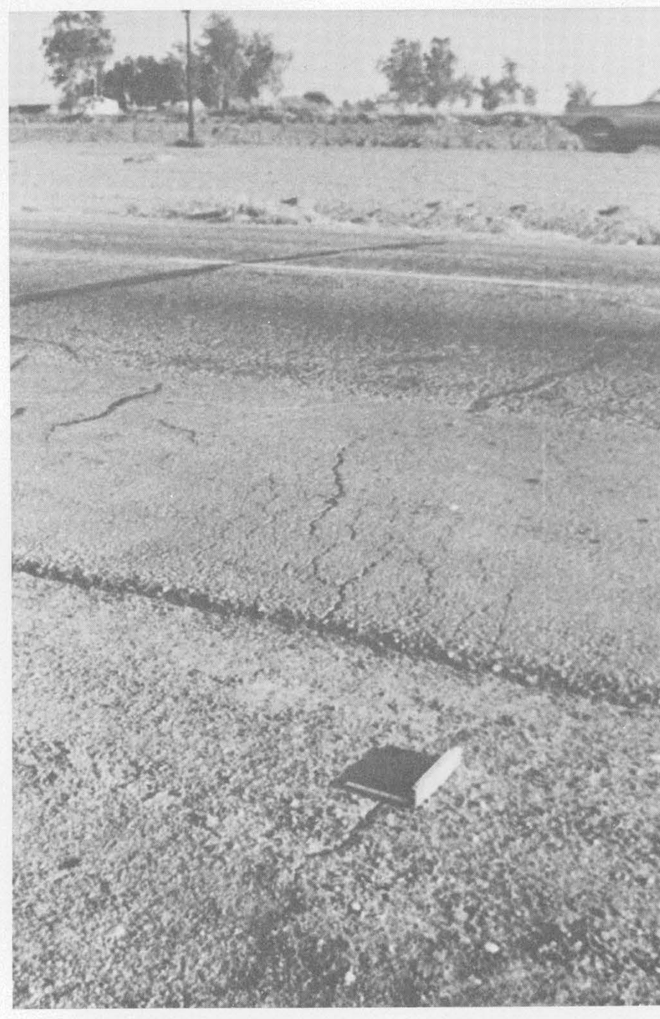

FIGURE 53. — Fresh cracks in unconsolidated material (beneath ruler) at north edge of Highway 80. Older tar-filled cracks in pavement resulted from earlier movements at this locality. (See Brune and Allen, 1967a.) Photograph by R. D. Nason, April 13, 1968.

[3]Since completion of the adjacent freeway in 1971, the former Highway 80 is now known as Evan Hewes Highway, Imperial County route 80S.

detic networks that straddled the Imperial, Superstition Hills, and San Andreas faults. These networks, each comprising a single theodolite station and 5–10 markers within a few hundred meters on both sides of the fault trace, were patterned on the similar networks that had been established earlier across the San Andreas fault near Parkfield (Smith and Wyss, 1968). The locations of these stations are shown in figure 54 and on plate 2, and their coordinates are given in table 12.

TABLE 12. — *Caltech fault-crossing geodetic networks in the Imperial Valley area*

Station	Fault	Lat (N.)	Long (W.)	First observation	Number of observations to 1–1–71
All-American Canal.	Imperial	32°40.55′	115°21.45′	5–10–67	9
Baileys Well	Coyote Creek	33°06.20′	116°03.63′	3–31–69	3
Bertram	San Andreas	33°24.68′	115°47.54′	5– 5–68	6
Harris Road	Imperial	32°53.02′	115°32.34′	1– 5–68	10
Meloland	do	32°48.21′	115°28.01′	6–19–66	12
North Shore	San Andreas	33°31.71′	115°56.21′	6–20–69	3
Ocotillo Wells	Coyote Creek	33°09.65′	116°07.85′	4– 9–68	12
Red Canyon	San Andreas	33°37.62′	116°02.91′	5–11–67	8
Superstition Hills.	Superstition Hills.	32°55.60′	115°41.84′	5– 7–67	9
Worthington Road.	Imperial	32°50.85′	115°30.69′	5–10–67	11

Figure 55*C* shows that about 2 cm of right-lateral displacement took place along the Imperial fault at Highway 80 between January 5, 1968, and April 19, 1968, and evidence is presented in a later section to indicate that this displacement took place at about the time of the Borrego Mountain earthquake and not as creep distributed throughout the 3-month interval. Three additional geodetic networks had been established across the Imperial fault prior to the earthquake (figs. 54, 55). The southernmost network, at the All-American Canal, showed no obvious displacement during the 3-year period shown in figure 55. The northernmost station, at Harris Road (fig. 55*A*), showed a clear displacement of about 0.8 cm at about the time of the earthquake. However, the intervening network at Worthington Road (fig. 55*B*) showed a displacement of about 1.1 cm between May 1 and December 29, 1967 (the year before the earthquake) and no displacement at the time of the earthquake. We feel that these findings are consistent with our argument that the Borrego Mountain earthquake triggered the release of elastic strain along most of the fault; if the strain had already been relieved shortly prior to that time, as it was near Worthington Road, then no further displacement took place.

The geodetic observations were supported by field evidence of intermittent surface faulting along more than 22 km of the Imperial fault, extending distinctly farther both to the north and to the south than the 10-km segment broken during the 1966 Imperial earthquake (Brune and Allen, 1967a). Clear en echelon cracks were observed at several localities from Harris Road on the north to Heber Road on the south (figs. 54, 56–58), although they could not be followed continuously throughout the intervening area because of extensive and continuing cultivation; cracks were not present near Worthington Road, where geodetic data indicated no movement. Fresh cracks in soil were generally observed only on the shoulders of roads between cultivated fields. En echelon cracks showed up particularly well in many asphalt roads that were crossed by the fault (fig. 56), although in some places it was difficult to distinguish cracks still existing from the 1966 earthquake from further cracking caused by the 1968 event (fig. 57). The absence of obvious cracking at some localities suggests that not everywhere did the fracture reach the surface as a discrete plane, which is not surprising in view of the small displacement and the known discontinuous nature of the much larger 1940 displacement in some localities (fig. 54). It is significant however, that wherever fresh cracks were observed, they followed precisely the trace of the 1940 break, which in some areas is well documented to within 1 m (J. P. Buwalda, unpub. data). Although the full extent of the 1968 trace is not known because of agricultural developments at the north end and sand dunes at the south end, careful examination revealed no fresh cracks where the Imperial fault crosses Keystone Road on the north and Highway 98 on the south (fig. 54), thus giving a total length of between 22 and 30 km.

For more than 3 years after the Borrego Mountain earthquake, no further slip on the Imperial fault at Highway 80 was observed visually or indicated by surveying records. On September 30, 1971, however, a further displacement was observed after an earthquake of magnitude 5.3 in the Superstition Hills, 37 km northwest of the Highway 80 locality; this earthquake represents the heaviest shaking the region had experienced since the Borrego Mountain event of 1968. Six days after the shock, right-lateral displacements of about 1½ cm were clearly visible in the pavement of Highway 80, and a resurvey of the geodetic network on October 13 showed a displacement at this time of 1.4 cm (calculated on the same basis as that used for the earlier measurements shown in fig. 55*C*). As discussed in a later section, however, there is some evidence that the observed displacement did not take place exactly at the time of the earthquake, but between 3 and 6 days later.

