UNITED STATES DEPARTMENT OF INTERIOR
GEOLOGICAL SURVEY

SURFACE DISPLACEMENT ON THE IMPERIAL AND SUPERSTITION HILLS FAULTS TRIGGERED BY THE WESTMORLAND, CALIFORNIA, EARTHQUAKE OF 26 APRIL 1981

By

Robert V. Sharp, James J. Lienkaemper, and
Michael J. Rymer

Open File Report
82-282

This report is preliminary and
has not been edited or reviewed
for conformity with Geological
Survey standards or nomenclature

ABSTRACT

Parts of the Imperial and the Superstition Hills faults moved right-laterally at the ground surface at the time of or shortly following the M_L 5.6 Westmorland earthquake of 26 April 1981. The displacements occurred prior to any significant aftershocks on either fault and thus are classed as sympathetic. Although the main shock was located in an exceptionally seismogenic part of Imperial Valley, about 20 km distant from either fault, no clear evidence of surface faulting has yet been found in the epicentral area. Horizontal displacement on the Imperial and Superstition Hills faults, southeast and southwest of the epicenter, respectively, reached maxima of 8 mm and 14 mm, and the discontinuous surface ruptures formed along approximately equal lengths of northern segments of the two structures (16.8 km and 15.7 km, respectively). The maximum vertical component of slip on the Imperial fault, 6 mm, was observed 3.4 km north of the point of largest horizontal slip. Vertical movement on the Superstition Hills fault was less than 1 mm. No new displacement was found along the traces of the Brawley fault zone, the San Andreas fault, or the part of the Coyote Creek fault that slipped during the 1968 Borrego Mountain earthquake. A careful search in the epicentral area of the main shock failed to locate any definite evidence of surface faulting. Concentrations of late aftershocks north and northeast of Calipatria near the southeastward projection of the San Andreas fault occurred mostly after our field check; this area was not investigated.

INTRODUCTION

The M_L 5.6 earthquake of 26 April 1981 near Westmorland, California, together with its foreshocks and aftershocks marks the first significant resurgence of swarm-like seismicity and the first surface faulting in the Imperial Valley region since the M_L 6.6 earthquake of 15 October 1979. Following that earlier event, surface displacement was detected along the northern half of the Imperial fault, along the southern part of the Brawley fault zone, along the known length of the Superstition Hills fault, and along scattered parts of the southern San Andreas fault north of the Salton Sea (Sharp and others, 1982; Fuis, 1982; Sieh, 1982). Because the San Andreas and Superstition Hills faults lay outside the 1979 aftershock area, their movements were interpreted to have been sympathetic to the 1979 main shock near the U.S.-Mexico border or possible aftershocks (Sieh, 1982; Fuis, 1982). Much of the aftershock activity of the 1979 event occurred in the same part of Imperial Valley where the earthquake described in this volume was located. Because of the changing roles of these faults in patterns of "triggering" versus "triggered" movements from the 1968 Borrego Mountain earthquake to the 1979 earthquake, new displacements that were found on the Imperial and Superstition Hills faults shortly after the 1981 Westmorland earthquake are of special interest. These offsets join the few reported examples of sympathetic movements caused by earthquakes on faults which themselves have not apparently displaced the earth's surface in historic time.

The main shock and many of the aftershock epicenters for this event lie astride the seismic corridor that traverses northern Imperial Valley, connecting the southernmost San Andreas fault and the Imperial fault (see Johnson and Hill, Fig. 8, 1982). Inasmuch as no surface expression of past faulting and no historic surface ruptures are known in the area between the Salton Sea and the town of Brawley the prospect of locating new faulting associated with this event placed special importance on our field checking in the epicentral region.

FAULTS THAT WERE FIELD CHECKED

Searches for surface ruptures began in the evening of April 26 and continued to May 1. Our initial efforts to look for faulting focussed on the epicentral area where surface expression of past faulting never had been recognized. The distribution of aftershock activity at the time of our field study was mostly unknown. After failing to find new faulting near the main-shock epicenter we checked the principal faults in the region and found new surface movement on the northern Imperial fault, southeast of the main shock epicenter, and along the Superstition Hills fault, southwest of the epicenter (Fig. 1). The southern San Andreas fault, the central and southern segments of 1968 surface rupturing on the Coyote Creek fault, the Brawley fault zone, and an unnamed fault 9 km west of Westmorland in Imperial Valley, however, revealed no evidence of new surface movement.

Imperial Fault

Right-lateral surface displacement not exceeding 1 cm was found discontinuously along the northern part of the Imperial fault, beginning on April 26, the day of the main shock. Fresh cracks formed intermittently along 16.8 km of the fault, but because several relatively long intervals in the activated part of the fault did not break at the surface, the sum of lengths of the ruptured segments is substantially less (Figs. 2 and 3). As in past faulting events on the Imperial fault (see Brune and Allen, 1967; Allen and others, 1972; Sharp and others, 1982) displacement was principally right-lateral, especially south of the convergence of the Brawley fault zone; farther north the vertical component of slip was dominant at many places.

One of us (M.R.) walked out the new surface breaks along the Imperial fault to establish the distribution of rupture and to measure displacements. The detailed distribution of cracking along the fault trace, as well as the right-lateral and relative vertical components of displacement that were recorded between April 29 and May 1 are shown in Figure 3. Ground conditions that were favorable for observation of the fault ruptures included smooth dirt shoulders of roads, asphalt-surfaced roadways, and smoothed fields not then under cultivation. Where the ground surface was obscured with high-standing crops, cracked from desiccation of the soil after irrigation, recently plowed, or covered with loose fill, no determination of new movement could be made. As a consequence, additional new cracking may have actually occurred in some of the gaps where none is shown in Figure 3. In some cases, new ruptures were seen at opposite edges of a single field; in Figure 3 dots represent unobserved fractures that probably crossed (or at least entered) such fields.

New fractures along the Imperial fault were nearly uniform in appearance; they consisted of sets and groups of short (0.1-0.4 m), left-stepping, en echelon cracks (Fig. 4). Some of the groups of en echelon cracks, about 5 m to several tens of meters in length, were also alined in left-stepping arrangement with other similar groups of cracks. Stepover distances (normal to the fault trend) usually were less than 0.1 m between the short sets of cracks but were as great as 2 m between the largest groups.

The maximum recorded right-lateral slip across the surface cracks was 8 mm, located 0.48 km north of Robinson Road (Fig. 3, panel B-C). All of the lateral components of displacement larger than 4 mm were measured between Worthington Road and Harris Road (Fig. 3, panels A-B and B-C), although many of the measurements were less. The average horizontal component for all segments of the fault that ruptured was between 2 and 3 mm. Two noteworthy features of the new displacement were the abrupt variations in the amount of slip and in the ratio of the horizontal and vertical components of slip.

Where present the vertical components of slip were consistently in the same relative direction--up on the west side of the fault. Quaternary movements on the northern part of the fault have produced an east-facing scarp that stands as much as 8 m higher than the basin of former Mesquite Lake to the east. The largest vertical component of slip, 6 mm, was observed across fractures just south of Harris Road, about 3.4 km north of the point where the largest right-lateral component was recorded.

Three additional measurements of the vertical component were obtained by releveling of arrays of survey marks across the fault trace at Ralph Road, Harris Road, and midway between Harris and Keystone Roads (Fig. 2). The releveling, done on April 29-30, showed vertical displacements of about 5 mm, 12 mm, and 12 mm, respectively since January 6-8, 1981. The profile of the elevation changes at Harris Road are shown in Figure 5. Because the Imperial fault was still relieving strain in the form of afterslip of the October 1979 Imperial Valley earthquake at the time of the Westmorland shock, these values of elevation change must be corrected by the expected amount of afterslip between the two surveys. A long-term record for the vertical afterslip history is available only for Harris Road, approximately in the center of the most continuous northern segment of new rupture; deducting an estimated after-slip between the surveys (Fig. 6) suggests 4 to 10 mm of new slip triggered by the 1981 Westmorland main shock there. The leveling data for Harris Road thus indicates a vertical component of slip that is about equal to the 6 mm recorded just south of the pavement on cracks along the fault trace. Although the leveling data do not permit a more refined picture of the deformation at the time of the earthquake, it is noteworthy that the changes in elevations along Harris Road between the two surveys (including contributions from both afterslip and new coseismic slip) are similar in profile to those observed after the 1979 earthquake when afterslip was recorded independently of coseismic slip (Sharp and Lienkaemper, 1982).

The locations of most of the new fractures along the Imperial fault coincide with the rupture trace of the 1979 earthquake. Because the scarp formed in 1979 could still be recognized along much of the northeast-facing older scarp north of Huston Road (Fig. 3, panels A-B, B-C, and C-D), comparison of the positions was easily made. With one exception in that segment of the fault, the ground surface broke within a few centimeters of the 1979 trace. Although southeastward from Highway S-80 (Fig. 3, panel D-F) the 1979 fractures were no longer visible on the ground, the new ruptures there likewise were alined with previous offsets and repairs to the roadway and three east-west canals. Only in one short segment 0.98 to 1.06 km south of Keystone Road (Fig. 3, panel A-B) did the new fractures lay noticeably off the 1979 break; the new cracks there were located 1 to 2 m northeast of the preceding fractures.