The Imperial fault was first noticed and named at the time of the 1940 El Centro earthquake, but a history of repeated Quaternary displacements along the fault is indicated by (1) a conspicuous scarp as

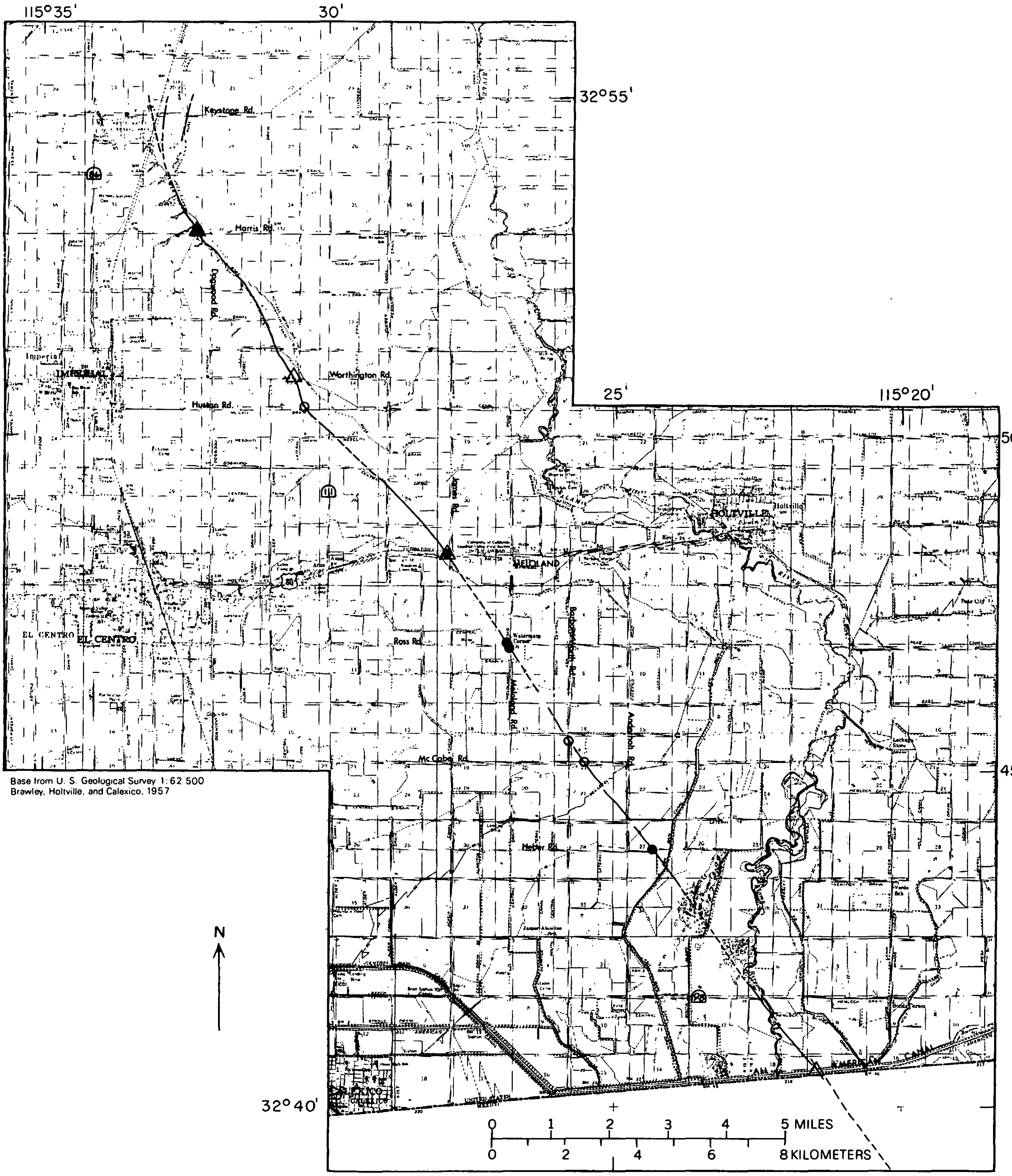

FIGURE 54. — Map of Imperial fault trace based primarily on aerial photographs taken shortly after the 1940 El Centro earthquake and on the unpublished 1940 field notes of J. P. Buwalda. Triangles show locations of Caltech fault-crossing geodetic networks that were surveyed before and after the Borrego Mountain earthquake of April 9, 1968. Solid circles show localities where fresh cracks were observed in loose soil on April 19–28, 1968, presumably resulting from triggered fault displacement on April 9. Open circles are localities where freshness or significance of cracks was questionable. Trace is dashed where projected across areas where surficial evidence of faulting (scarps, ground-water barriers, or lineaments on aerial photographs) is indistinct or absent. See figure 52 for location.

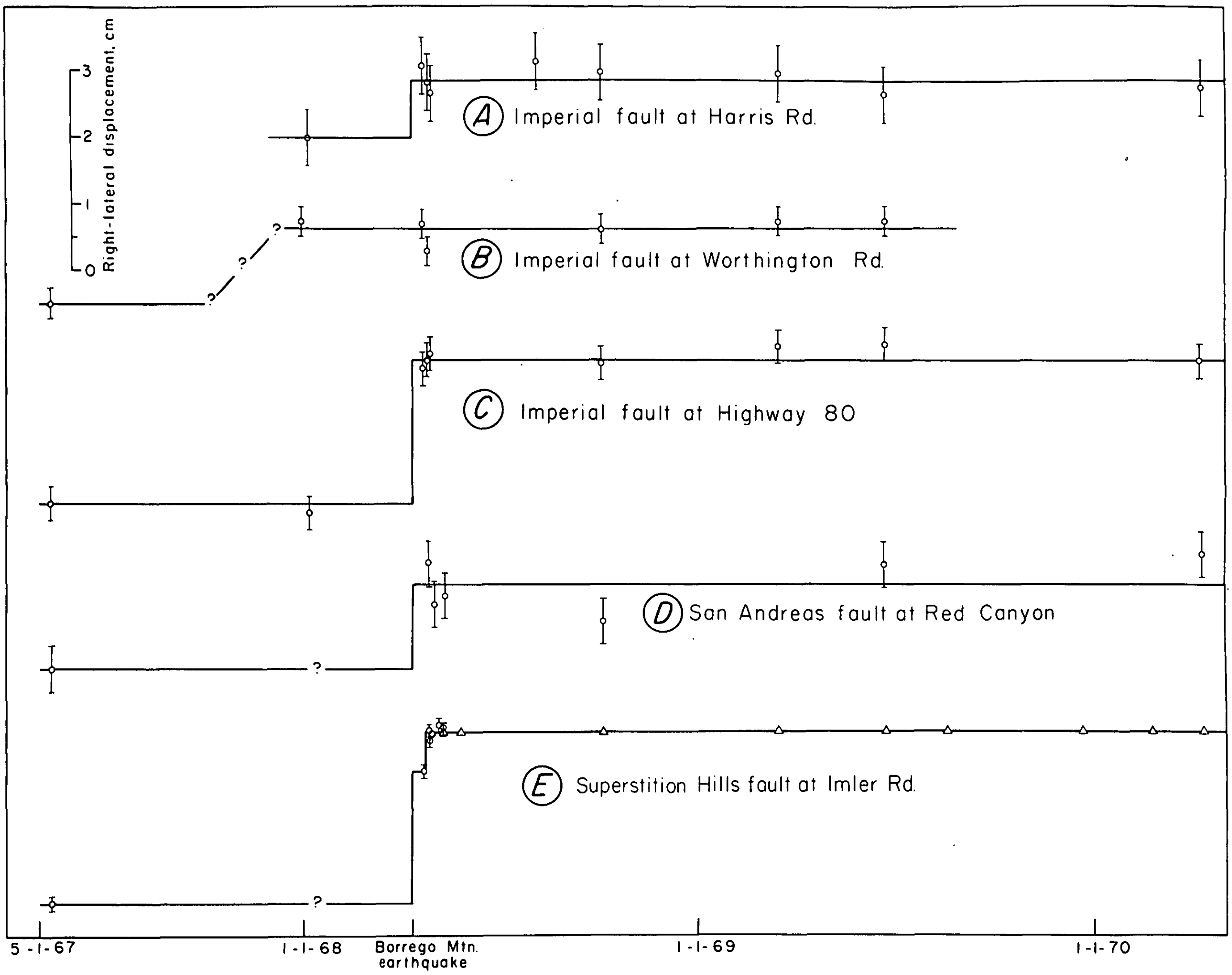

FIGURE 55. — Measurements of fault-crossing geodetic networks between May 1, 1967, and May 1, 1970, showing displacements at time of Borrego Mountain earthquake. Localities are shown in figure 54 and on plate 2. Circles represent averages of measurements of 2–4 independent lines crossing the fault at each locality, and error bars indicate twice the standard deviation of repeated measurements of individual lines in the surveys following the earthquake. Survey lines average 90 m long. Triangles in diagram *E* show readings of taut-wire creepmeter located 3½ km north of Imler Road, showing lack of further displacement there after installation of creepmeter on May 7, 1968.

much as 7 m high that delineates the northern 11 km of the fault trace, (2) a marked ground-water barrier that is sometimes visible from the air even in cultivated fields, and (3) a pronounced gravity anomaly along the fault trace (Kovach and others, 1962). However, the total extent of the Imperial fault beyond the 60-km segment broken in 1940 is not known; there is as yet no good geological or geophysical evidence of the fault north of Keystone Road, where the 1940 trace died out, or south of a point near Tortuosa Check (Mexico), at the south end of the 1940 break. Possibly, the Imperial fault is a transform fault whose active segments indeed do not extend much beyond its presently known length (Lomnitz and others, 1970).

SUPERSTITION HILLS FAULT

On May 11, 1967, Allen and Brune had established a small geodetic network across the Superstition Hills fault where it crosses Imler Road (pl. 2); reoccupation of this station on April 19, 1968, 10 days after the Borrego Mountain earthquake, revealed about 2½ cm of right-lateral displacement (fig. 55*E*). At the same time, fresh en echelon cracks showing as much as 1.5 cm of right-lateral displacement were discovered along the Quaternary fault trace in the same vicinity (figs. 59, 60). On April 25, these cracks were followed northwest for about 8 km along the fault trace, and on May 13–15, Grantz and Wyss mapped the entire broken zone, which extended for 23 km (pl. 2).

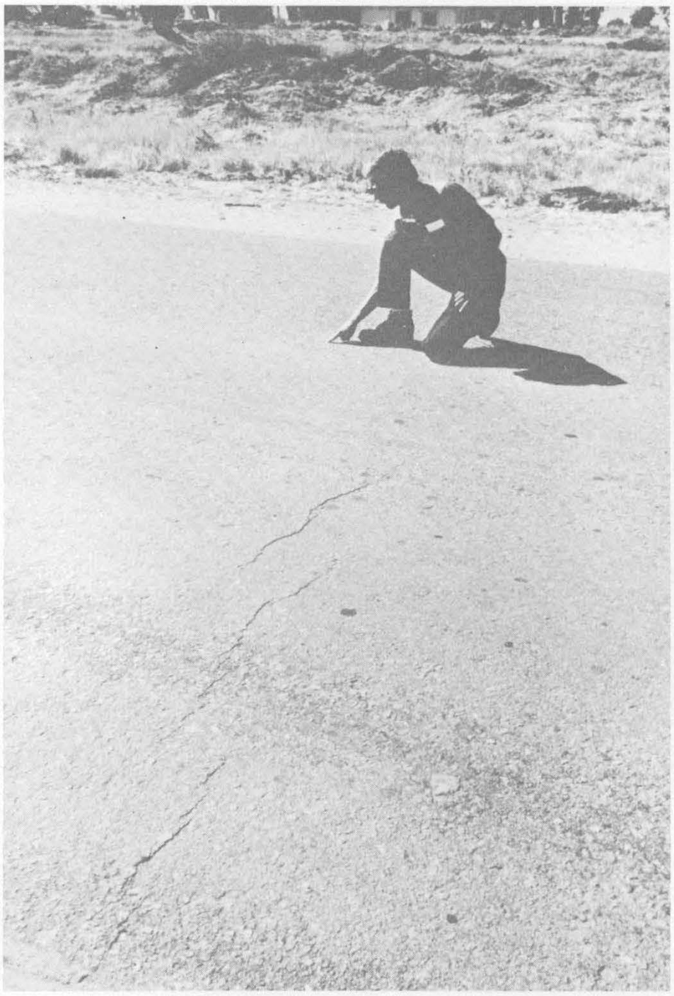

FIGURE 56. — Fresh en echelon cracks crossing Ross Road. View southeast. Photograph taken April 28, 1968.

FIGURE 57. — En echelon cracks on Meloland Road first observed following the Imperial earthquake of 1966 (Brune and Allen, 1967a) but slightly widened during the Borrego Mountain earthquake. Fault displacement of about one-half m occurred at this same locality in 1940. Photograph taken April 28, 1968.

The cracks, as mapped on May 13–15, varied from a single, narrow well-defined break several centimeters to a meter wide, the most common type, to zones of en echelon cracks as much as 7–10 m wide in which the individual cracks stepped to the left in the manner of ground cracking along right-lateral strike-slip faults. Their dip, as recorded at four near-vertical exposures, were 80°–90°. The cracks followed very closely the trace of the Superstition Hills fault across the strongly folded Pleistocene sedimentary rocks of the Superstition Hills and vicinity. Commonly, they lay within the ⅓–1⅔-m-wide gouge zone of the Quaternary Superstition Hills fault, but in a number of places, the cracks occurred in the Pleistocene sediments as much as 7 m from the Quaternary fault. Where they departed from the Quaternary fault gouge zone, the cracks usually, but not always, lay northeast of it.