The pattern of the new fault ruptures at the north end of the Imperial fault may reveal for the first time the location of the main fault strand among the various branches. Although the detailed geometry of the branching west of Mesquite basin was established by mapping of the 1979 surface displacement, the identity of the main strand was not clear because all of the known branches moved at that time. The new ruptures associated with the Westmorland shock lie in alinement mostly along the westernmost strands of the 1979 rupture north of Ralph Road; indeed, the linearity suggests a fault that may be straight and continuous at depth (Fig. 2). All strands to the east were inactive in this event (Figs. 2 and 7), and this relation may reflect a substantially different state of stress for the main strand of the Imperial fault than for its north- and northeast-trending branches. The branch faults with north to northeast strike may be subjected to smaller normal stress than the northwest-trending breaks, and thus may more easily release built-up strain at the time of earthquakes. Accordingly, the 1979 movements may have released strain east of the main Imperial fault sufficiently to inhibit further movement in the 1981 Westmorland event, but the northwest-trending structure that was known to have been yielding in afterslip experienced a new increment of displacement triggered by the 1981 shock.

A study of horizontal strain release after the 1979 Imperial Valley earthquake by Langbein and others (1982) showed the Mesquite basin to be extending in the north-south direction and possibly contracting east-west, at least locally. The branches of the Imperial fault that project northward and northeastward in this area moved slightly in the right-lateral direction in the 1979 event (Sharp and others, 1982), which is consistent with the post-seismic horizontal strains recorded by Langbein and others (1982). However, the dip-slip component on the same faults would have the opposite effect on the strains if they dip eastward and southeastward, respectively, as suggested by surface observations and by interpretation of earthquake spatial distributions by Johnson and Hill (1982).

The movements on the Imperial fault associated with the 1981 Westmorland earthquake appear to be nearly aseismic (see seismicity plots by C. E. Johnson elsewhere in this volume). Although in April, prior to the earthquake, a cluster of small shocks occurred on the Imperial fault southeast of the surface ruptures, during the same period there was virtually no activity farther north where the surface later broke. Some scattered small shocks were located near the north end of the fault in the six days following the main-shock, but activity ceased there until after May 6 when several events spread along the entire length of the already formed new rupture. These last events occurred subsequent to our observations of the ground rupture.

Superstition Hills fault

Surface displacement along the Superstition Hills fault has been detected on several occasions in the three decades prior to the 1981 Westmorland earthquake (Allen and others, 1972; Fuis, 1982). Although some movements may have been associated with earthquakes located near the fault, such as the slip events of 1951 and 1965, the only other displacements that are known to have affected substantial lengths of the fault in historic time are those of 1968 and 1979, each sympathetic to the distant strong earthquakes near Borrego Mountain and in Imperial Valley, respectively (Allen and others, 1972; Fuis, 1982).

The new right-lateral displacement on the Superstition Hills fault associated with the Westmorland shock was discovered on April 28, and two of us (R.S. and J.L.) recorded the locations of the surface breaks and measured their displacement on April 28-29 and May 1.

The fault moved in discontinuous segments over a total distance of 15.7 km along the relatively smooth and single-stranded trace (Figs. 8 and 9). The northwest end of new rupture approaches to within 0.6 km of the termination of the earlier historic movements that also corresponds to the end of the geologically demonstrable fault. Toward the southeast, however, the rupturing died out about 6.4 km short of the end points of the 1968 and 1979 surface movements. Fractures in the northwestern 4.6 km of rupture (Fig. 9, panel A-B) were widely scattered and very minor in displacement, in marked contrast to the next segment farther southeast where the longest nearly continuous strand of new breaks extended for about 7.2 km (Fig. 9, panels B-C and C-D).

The largest right-lateral component of slip, 14 mm, occurred near the southeast end of this segment (11.3 km in the longitudinal distance scale in Fig. 9, panel C-D).

Fractures that formed along the Superstition Hills fault during the Westmorland earthquake closely resemble fractures that formed there at the times of the 1968 Borrego Mountain earthquake and the 1979 Imperial Valley earthquake (Allen and others, 1972; Fuis, 1982), as well as new ruptures along the Imperial fault, described above. The small, left-stepping en echelon fractures (Fig. 11) were easily detected on the ground surface, which, in contrast to the cultivated part of Imperial Valley, has not been disturbed by man to any significant extent.

The trace of the surface rupture shown in Figure 9 was mapped in the field on 1:24,000-scale aerial photographs and transferred to the topographic base by making the best fit of topographic features on the photographs to their correspondents on the base map with a variable power camera lucida. Although the earlier rupture traces in places were mapped at locations as far as 50 meters from those shown here, there is no geologic or geomorphic evidence to confirm that movement occurred along separate traces during the historic slip events. Geologic mapping of the Superstition Hills fault a month prior to the Westmorland earthquake by two of us (R.S. and J.L.) showed the fault to be restricted to a corridor of crushed and locally cemented materials usually less than two meters wide. All of the surface ruptures of the Westmorland earthquake followed this corridor exactly. The discrepancies between locations of previously measured displacements and the trace shown here are probably best resolved by projecting those measures perpendicularly onto the fault trace shown in Figure 9.

The 1981 displacement on the Superstition Hills fault is similar to the 1968 and 1979 movements in at least two ways: (1) the physical expression of the cracks along the trace is nearly identical, although we could not determine whether individual en echelon cracks were reactivated from earlier events; (2) the abruptness and range in short-distance variation of right-lateral movement along the fault are about the same, even though the amount of slip at any given point may have differed appreciably for each of the three movements.

Figure 10 displays graphically some differences of the documented movements that are worth noting. Although the amount of maximum displacement for each of the three events is small, that of the 1981 slip was less at most places, a feature that is consistent with the smaller length of rupture. Perhaps the most significant contrast of the 1981 slip relative to the earlier displacements is the location of the segment having the largest slip slightly southeast of the center of rupture. This part, moreover, is the only place where the new horizontal displacement exceeded those accompanying the 1968 and 1979 shocks.

Both the 1968 and 1979 slip maxima were located toward the end of rupture that was distal with respect to the main shock epicentral location (see also Fuis, 1982, Fig. 5). Because the 1981 Westmorland main shock was northeast of the Superstition Hills fault rupture, an analogous relation isn't possible. The slip profile, like that of the 1968 movement, however, has its maximum skewed to the southeast. Its location is centered between the 1968 and 1979 maxima, and its effect on cumulative right-lateral displacement along the Superstition Hills fault is to partly fill the intermediate minimum (see upper curves in Figure 10). From this relation, the slip associated with the Westmorland earthquake may have released strain in a part of the fault where previous movements had lagged behind other segments of the fault. However, inasmuch as the history of slip is largely unknown prior to 1968, this interpretation could be superficial if we allow that pre-1968 right slip may have been centrally concentrated to the extent that no minimum at that location ever existed.

Some of the gaps in the 1981 rupture were significantly longer than those of the earlier events, a relation that is also compatible with the smaller displacement. The positions of small gaps, however, were different in most cases for the three events, although at least two short segments of the fault (locations at about 12.5 km and 13.9 km in Figure 9) have not broken during any of the three movements. Although major washes cross the fault at these two places, why the fault did not break the surface there is not clear. Hard-packed alluvium in other washes along the fault trace showed well developed fractures.

No systematic measures of vertical components of slip along the 1981 rupture on the Superstition Hills fault are reported here. Although barely detectable vertical movement was noticed at several locations, the amount of vertical slip never exceeded one millimeter across any crack where displacement was measured.

Three small aftershocks that were located near the segment of the Superstition Hills fault where the right-lateral displacement reached its maximum (see Johnson, this volume, Fig. ___) occurred before we detected the new rupture. It is possible that the observed displacements were triggered by small seismic events on the Superstition Hills fault rather than by the main shock near Westmorland, although we have no evidence to confirm this. At about 5:00 p.m. (local time) on May 1, we remeasured the displacement in the segment of maximum slip and found it to be unchanged from the first measurements obtained at about 8:00 a.m. on April 28. Because several additional aftershocks near the same part of the fault occurred between the times of measurement, apparently without producing additional slip, we conclude that the entire slip probably was associated in time with the main shock on April 26.

Epicentral Area

The locations of epicenters of the main shock and aftershocks, shown in Figure ____ of Johnson (this volume) lie in a part of northern Imperial Valley, in which no surface evidence of recent faulting is known. If active faults in this area were surficially expressed at one time, the Colorado River flooding of Salton Basin in 1905 to 1907 together with the accompanying erosion and deposition along and near the New and Alamo Rivers probably created a new land surface devoid of evidence of pre-flood faulting. In April 1907, the surface of the Salton Sea stood at 60 meters below sea level (Douglas and others, 1908) or approximately 10 m above its present level (Fig. 12). The epicenter of the 1981 Westmorland earthquake and many of the areas of its aftershock activity lay in the part of Imperial Valley that was submerged in the floods of 1905-1907. Reworking of sediments within the flood channels and over their banks at that time probably modified the landscape even above the -60 m shoreline. Lineaments that appear on early aerial photographs of the Imperial Valley region, taken in 1937, had been field checked in the past, but none were associated with unambiguous evidence of fault offset of structures such as roads and canals. Although quests for evidence of past movement have been made on other occasions, particularly after earthquake swarms such as that in May, 1975, they too failed to produce any clues to the locations of active fault traces between the Salton Sea and the towns of Westmorland and Brawley.