Where the cracks formed a narrow well-defined zone, they commonly coincided exactly with a single fault-controlled line of desert shrubs (fig. 61), small drainage sumps and collapse pits or trenches (fig. 62), local ground-water barriers, small fault scarps in soft sediments, or, at a few places, right-laterally offset small ridges and gullies. This alinement and the character of the alined features indicate that the fault cracks of April 1968 follow a well-established line of latest Holocene faulting as well as a Quaternary bedrock fault.

The displacements measured on May 13–15 along the partly wind-eroded and sand-filled fault cracks indicated dominantly right-lateral strike slip, with only local vertical displacement and no instances of left-lateral slip. The right slip was as much as 1.8 cm but averaged about 0.8 or 0.9 cm. Of only possible significance, because of the erosion and filling of the

FIGURE 58. — Fresh cracks across Heber Road. Displacement of about 1½ m took place here in 1940, but no further displacements are known to have occurred here until 1968. Photograph taken April 28, 1968.

FIGURE 59. — Right-lateral displacement of about 2 cm on the Superstition Hills fault in sec. 23, R. 12 E., T. 14 S. Diameter of coin is 1.7 cm. Photograph taken April 22, 1968; note that crack has filled in since time of probable formation on April 9.

cracks, is the fact that most of the largest right-lateral displacements were recorded near, although not at, the ends of the fault break of April 1968. Most displacements of 1¼ cm and greater occurred between 1.7 and 5.8 km of the southeast end and between 2.8 and 4.7 km of the northwest end of the 23-km-long fault break. Displacements of between 0.4 and 1.0 cm were common along the central part of the break. Vertical displacements, along three short ($\approx$75 m) segments of the fault, were as much as 2½ cm. Two, at the northwest end of the break, were up on the northeast; one, near the middle of the break, was up on the southwest. In all three places, the uplifted side is also the topographically higher side, and in two of them the uplifted side holds up a low scarp cut in soft Pleistocene sediments. These relations indicate that the local vertical components of slip in April 1968 acted in the same sense as the latest Holocene displacements at those places.

When the cracks were first observed on April 19, they were relatively fresh appearing, but by the time mapping was completed on May 15, windblown sand had already obscured much of the fault trace. We conclude that the cracks could not have come into existence long before April 19, and their origin in association with the Borrego Mountain earthquake on April 9 seems highly probable. Because of suspicion that creep might be taking place on this fault following the earthquake, a creepmeter was installed across the fault on May 7 at a locality midway along its length (pl. 2). A recorder registered the displacement as measured by a taut 10-m Invar wire, similar to an instrument previously used at Parkfield (Smith and Wyss, 1968). Seventeen subsequent readings of

FIGURE 60. — En echelon cracks indicative of right-lateral displacement along Superstition Hills fault in sec. 9, R. 12 E., T. 14 S. Photograph taken April 27, 1968.

FIGURE 61. — New en echelon cracks of right-lateral habit following the line of desert plants that marks the Superstition Hills fault in NW¼ sec. 26, T. 13 S., R. 11 E. The larger plants are about 1 foot high. Photograph taken May 13, 1968.

the creepmeter, through November 1971, revealed no evidence of further significant movement on this segment of the Superstition Hills fault, nor have any further cracks appeared in the nearby paved road where it is crossed by the fault. These observations further support the inference that the displacement observed on April 19, 1968, occurred relatively suddenly in association with the Borrego Mountain earthquake.

Minor displacements on the Superstition Hills fault similar to those observed in 1968 have occurred at least three other times in recent years. In 1951, Joseph Ernst (written commun.) noted fresh en echelon cracks along about 3 km of the Superstition Hills fault, approximately centered within the segment that broke in 1968 and along exactly the same trace. A magnitude 5.6 earthquake had been centered in this area about 2 weeks earlier, and Ernst concluded that the rate at which windblown sand was filling the cracks demanded their origin within about this period. Similarly, in late December of 1965, Brune noticed fresh en echelon cracks along the Superstition Hills fault at Imler Road, and he and Allen subsequently followed these for about 1 km north and south of the road; these cracks may have been triggered by a nearby magnitude 4.0 shock on November 30, 1965. The cracks were quickly obscured by blowing sand, and it is clear from repeated subsequent visits to the area that significant creep is not occurring continuously. Similarly, fresh cracks were noted along the fault south of Imler Road during a visit to the area on December 20, 1969, although they could not be correlated with a specific local earthquake. The movement did not extend far enough north to affect the creepmeter. The movement in April 1968 is evidently only one in a series of small episodic surface displacements that have characterized this fault in recent years; the same behavior may well be true of the segments of the

FIGURE 62. — Small collapse pits, alined vegetation, and variation in abundance of vegetation along the Superstition Hills fault in SW¼ sec. 9, T. 14 S., R. 12 E. New hairline cracks follow the alined features but are largely obscured by windblown sand and silt. Photograph taken May 14, 1968.

Imperial fault and San Andreas fault that broke at about the same time.

Like the Imperial fault, little is known about the possible extent, if any, of the Superstition Hills fault beyond the segment broken in 1968. On the southeast, the 1968 fractures ended about 1 km north of Edgar Road, at very nearly the same point that the Quaternary trace disappears as observed on aerial photographs and in the field. Likewise, the fractures continued northwest only about as far as the mapped trace of the Quaternary fault (Dibblee, 1954; unpub. data). The Superstition Hills fault, together with the nearby Superstition Mountain fault, appear to be branches of the San Jacinto fault zone, and if projected still farther northwest, they would join the Coyote Creek fault — also a branch of the San Jacinto zone — on which the Borrego Mountain earthquake occurred.

SAN ANDREAS FAULT

In February 1967, A. G. Sylvester (oral commun.) found fresh cracks along the trace of the San Andreas fault in the Mecca Hills north of the Salton Sea; they were particularly evident in the 4-km segment between Painted Canyon and the unnamed canyon (locally called Red Canyon) in sec. 28, T. 6 S., R. 9 E. (Thermal Canyon quadrangle). We were not convinced at that time that the cracks necessarily reflected tectonic movements, because among other reasons there has been very little historic seismicity (Allen and others, 1965) or microearthquake activity (Brune and Allen, 1967b) along this segment of the San Andreas fault zone. However, to check this possibility, we established a small geodetic network across the fault in the unnamed canyon noted (station "Red Canyon" in table 12; pl. 2) on May 11, 1967. Resurvey of this network on April 24, 1968, indicated 1.3 cm of right-lateral displacement, and since that time there has been no significant additional change (fig. 55*D*). A second fault-crossing geodetic network was established across the fault near Bertram (station "Bertram" in table 12; pl. 2) on May 5, 1968, and it likewise has shown no significant change in six subsequent surveys through August 7, 1970.

Despite the low seismicity along this segment of the San Andreas fault, the fault trace is so clearly marked in the field that displacements along it must have occurred in very recent years. Small scarplets as much as 50 cm high and only slightly eroded are abundant along the fault (fig. 63). Zones of en echelon fractures, eroded and distinctly older than the recent fractures (fig. 64), appear to be too transient to have persisted for much more than a decade; conceivably, all the erosion along the older fractures could have been accomplished by one heavy rainstorm. Similarly, piping of rainwater into the fracture zone in places appears very recent. From this evidence, it would appear that more than one episode of recent fault displacement has occurred in this area despite the scarcity of historic seismic activity. Whether such previous displacements likewise accompanied distant earthquakes is unknown.

When this area was first visited after the Borrego Mountain earthquake on April 24, fresh en echelon cracks were observed at the base of the scarplets (fig. 65) and at several other localities along the fault trace. Wallace and Wyss subsequently mapped the fresh break for more than 30 km from near Bertram on the south to Thermal Canyon on the north (pl. 2), although it is significant that surface fracturing was by no means continuous throughout the 30-km segment. The average right-lateral dis-

FIGURE 63. — En echelon cracks (in shadow, foreground) at base of scarplet along San Andreas fault in sec. 28, R. 9 E., T. 6 S. View northwest. Geodetic data at nearby station "Red Canyon" indicated about 1.3 cm right-lateral displacement (fig. 55*D*). Photograph taken April 28, 1968.

FIGURE 64. — New fracture in old fracture zone along San Andreas fault in sec. 28, R. 9 E., T. 6 S. New en echelon fractures are subparallel to old en echelon fractures. Note that erosion has progressed along old fractures. Photograph taken May 9, 1965.

placement was estimated to be between 0.5 and 1.0 cm.

One of the puzzling features of the San Andreas fault in this region is its apparent termination opposite the south end of the Salton Sea, particularly because this segment of the fault may have as much as 260 km of post-early-Miocene strike-slip displacement (Crowell, 1962). The apparent termination might be explained simply by concealment of the fault trace southeast of this point by Quaternary sediments, including those of Lake Cahuilla that inundated all this region for 1,300 years, ending perhaps as recently as 300 years ago (Lake LeConte in Hubbs and others, 1960). Likewise, there is some geophysical evidence suggesting continuity of the fault farther southeast (Kovach and others, 1962; S. Biehler, unpub. data). On the other hand, the San Andreas fault may be a transform fault whose active segment does indeed terminate near the Salton Sea. Adding weight to such a hypothesis is the presence of the northeast-trending Salton volcanic domes that might be a manifestation of a ridge segment in a transform fault system (Lomnitz and others, 1970). Nonetheless, it is significant that the 1968 fractures on the San Andreas fault extended southeast to almost exactly the same point where the continuous Quaternary trace disappears (Hope, 1969).

DESCRIPTION OF THE SURFACE DISPLACEMENTS

En echelon cracking oriented so as to clearly indicate right-lateral displacement was the typical style of surface rupture along the Imperial, Superstition Hills, and San Andreas faults (figs. 65–67). Individual cracks rarely gaped more than 1 or 2 mm when fresh. Individual en echelon breaks were typi-

FIGURE 65. — En echelon cracks along the San Andreas fault near Salt Creek, in the center of sec. 28, T. 8 S., R. 11 E. View northwest. The fault here brings rocks of the Palm Spring Formation (right) into contact with those of the Borrego Formation (left), and the contact is visible in line with the cracks in the middle distance. Photograph taken April 28, 1968.

cally less than 1 m long where the zone of cracks was several centimeters to less than 1 m wide, but they ranged in length from 2 to 30 m in those less common places where the fractured zone was 1–7 m or more wide. The fractures showed up not only in undisturbed soil but also in asphalt roads that were crossed by each of the three faults. All the broken sections of the Superstition Hills and San Andreas faults were traversed in their entirety by one or more of the authors. This was not possible along the Imperial fault because of intensive cultivation of most of the area; instead, each road and canal crossing was checked.

The newly formed fractures along the three distant faults were such minor features that they would easily have escaped detection if we had not specifically looked for them and if we had not known from

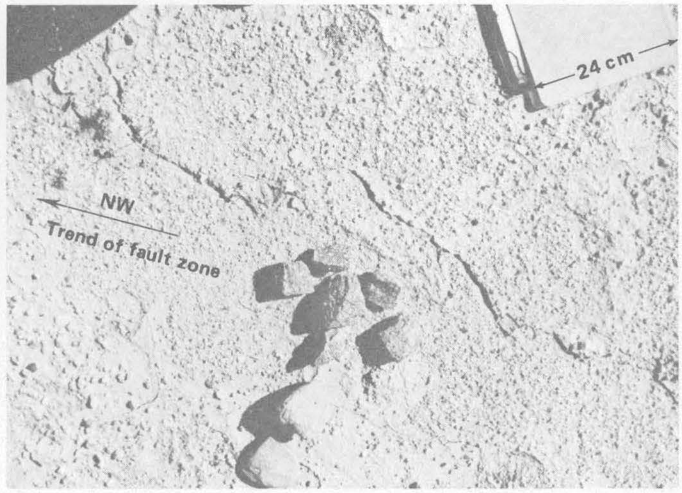

FIGURE 66. — En echelon fractures along the San Andreas fault approximately 2 km south of Salt Creek, in SW¼ sec. 34, T. 8 S., R. 11 E. Photograph taken May 10, 1968.

FIGURE 67. — En echelon fractures, sec. 28, T. 6 S., R. 9 E. Scale is 19 cm long. View southeast. Photograph taken May 9, 1968.

other geologic evidence the exact locations of the active fault traces to within a very few meters. The precise trace of the Imperial fault, despite its location within the heavily cultivated floor of the Imperial Valley, was known from J. P. Buwalda's very detailed notes on the much larger 1940 earthquake displacements, as well as from the subsequent displacements along part of the trace in 1966 (Brune and Allen, 1967a). The detailed trace of the Superstition Hills fault is clear on large-scale aerial photographs and on the ground because of the abrupt truncation of well-exposed and highly deformed Pleistocene sedimentary rocks at the fault. Similarly, segments of the San Andreas fault are well delineated on detailed aerial photographs because of ground-water damming and the truncation of young sedimentary rocks (figs. 68, 69) (Hope, 1969). Both the Superstition Hills and San Andreas faults traverse desert areas that, for the most part, have never been cultivated or otherwise culturally modified. Considerable stretches of both faults are mantled with a veneer of sediments dating from the last major filling of the Salton depression by Lake Cahuilla between about 300 and 1,600 years ago.

Seldom have such well-defined faults been examined in such great detail after a major nearby earthquake, and although this may be the first documentation of fault displacements caused by seismic shaking, the same phenomenon may have happened many times before, not only here, but also on other active faults in similar tectonic environments.