Our search, covering most of the areas that eventually experienced aftershock activity, produced no clear evidence of new surface faulting (see Fig. 12). Surface failures were found, but all were attributed to movements within the soil produced by liquefaction, spreading, slumping, or lurching. These effects of the earthquake are described in detail by Youd elsewhere in this volume. One area that exhibited considerable seismic activity, that east of Calipatria and Niland, was not checked in the field because we were unaware of aftershocks there. Although our search yielded no positive evidence of faulting, we must allow that some of the small ground breaks that formed in the epicentral area may be related to subsurface faults. Field investigations after future earthquakes may establish in an unambiguous way the presence of surface movement on now unproveable fault traces.

Among the many surficially expressed faults on the west side of Imperial Valley the fault whose trace lay nearest the main shock was checked on April 29 (see small fault west of Westmorland in Superstition Hills fault inset in Figure 1). No evidence of new movement was found along this short unnamed fault, but a remarkably dense cluster of small seismic events whose epicenters were distributed parallel to, but about 2.2 to 2.4 km east of the fault's trace, began shortly after the main shock and continued to be active into May (see Johnson, this volume, Fig. ___). Although the similar orientation and length, as well as epicentral locations to the east of the trace (the probable down-dip direction) hint that the aftershocks might have been associated with that structure at depth, they do not prove the relation. The most interesting aspect of this cluster of aftershocks is that the slightly west-of-north alinement of epicenters is imbedded, at least for part of the aftershock period, in a more diffuse zone of epicenters with a northeast trend.

Although one might argue that the northeast-trending zone of epicenters represents a fault of that orientation at depth, the relation of the denser cluster of events within this belt to the fault trace on the surface would then have to be described as fortuitous. The chance that they are not fortuitous emphasizes the ambiguity intrinsic to interpreting epicentral patterns, particularly in areas where multitudes of faults may be actively participating in strain release.

The field checking for surface ruptures did not extend into the region north and northeast of Calipatria (Fig. 12) where many aftershocks were concentrated, especially after May 2 when the field investigation ended. This part of Imperial Valley is especially significant because it lies approximately on the linear projection of the San Andreas fault from northeast of the Salton Sea, where its surface expression is known to die out. Babcock (1971) has claimed that active fault strands, including a possible extension of the San Andreas fault, exist in this area; this interpretation was based both on linear features discovered with infrared aerial photography and on displaced canals. However, his conclusion is not supported by careful study of the features he discovered. Aerial photographs taken in 1937 prior to agricultural development of the fields where Babcock later located the photographic lineaments clearly show them to be recessional shorelines of ancient Lake Cahuilla which occupied the basin of the Salton Sink, perhaps as recently as 300 years before present (Sharp, 1981). A canal said by Babcock (1971, Fig. 4) to be right-laterally offset was carefully checked in the field, but its construction and alinement were too marginal in quality to safely conclude that it was faulted. Broken and patched concrete canal liners are very common throughout Imperial Valley, and because of their ubiquity, a succession of offset liners along a suspected fault trace must be sought. Two independent searches by R. V. Sharp and M. M. Clark of the U.S. Geological Survey failed to locate any such succession. Although these negative findings cast doubt on the features in question, they do not refute the notion that surficially active faults do exist in this area. The concentrated aftershocks in May 1981 reinforce this possibility and call for further close inspection of man-made structures.

Brawley fault zone

Road intercepts of the various known strands within the Brawley fault zone were checked for new rupture. No evidence of surface fracturing was found, but to check for possible ground deformation not associated with obvious fracturing, resurveys of four leveling arrays across the fault zone at Keystone Road, Harris Road, Worthington Road, and at McConnell Road (Fig. 2) were made. Only the array at Keystone Road showed appreciable changes in elevation relative to January 6, 1981 (Fig. 13). Despite the fact that the east side of the fault had risen slightly relative to the west, the significance of the irregular profile is not clear. The profile of deformation is unlike any past change observed on any of the leveling lines across the Brawley fault zone. None of the other relevelings across the Brawley fault zone showed appreciable change in relative elevation that could be ascribed to fault displacement since their previous measurement less than four months earlier.

San Andreas fault

The San Andreas fault trace was spot checked at several localities between North Shore and Bombay Beach at the Salton Sea (Fig. 1). No evidence of new fracture was found. Releveling of an array at North Shore showed no significant relative vertical deformation at the trace of the fault.

Coyote Creek fault

The Coyote Creek fault strand of the San Jacinto fault zone was checked for sympathetic rupture along the central and south breaks of the surface rupture of the 1968 Borrego Mountain earthquake. On the basis of the pattern of continuing movement after that earthquake (Clark, 1972), these segments of the fault were considered the most likely parts of the Coyote Creek fault to exhibit new movement. A detailed search of the southernmost part of the 1968 rupture by M. M. Clark of the U.S. Geological Survey failed to find any evidence of sympathetic movement. In addition, releveling of an array located on the central break of the 1968 faulting, at a position nearly due west of the epicenter of the 1981 Westmorland earthquake, showed no sign of new vertical displacement on the Coyote Creek fault.

CONCLUSIONS

Surface faulting associated with the 1981 Westmorland earthquake was restricted to triggered movements on parts of the Imperial fault and Superstition Hills fault. Although this earthquake held promise of providing important new information on the details of faulting within the very active seismic belt extending through the Salton Trough between the town of Brawley and the Salton Sea, no unambiguous evidence of surface disturbance attributable to tectonic movement was found after a detailed search that was comprehensive in the epicentral area of the main shock, but incomplete in some of the distant areas of aftershock activity. We may assume, because past seismic activity in central Imperial Valley extended continuously from near the U.S.-Mexico border northward to the Salton Sea, that active faults exist within the belt north of the surface expression of the Imperial fault and

Brawley fault zone. Apparently, the current state of strain buildup within the northern part of this seismic corridor was insufficient to produce fault displacements large enough to propagate ruptures to the ground surface. Perhaps future earthquakes within this belt may generate surface displacements, but the threshold magnitude for surface faulting may be greater than 6. In the last eight decades no shocks of this size have occurred in northern Imperial Valley (Toppozada and others, 1978; Hileman and others, 1973), although the time span of the catalogue of earthquakes probably is insufficient to determine what maximum magnitudes may occur.

REFERENCES CITED

Allen, C. R., Wyss, Max, Brune, J. N., Grantz, Arthur, and Wallace, R. E., 1972, Displacements on the Imperial, Superstition Hills, and San Andreas faults triggered by the Borrego Mountain earthquake, in The Borrego Mountain earthquake of April 9, 1968: U. S. Geol. Survey Prof. Paper 787, p. 87-104.

Babcock, E. A., 1971, Detection of active faulting using oblique infrared aerial photography in the Imperial Valley, California: Geol. Soc. America Bull., v. 82, p. 3189-3196.

Brune, J. N., and Allen, C. R., 1967, A low-stress-drop, low-magnitude earthquake with surface faulting: The Imperial, California, earthquake of March 4, 1966: Seismol. Soc. America Bull., v. 57, p. 501-514.

Clark, M. M., 1972, Surface rupture along the Coyote Creek fault, in The Borrego Mountain earthquake of April 9, 1968: U.S. Geol. Survey Prof. Paper 787, p. 55-86.

Douglas, E. M., Marshall, R. B., and Hall, W. C., 1908, Reconnaissance map of the Salton sink, California: U.S. Geol. Survey Topographic Map, scale 1:500,000.

Fuis, G. S., 1982, Displacement on the Superstition Hills fault triggered by the 1979 Imperial Valley earthquake, in The Imperial Valley, California, earthquake of 15 October 1979: U.S. Geol. Survey Prof. Paper (in press).

Hileman, J. A., Allen, C. R., and Nordquist, J. M., 1973, Seismicity of the southern California region, 1 January 1932 to 31 December 1972: Seismological Laboratory, California Institute of Technology, Pasadena, 487 p.

Johnson, C. E., and Hill, D. P., 1982, Seismicity of Imperial Valley, in The Imperial Valley, California, earthquake of 15 October 1979: U.S. Geol. Survey Prof. Paper (in press).

Langbein, J. O., Johnston, M. J. S., and McGarr, A. F., 1982, Geodetic observation of postseismic deformation around the northern end of the surface rupture of the October 15, 1979 Imperial Valley earthquake, in The Imperial Valley, California, earthquake of 15 October 1979: U.S. Geol. Survey Prof. Paper (in press).

Sharp, R. V., 1981, Variable rates of late Quaternary strike slip on the San Jacinto fault zone, southern California: Jour. Geophysical Research, v. 86, p. 1754-1762.