It is particularly significant that, with minor exceptions, surface fracturing occurred in 1968 only along those segments of the Superstition Hills and San Andreas faults where examination of aerial photographs and field exposures could clearly delineate preexisting active breaks. Several examples have already been cited in the preceding section, but perhaps the most intriguing localities are along the San Andreas fault northeast of the Salton Sea. In this area, some segments of the fault are much more clearly delineated by features of recent displacement than others, and it is only on the clearly delineated parts that fresh fractures were found after the Borrego Mountain earthquake, despite careful searches in some of the intervening "inactive" segments (for example, Box Canyon Wash, Salton Sea State Park headquarters area, Highway 111 northeast of Bombay Beach). This distribution is well illustrated by Hope's (1969) map, which shows both the 1968 fractures and the Quaternary breaks that were visible on 1:14,000-scale aerial photographs flown in 1966. Either (1) contemporary movements are taking place along a discrete fault plane at the surface in some segments and throughout a distributed zone in other segments or (2) contemporary displacements are limited to certain weak segments of the fault in contrast to other stronger segments that are temporarily locked, to be broken through during a larger earthquake at some time in the future. The second argument is analogous to that sometimes used for the San Andreas fault as a whole (for example, Allen, 1968), but whether this kind of reasoning is applicable on such a small scale is unknown.

It should also be noted that the geodetically measured displacements (fig. 55) were consistently larger than those estimated from field observations of the faulting. Inasmuch as the geodetic lines used for the calculations of figure 55 were typically about 100 m long, this variation suggests that some shear deformation was taking place that was not expressed as discrete visible fractures at the surface. Indeed, in attempting to interpret the geodetic data at localities where many stations were surveyed, one could not escape the conclusion that, at least at some localities, deformation took place in a distributed fashion rather than entirely along a single fault plane. The accumulation of such distributed deformation during repeated fault displacements is the mechanism that produces the drag so commonly observed along faults in layered rocks. At the Coyote Creek fault rupture of April 9, 1968, this mechanism produced pronounced drag in late Holocene sedimentary rocks and in places produced more than half the total late Holocene deformation. (See Clark and others, this volume.)

OTHER FAULTS

At the same time that fresh displacements were being discovered on the Imperial, Superstition Hills, and San Andreas faults, a number of other faults in the region were carefully checked in the field and found to show no evidence of surface displacements. These include the Superstition Mountain fault, Elsinore fault, Laguna Salada fault, Earthquake Valley fault, San Felipe fault, and branches of the San Jacinto fault system north of Borrego Valley. One feature that distinguishes these faults is that they are predominantly in crystalline rocks, whereas the parts of the three faults that moved are all in deep alluvium or late Cenozoic sedimentary deposits. The estimated minimum distance to crystalline basement based on seismic work (Kovach and others, 1962; Biehler and others, 1964) is 3,500 m along the Superstition Hills fault, 6,000 m along the Imperial fault, and perhaps 2,000 m, but locally only 400 m (Babcock, 1970), along the San Andreas fault. It is also probably significant that the only three faults in southeastern California for which we had some evidence of slippage before the earthquake (and which had therefore been straddled with small geodetic networks) were the same three faults that moved during the Borrego Mountain earthquake.

MECHANISM OF DISPLACEMENT

Three lines of evidence lead us to believe that the observed fault displacements took place on or about April 9, 1968: (1) The geodetic measurements that were made during the year before and the year after

FIGURE 68. — Linear valley eroded along San Andreas fault, Mecca Hills. New fractures followed this valley but could not be found in the dry alluvium of Painted Canyon (far background).

the earthquake indicate little or no creep, except at Worthington Road. It thus seems unlikely that creep should have characterized only the short interval that included the earthquake, unless triggered by it. (2) On March 8, 1968, 1 month before the earthquake, a heavy and unusual rainstorm brought approximately 5 cm of precipitation to the entire Imperial Valley–Coachella Valley area, causing considerable runoff and local flooding. All the fresh cracks observed after the earthquake must have originated after this rainstorm. (3) Blowing dust and sand are characteristic of the entire region, and everyone who studied the displacements on these three faults, as well as the main break near Ocotillo Wells, was impressed with the rate at which fresh features disappeared. Within 2 weeks of the earthquake, many of the cracks along the main break had become barely recognizable because of windblown