Sharp, R. V., Lienkaemper, J. J., Bonilla, M. G., Burke, D. B., Cox, B. F., Herd, D. G., Miller, D. M., Morton, D. M., Ponti, D. J., Rymer, M. J., Tinsley, J. C., Yount, J. C., Kahle, J. F., Hart, E. W., and Sieh, K. E., 1982, Surface faulting in Imperial Valley, in The Imperial Valley, California, earthquake of 15 October 1979: U.S. Geol. Survey Prof. Paper (in press).

Sharp, R. V., and Lienkaemper, J. J., 1982, Pre- and postearthquake near-field leveling across the Imperial and Brawley faults, _in_ The Imperial Valley, California, earthquake of 15 October 1979: U.S. Geol. Survey Prof. Paper (in press).

Sieh, K. E., 1982, Slip along the San Andreas fault associated with the October 15, 1979, Imperial Valley earthquake, _in_ The Imperial Valley, California, earthquake of 15 October 1979: U.S. Geol. Survey Prof. Paper (in press).

Toppozada, T. R., Parke, D. L., and Higgins, C. T., 1978, Seismicity of California 1900-1931: Calif. Div. Mines and Geology Special Report 135, 39 p.

Figure Captions

Figure 1. Index map showing major faults in the Imperial Valley region. Epicenter of the 26 April, 1981, Westmorland earthquake is shown with an asterisk.

Figure 2. Distribution of new surface movement on the northern Imperial fault relative to the traces of earlier historic movement. Heavy lines show location of new fractures, and dotted lines represent known traces of past historic faulting. Letters denote locations of leveling arrays at Keystone Road (K), Harris Road (H), Ralph Road (R), Worthington Road (W), McConnell Road (M), and between Keystone and Harris Roads (KH).

Figure 3. Detailed map of new surface breaks along the northern Imperial fault.

Figure 4. En echelon fractures in alluvium along the trace of the Imperial fault, about 2.2 km north of Harris Road. The smallest cracks (mostly shorter than the pencil) are arranged in sets (about twice the length of the pencil). These in turn form larger groups (three sets of one group shown here). At some locations, the groups occur in yet bigger en echelon configurations (not visible here). The leftward sense of stepover for cracks, sets of cracks, and groups of sets is a characteristic of right-lateral surface faulting in poorly consolidated material.

Figure 5. Profile of changes in relative elevation across the Imperial fault at Harris Road. Dotted lines represent the estimated profile where survey marks established prior to the fault movement had been destroyed during road repairs. The form of this deformation profile is similar to those recorded earlier at the same location

after the 1979 Imperial Valley earthquake (Sharp and Lienkaemper, 1982).

Figure 6. Cumulative elevation change across the Imperial fault at Harris Road between stations 45 m east and 45 m west of the fault trace. The line through the observations (circles) represents the least squares best fit. The observed change in elevation after the Westmorland earthquake exceeds that predicted by the least squares fit by about 10 mm, an amount that is larger than the separation between any previous observation and the line of best fit.

Figure 7. Scarp on northeast-trending branch of the Imperial fault 0.8 km south of Keystone Road. The slightly eroded low scarp was formed by the 1979 Imperial Valley earthquake. It followed the older, higher, and more eroded scarp visible here as a slope rising toward the rear of the view. New crust on the soil surface along this scarp clearly showed that new movement did not occur.

Figure 8. Distribution of new surface movement on the Superstition Hills fault relative to the trace of earlier historic movement. Heavy line shows location of new fractures, and dotted line indicates the trace of earlier faulting. The downslope direction at the sea level contour is toward the northeast. Dotted line at upper right is the trace of an unnamed fault with a low east-facing scarp along part of its length; no historic movement is known on this feature.

Figure 9. Detailed map of new surface breaks along the Superstition Hills fault.

Figure 10. Plots of maximum right-lateral displacement versus distance along the Superstition Hills fault. The displacement curve for the Westmorland earthquake, smoothed from the data shown in Figure 9 by joining local maxima, is shown in the lower curve. Curves showing the cumulative slips after the 1968 (Allen and others, 1972), 1979 (Fuis, 1982), and 1981 earthquakes are shown at the top. Dashed lines represent uncertainty in displacement profiles near the Caltech geodetic network where slip was detected in 1968 (Allen and others, 1972).

Figure 11. Single fracture among an en echelon set of fractures on the Superstition Hills fault (location 10.12 km in Fig. 9, panel C-D).

Figure 12. Map showing route that was carefully inspected for surface rupture. Many of the closely spaced traverses were made to determine the continuity of small surface breaks that were finally deemed nontectonic. Asterisk shows location of main shock epicenter.

Figure 13. Profile of changes in relative elevation at the Brawley fault zone at Keystone Road.

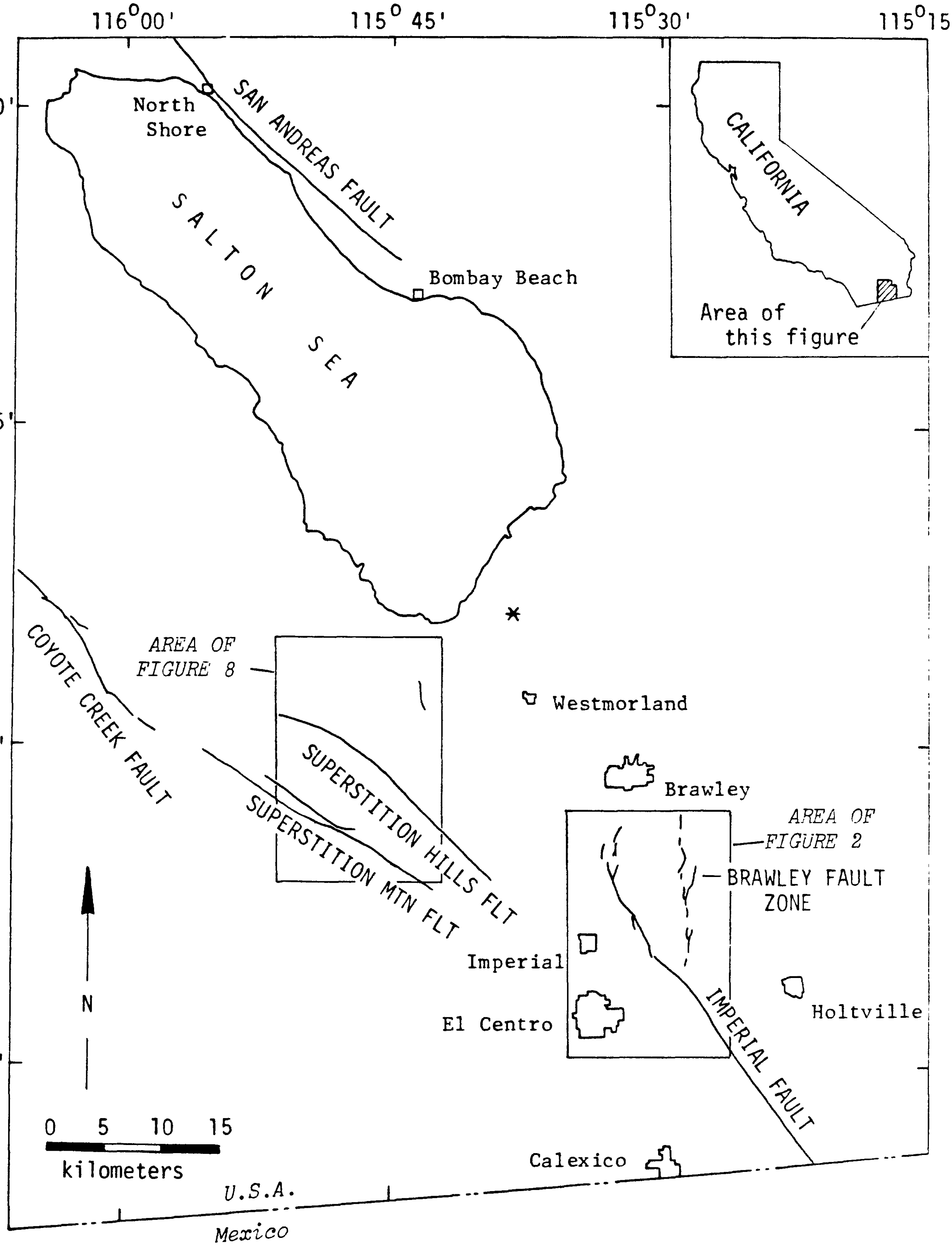

116°00'
115° 45'
115°30'
115°15'
33°30'
33°15'
33°00'
32°45'
North Shore
SAN ANDREAS FAULT
SALTON SEA
Bombay Beach
CALIFORNIA
Area of this figure
AREA OF FIGURE 8
Westmorland
COYOTE CREEK FAULT
SUPERSTITION HILLS FLT
SUPERSTITION MTN FLT
Brawley
AREA OF FIGURE 2
BRAWLEY FAULT ZONE
Imperial
El Centro
Holtville
IMPERIAL FAULT
N
0 5 10 15
kilometers
Calexico
U.S.A.
Mexico

Figure 1

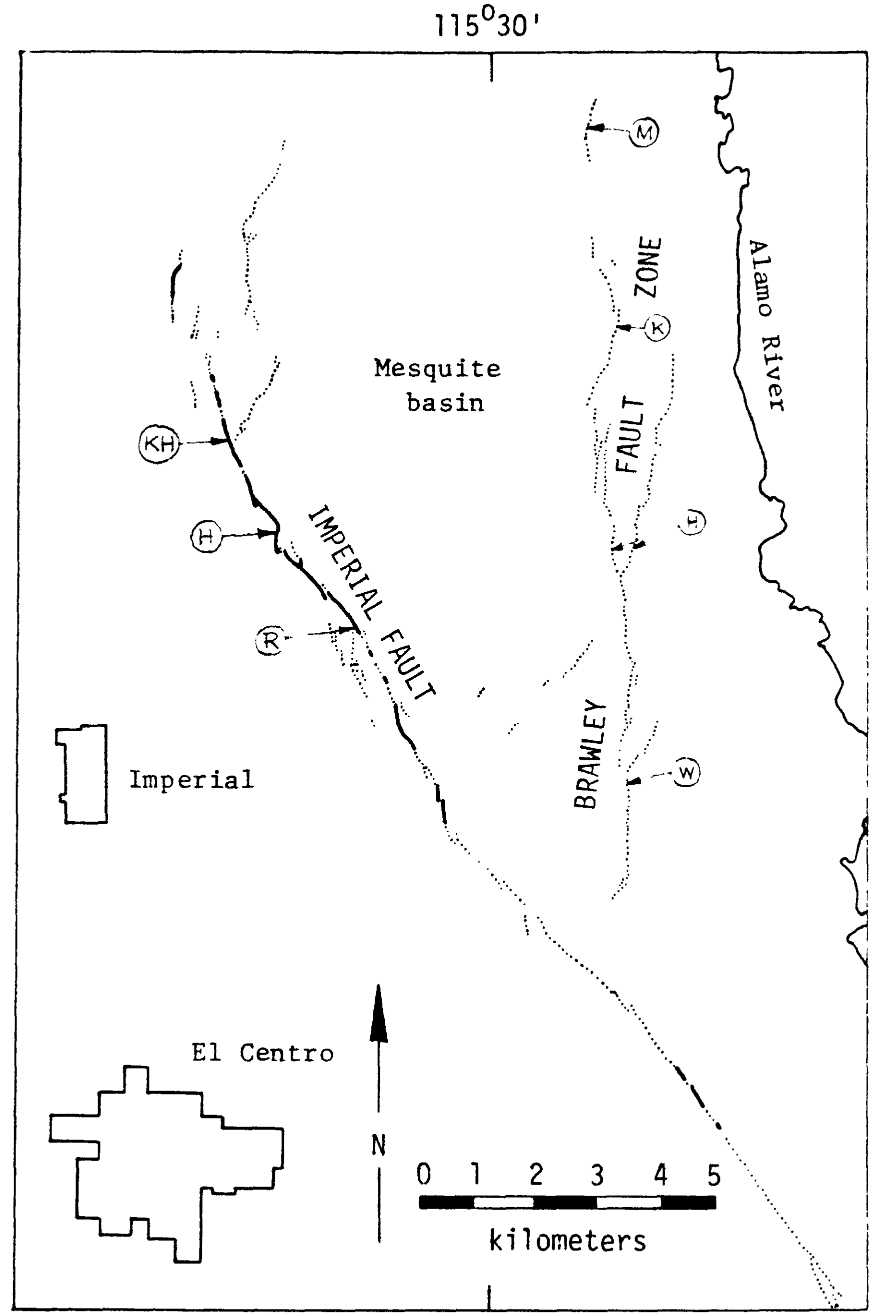
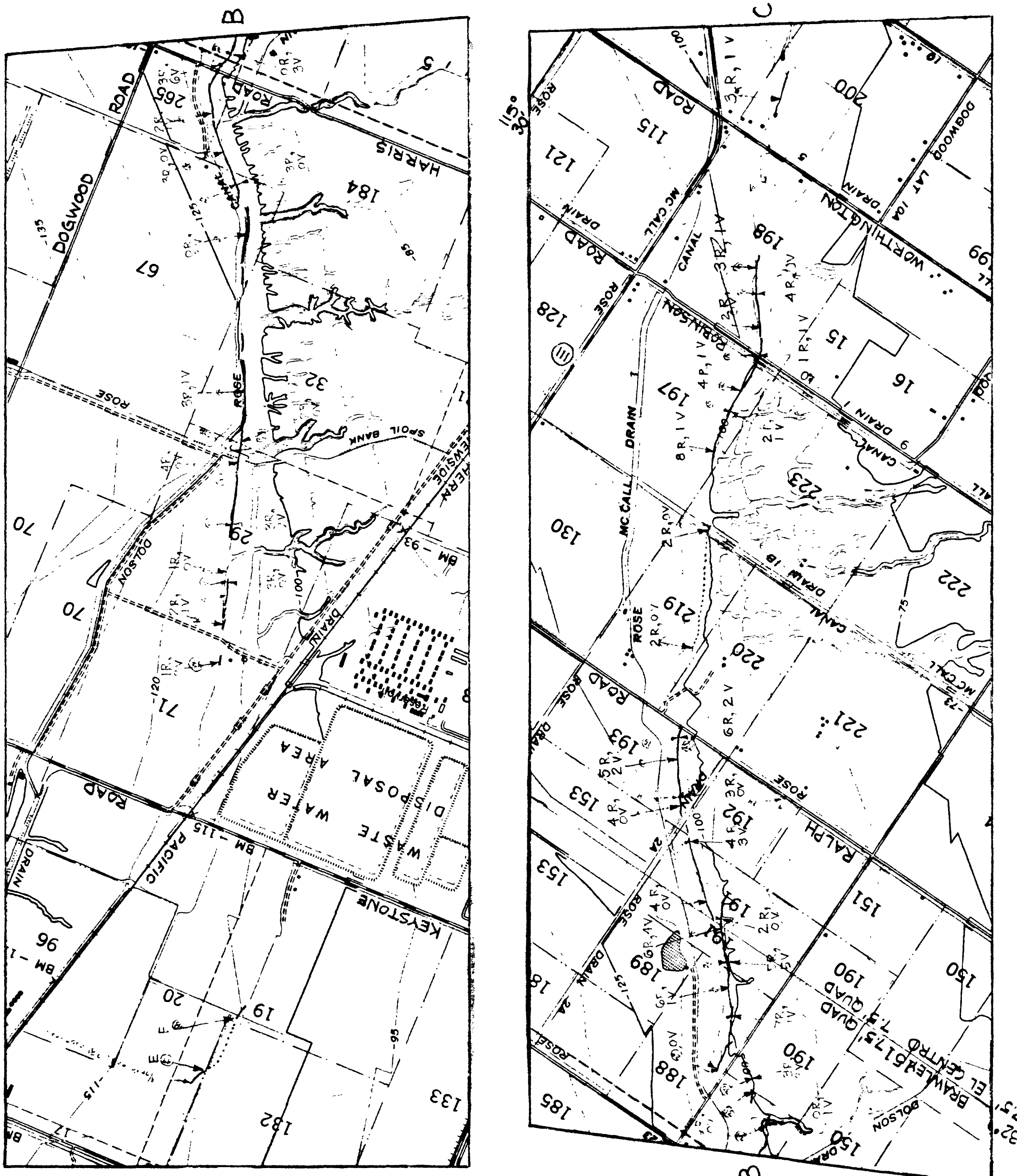

115°30'
Mesquite
basin
ZONE
FAULT
BRAWLEY
Alamo River
IMPERIAL FAULT
Imperial
El Centro
N
0 1 2 3 4 5
kilometers
M
K
KH
H
I
R
W