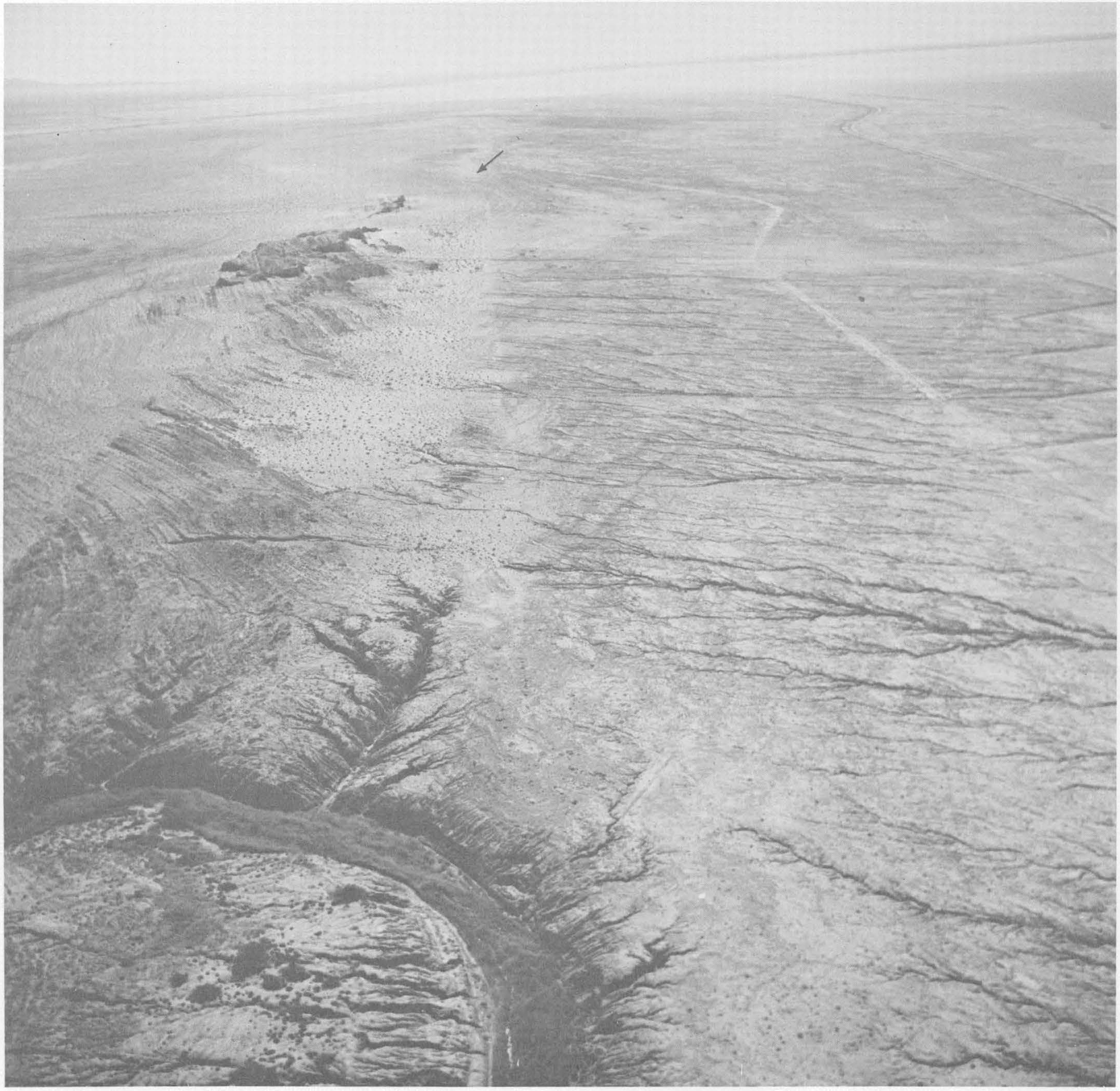

FIGURE 69. — View southeast along San Andreas fault. New fractures closely followed this lineament to point shown by arrow in distance. Bat Caves Buttes on left; Salton Sea in distance; Salt Creek in foreground.

sand. It is our judgment, based on field experience in this area, that the fractures first observed between April 13 and April 24 must have come into existence during the first 2 weeks in April. Particularly along the Imperial fault, the fresh cracks in powdery alluvium that were first observed on April 13 must have originated within the preceding few days. It seems to us to be a reasonable, indeed a highly likely, conclusion that all the fractures came into existence at the approximate time of the Borrego Mountain earthquake on April 9.

STATIC VERSUS DYNAMIC STRAIN

If the hypothesis is accepted that the breaks on the Imperial, Superstition Hills, and San Andreas faults were caused by the Borrego Mountain earthquake, the important question still remains as to whether the displacements were caused by the dynamic strain associated with the shaking or by the static strain associated with the main fault break. The static strain is the permanent strain field caused by the 33-km-long break on the Coyote Creek fault; the dynamic strain is the transitory strain associated with the seismic waves generated by the earthquake.

For an estimate of the static strain, we use the diagrams of Press (1965). The length of the surface break is taken as 33 km, and the hypocentral depth now assigned by the Seismological Laboratory, California Institute of Technology, is 11 km. For an upper limit of the static strain at distance, we therefore use Press's case in which $L=D$; the far-field strains were calculated by scaling down Press's figures to correspond to an average fault displacement of 30 cm. The resulting static strains at distances of 45, 70, and 50 km in the directions of the Superstition Hills, Imperial, and San Andreas faults are 4×10^{-7}, 1×10^{-7}, and -3×10^{-7} respectively, assuming these faults to be parallel to the Coyote Creek fault. The minus sign for the San Andreas fault indicates that the residual static strain induced by the Coyote Creek fault displacement was left lateral (Dr. John McGinley, California Inst. Technology, oral commun., 1968).

The dynamic strain caused by S waves with a period of approximately 4.3 sec, recorded at El Centro near the Imperial fault, was about 1.1×10^{-5} (corresponding to a trace amplitude of 4.9 cm at a period of 4.3 sec on the strong-motion Wood-Anderson instruments). This dynamic strain is two orders of magnitude larger than the static strain at this distance. This fact, in addition to the persuasive argument that the static strain would have led to the opposite sense of displacement on the San Andreas fault, strongly indicates that the dynamic (vibratory) strains rather than the static strain induced the observed ruptures on the distant faults.

SUDDEN DISPLACEMENT VERSUS CREEP

Even granting that the dynamic strains caused the displacements, the question remains as to whether these displacements took place suddenly or during a period of creep lasting several minutes, hours, or days. After the distant displacements were first noticed, geodetic measurements were repeated at closely spaced intervals to determine if creep was perhaps still taking place (fig. 55); it appears that within the accuracy of the measurements, no creep was occurring at this time on any of the three distant faults except for one possible increment at Superstition Hills (fig. 55*E*). The sensitive creepmeter installed subsequently at Superstition Hills further substantiates this conclusion. The observations at Highway 80 indicate that if displacements occurred during a period of creep after the earthquake, this period must have been shorter than 4 days.

If any of the three distant breaks had occurred as sudden ruptures, however, seismic waves would have been radiated. Because the seismographic records of most southern California stations were off scale for several minutes following the Borrego Mountain earthquake, we cannot state with assurance that earthquakes did not occur at the three distant localities immediately following the main event, although it seems unlikely that the magnitudes of such events could have exceeded 4.5 without being detected. However, three lines of evidence suggest that such sudden displacements, if they did occur, were not in any sense "normal" earthquakes:

1. The fault lengths of 22, 23, and 30 km are much longer than could typically be associated with earthquakes of magnitude less than 4.5 (Wyss and Brune, 1968).
2. Only a very few possible aftershocks could be associated with the three distant faults, in sharp contrast to the usual high aftershock activity accompanying fault breaks of this length. Despite a careful search of seismic records from several stations close to the distant faults, including temporary stations within the Imperial Valley at Obsidian Butte and near Westmoreland, only six small shocks could be found that might possibly have been associated with the Superstitution Hills fault within a month after the earthquake, one small shock that might have been associated with the Imperial fault, and none in the area of the San Andreas fault. A particular search was made of the Hayfield[4] records for events with short S-P intervals, because the San Andreas fault is much closer to this station than to the Coyote Creek fault, near which the principal aftershock activity occurred. The absence of aftershocks in the vicinities of the distant faults is substantiated by microearthquake surveys in two of these areas by Walter Arabasz on April 20–21. Using a backpack instrument that recorded on smoked paper and operated at a magnification of 100,000 at 20 cps, he found no nearby microearthquakes during 13 hours of continuous recording at the Imperial fault near the south end of the fractured segment. Similar but shorter periods of recording farther north along the Imperial fault and in a granite quarry at Superstition Mountain (5 km from the Superstition Hills fault) like-

[4]For the location of the Hayfield station, see fig. 6.

wise revealed little or no microearthquake activity.

3. Another obvious peculiarity of these displacements is the unusually low ratio of average offset to length of rupture. For most earthquakes, when the faulting length is about 20–30 km, the average offset is about 10–100 cm, whereas the average offset observed here is only 1–2½ cm. In addition, it appears that the breaks may not have been continuous on the San Andreas and Imperial faults.

After the Borrego Mountain earthquake, we concluded (1) that the displacements on the three distant faults occurred rapidly, but with a mechanism of strain release different from that of typical earthquakes associated with fault breaks of these lengths, (2) that this relatively rapid motion commenced with the arrival of the first intense seismic energy from the Borrego Mountain earthquake, and (3) that it probably lasted at most only as long as the strong shaking persisted. The displacements were visualized to have been triggered by strong seismic shaking, which is a previously undocumented mechanism of strain release on active faults.