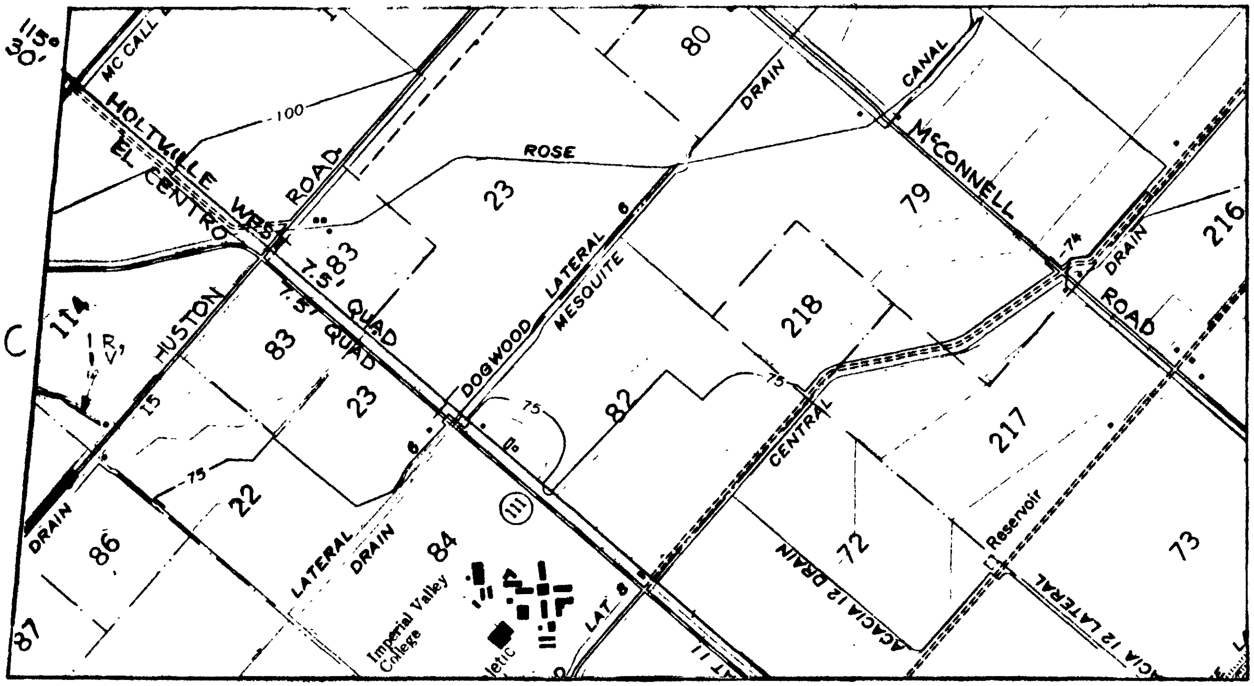
Figure 2



A
B
C
DOGWOOD ROAD
HARRIS ROAD
ROSE
SPOIL BANK
KEYSTONE ROAD
PACIFIC
WASTE WATER DISPOSAL AREA
MC CALL DRAIN
ROBINSON
WORTHINGTON
RALPH
CANAL

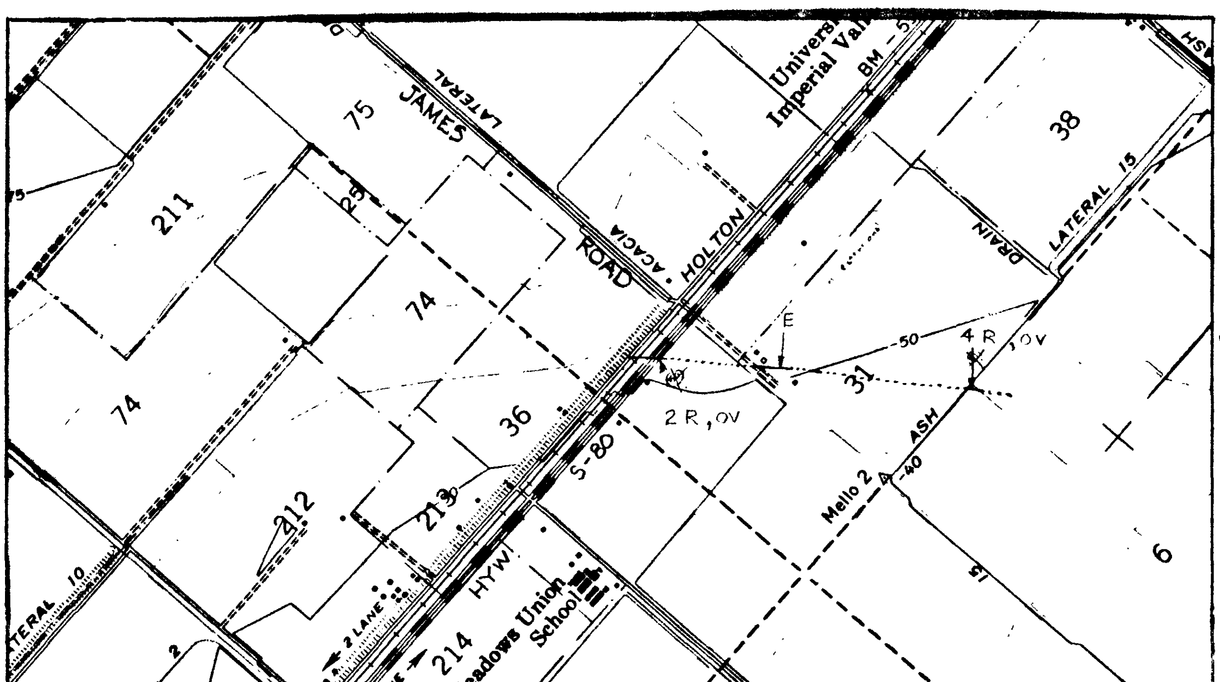
Figure 3

C

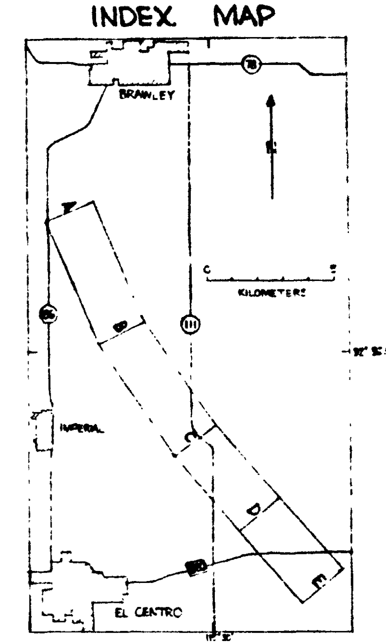


D

D



E



EXPLANATION

——————— . . . .

Fault rupture, solid where observed, dotted where probable rupture was concealed by vegetation.

5R, measured right-lateral component of displacement is 5 mm.

2V, measured vertical component of displacement is 2 mm, west side up.

E, extensional displacement only.

SCALE 1:24 000

0 — 1 KILOMETER

CONTOUR INTERVAL 5 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

Mapped by M. J. Rymer, April 29–May 2, 1981

Figure 3 (contd)

Figure 4

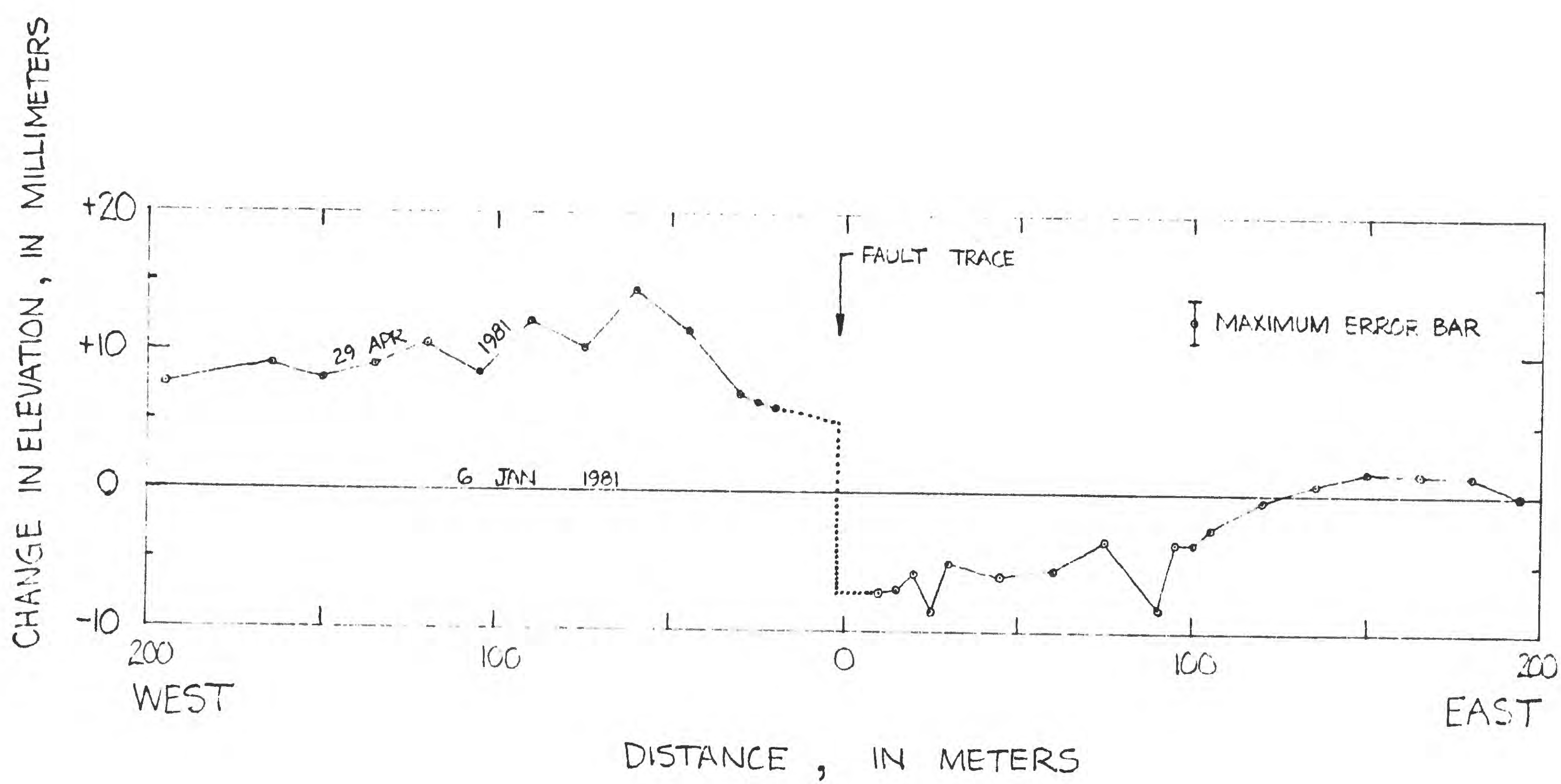

+20
+10
0
-10
CHANGE IN ELEVATION, IN MILLIMETERS
29 APR 1981
6 JAN 1981
FAULT TRACE
MAXIMUM ERROR BAR
200
100
0
100
200
WEST
EAST
DISTANCE , IN METERS

Figure 5

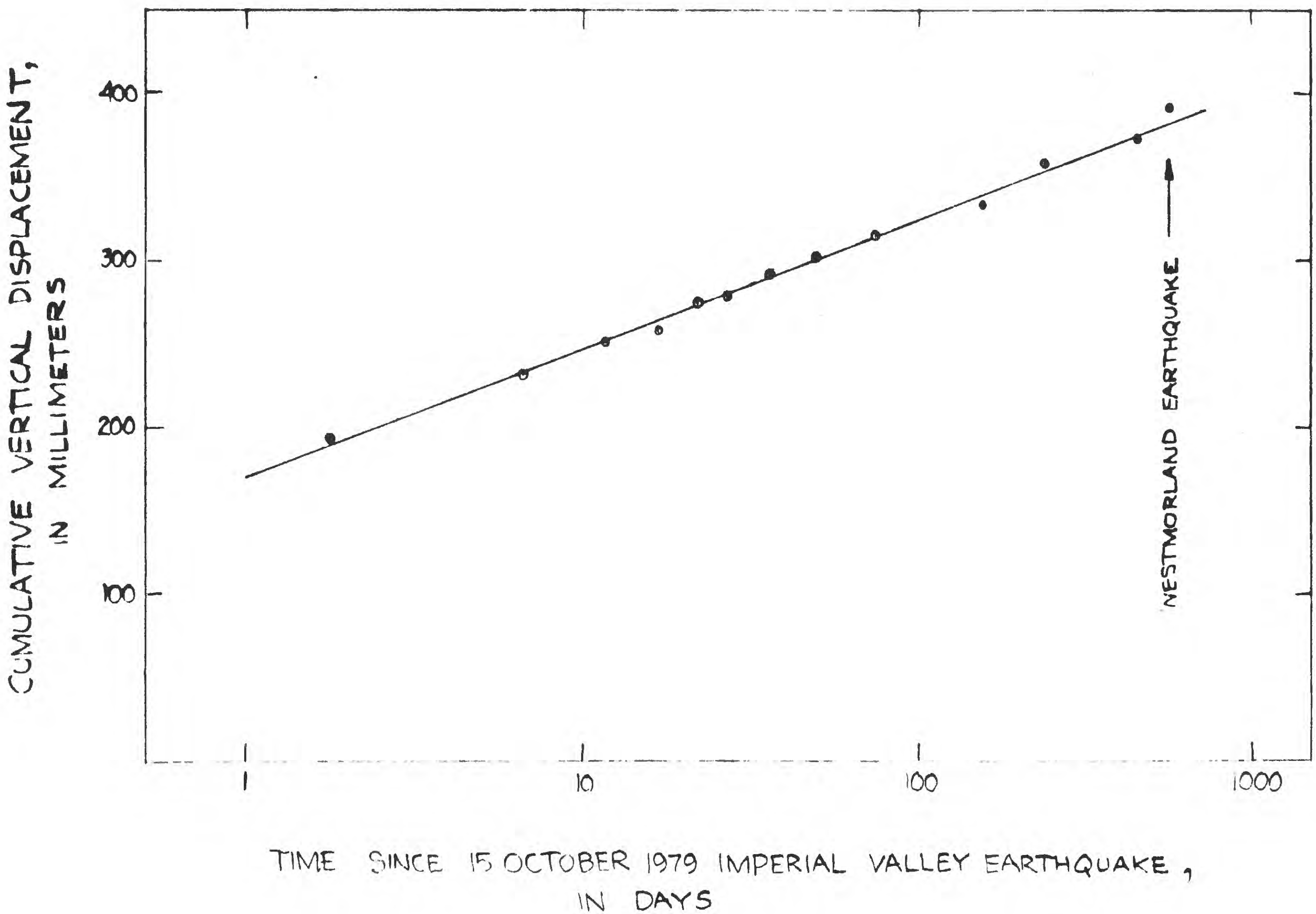

CUMULATIVE VERTICAL DISPLACEMENT, IN MILLIMETERS
400
300
200
100
WESTMORLAND EARTHQUAKE
1
10
100
1000
TIME SINCE 15 OCTOBER 1979 IMPERIAL VALLEY EARTHQUAKE, IN DAYS

Figure 6

Figure 7

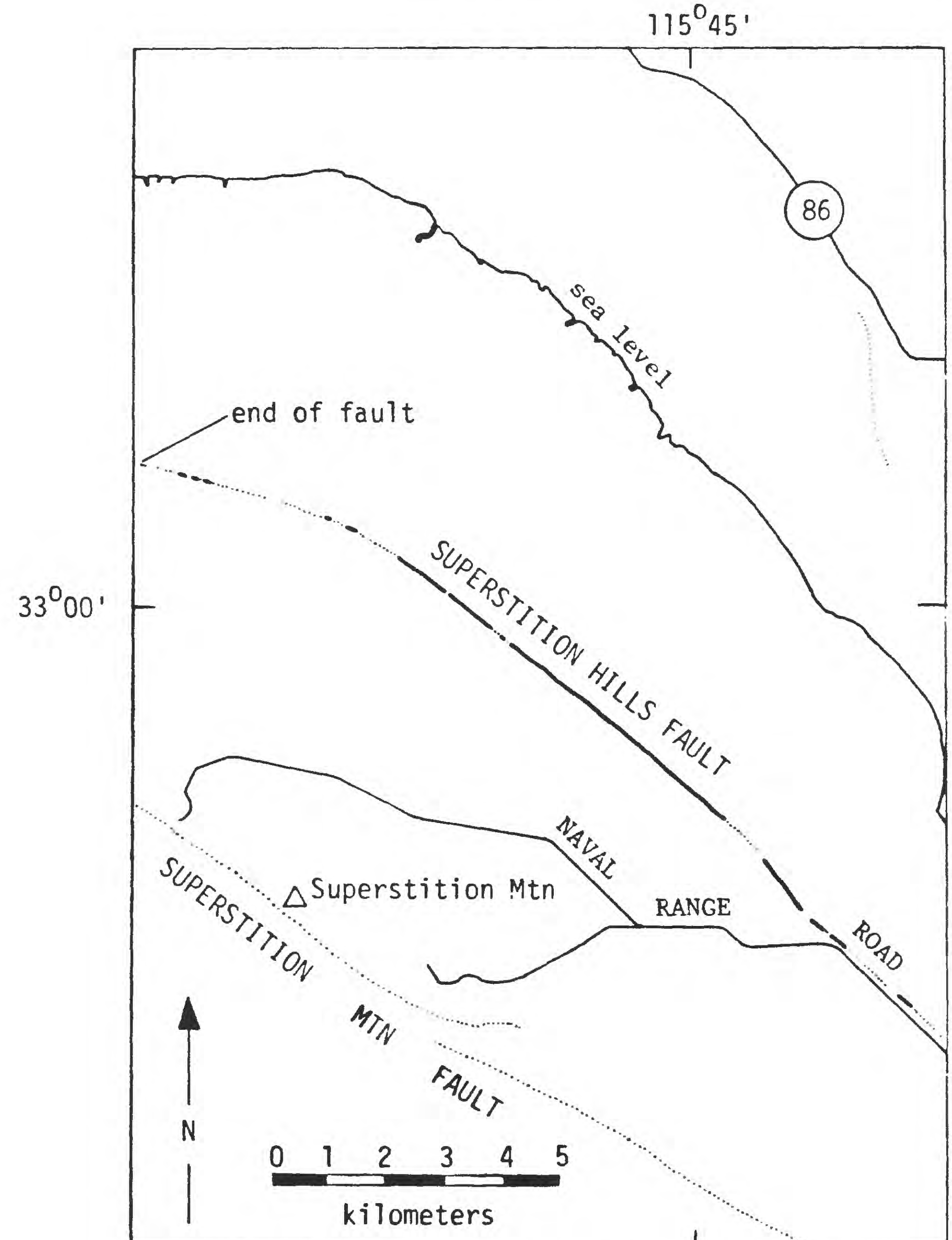

115°45'
86
sea level
end of fault
33°00'
SUPERSTITION HILLS FAULT
NAVAL
RANGE
ROAD
Superstition Mtn
SUPERSTITION
MTN
FAULT
N
0 1 2 3 4 5
kilometers