These three conclusions must be tempered, however, by subsequent events along the Imperial fault. As was mentioned in an earlier section, there was no further movement along the Imperial fault after the Borrego Mountain earthquake until September 30, 1971, when a magnitude 5.3 shock in the Superstition Hills, 37 km away, was followed by about 1.4 cm of right-lateral displacement on the Imperial fault at the Highway 80 locality. Fresh cracks were observed along a segment of the fault at least 10 km long extending from south of Ross Road to north of Robinson Road. But evidence suggests that the faulting did not occur at the same time as the earthquake: 3 days after the earthquake, Brian Tucker (oral commun., 1971) examined the Highway 80 locality and noticed no fresh cracks despite his familiarity with the locality and its history. However, 3 days later, on October 6, 1971, fresh cracks and lateral offsets were obvious to several visiting parties. Repeated subsequent visits to the site revealed no increase in displacement, so we must conclude that virtually all the surface faulting took place between 3 and 6 days after the earthquake. One might argue, of course, that the near coincidence of the two events was fortuitous, but this seems unlikely in view of the two earlier movement episodes, both of which (1966, 1968) also occurred in close association with large local shocks. As for the Borrego Mountain earthquake, we are forced to conclude that this later faulting was triggered by the dynamic waves of the nearby shock, but the mechanism of local strain release and its apparent delay remain problematical. Perhaps the Imperial fault was triggered only at depth at the time of the September 30 earthquake, and this dislocation then extended surfaceward only gradually, something like the situation visualized by Smith and Wyss (1968) for the Parkfield displacements and by Burford (this volume) for the Coyote Creek fault displacements. We must now recognize that the same sort of delay may have characterized the 1968 displacement as well; the actual triggering may have occurred at a depth of perhaps 4 km in the elastically strained sedimentary rocks, with the displacement then propagating to the surface within the following 4 days. Only continuously recording creepmeters will resolve this problem in future events.

Many additional aspects of the mechanics of displacements on the three distant faults remain unexplained. We assume that elastic strain was released by the displacements, but the depth at which this elastic strain had accumulated is problematical. An attractive but unproved hypothesis is that creep is taking place continually in the crystalline basement rocks along these three faults, partly reflecting the unusual semioceanic crust and complex fault pattern of the region (Allen, 1968). Elastic strain is visualized to accumulate only in the overlying thick section of indurated sedimentary rocks, to be relieved intermittently either by episodic creep, by very shallow small earthquakes such as the Imperial earthquake of 1966 (Brune and Allen, 1967a), or by occasional intermediate-sized shocks such as the El Centro earthquake of 1940 on the Imperial fault. Such events may in turn be triggered by externally caused shaking.

What determined the amount of displacement on the three distant faults is another unanswered question. Scholz, Wyss, and Smith (1969) argued that the amount of episodic creep displacement is not a function of the nature of the instigating event, but instead is related to the stress-drop between a constant rupture stress and a constant frictional stress on the fault. Had the tectonic stress accumulated to a critical value, the creep presumably would have started even without instigation by the earthquake, as presumably happened at Worthington Road before the earthquake (fig. 55*B*). On the other hand, field evidence may suggest that the total displacements on the three distant faults might have been at least partly a function of the strength of shaking; the larger displacement on the Superstition Hills fault as compared to the Imperial fault may be an indication not of higher stress accumulation but, at least in part, of stronger shaking closer to the source.

STRESS-DROPS

In order to estimate the stress-drops associated with the displacements on the distant faults, a fault depth must be assumed. We arbitrarily assume a depth of 4 km, equal to about half the thickness of the sedimentary section in the center of the Imperial Valley (Biehler and others, 1964) and corresponding to the depth of transition between stable sliding and stick-slip in the Parkfield model of Scholz, Wyss, and Smith (1969). If the average displacement is assumed to be 1.5 cm, the stress-drop is 0.5 bar, close to (that is one-half of) the value obtained by Brune and Allen (1967a) for the Imperial earthquake of 1966.

TRIGGERING

We have chosen to use the word "trigger" in connection with the displacements on the Imperial, Superstition Hills, and San Andreas faults in recognition of the fact that one event initiated other events. However, it must be recognized in these examples that the displacements were initiated by a much larger event than the displacements themselves. As was indicated in a previous section, the maximum dynamic strain at El Centro was about 1.5×10^{-5}, and assuming a fault depth of 4 km and an average displacement of 1.5 cm on the nearby Imperial fault, the calculated strain associated with the displacement was only 2.5×10^{-6}. In contrast, a different type of seismic triggering might be the multiple ruptures of the Alaska earthquake, where small events apparently triggered larger events (Wyss and Brune, 1967).

ENGINEERING IMPLICATIONS

In the planning of engineering structures adjacent to or across active faults, it has usually been assumed in the past that significant fault displacements would occur only infrequently — perhaps about once every few hundred years on even the most active faults. The documentation of semicontinuous creep along parts of the San Andreas fault has tended to modify this kind of thinking (for example, Wallace, 1970), and the present study emphasizes still further the difficult problems of estimating probabilities of fault displacements. A few years ago, for example, one might have estimated that the San Andreas fault opposite the Salton Sea would break perhaps once every hundred years, the inferred recurrence time for large earthquakes on this segment of the fault. However, if one now assumes, on the basis of the Borrego Mountain experience, that an earthquake of magnitude 6 or greater anywhere in the Imperial Valley area might cause a small displacement on parts of the San Andreas fault, then the estimated chances of fault displacement are considerably higher. The recurrence curve for the Imperial Valley region based on 1934–63 records (Allen and others, 1965) suggests that an earthquake of magnitude 6 or greater should occur about once every 6½ years. Perhaps the reason that some of the scarplets along the faults look so fresh (fig. 63) is that displacements indeed take place with about this frequency.

Although it does not necessarily follow that active faults in all parts of California would behave in the same manner as the Imperial, Superstition Hills, and San Andreas faults when heavily shaken, it seems clear, nevertheless, displacements occur more frequently than previously recognized along the myriad of active faults that underlie California and other tectonically similar regions. Although many types of engineering structures have sufficient flexibility to withstand fault displacements of a centimeter or two without significant damage, it should be remembered that the disastrous failure of the Baldwin Hills Reservoir in 1963 was caused by a fault displacement of a comparably small amount (Hudson and Scott, 1965).

Lest the impression be left that all faults in earthquake-prone regions should now be suspect of possible small but frequent displacements, we emphasize once again that the three distant faults that moved because of shaking generated by the Borrego Mountain earthquake were all "active" faults in that they showed abundant evidence of repeated Quaternary displacements. Furthermore, the only segments on which displacements took place were clearly delineated by surface exposures (at least in uncultivated areas), and each of the three faults had histories that suggested similar movements within the previous few years. These findings point out the need for thorough geologic studies prior to engineering developments in faulted areas but also give some confidence that even in highly faulted regions dangerous areas can reasonably be differentiated from safe areas.

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