Figure 8

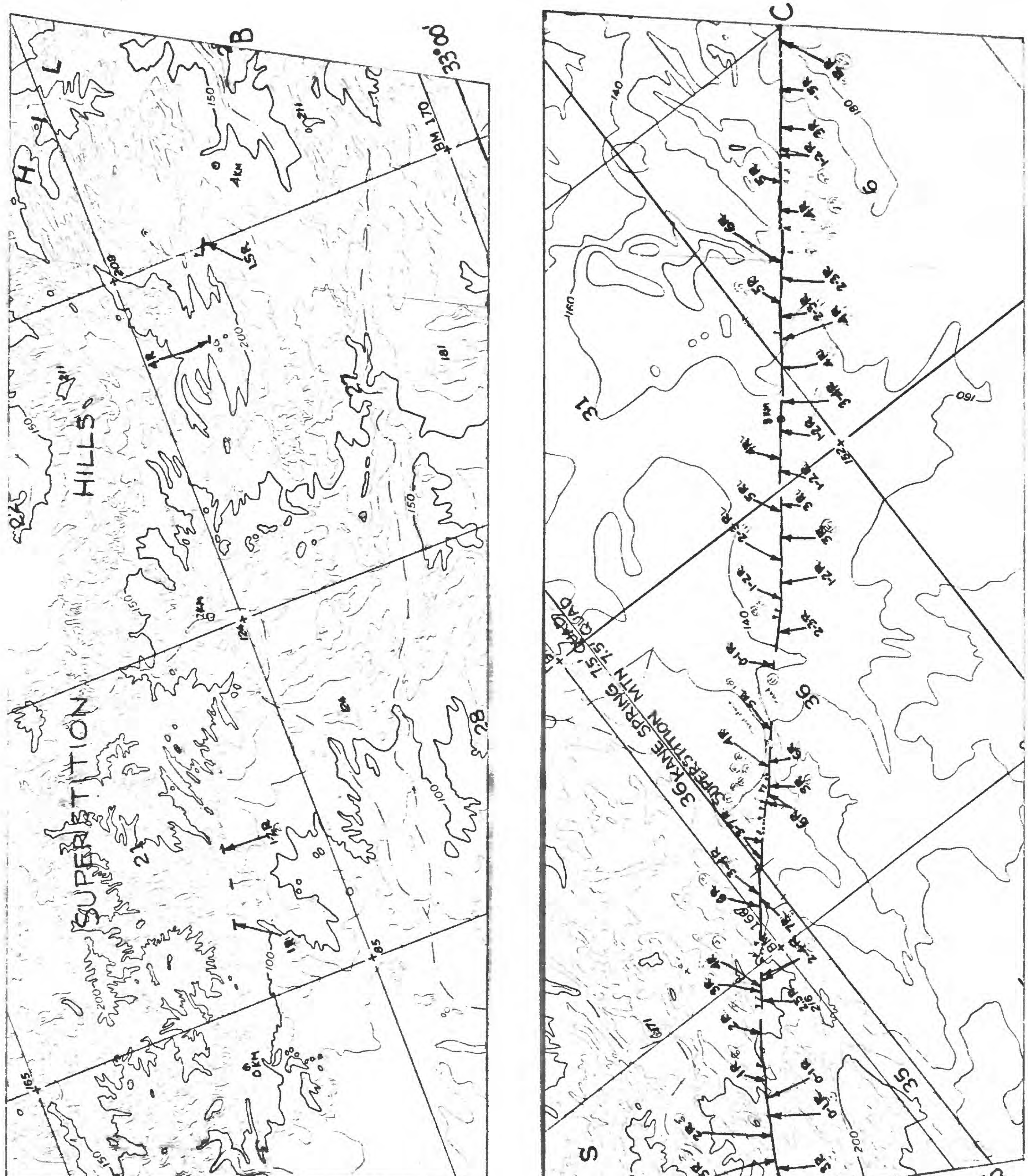
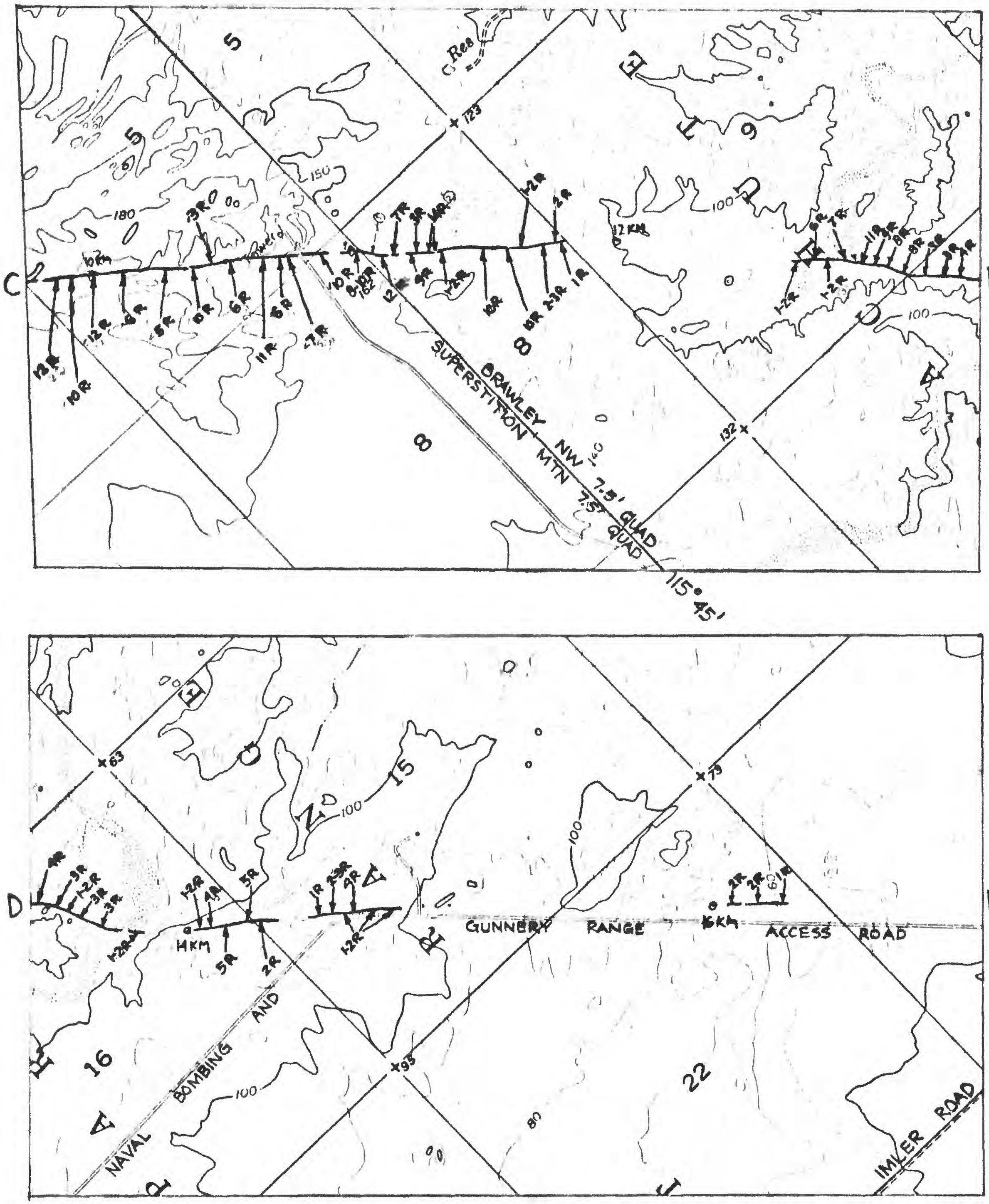
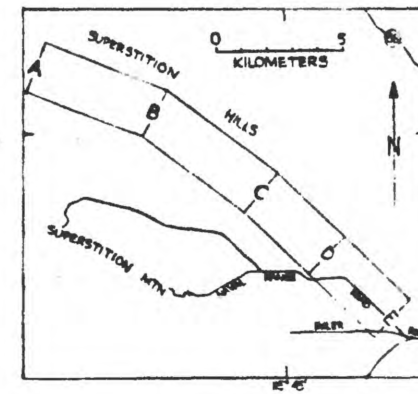

SUPERSTITION HILLS
A
B
C
33°00'
SUPERSTITION MTN 7.5' QUAD
KANE SPRING 7.5' QUAD

Figure 9



INDEX MAP



EXPLANATION

Fault rupture

10R, measured right-lateral component of displacement is 10 mm.

SCALE 1:24 000

0 — 1 KILOMETER

CONTOUR INTERVAL 10 FEET AND 5 FEET
DATUM IS MEAN SEA LEVEL

Mapped by R.V. Sharp and J. J. Lienkaemper, April 28 - May 1, 1981

Figure 9 (contd)

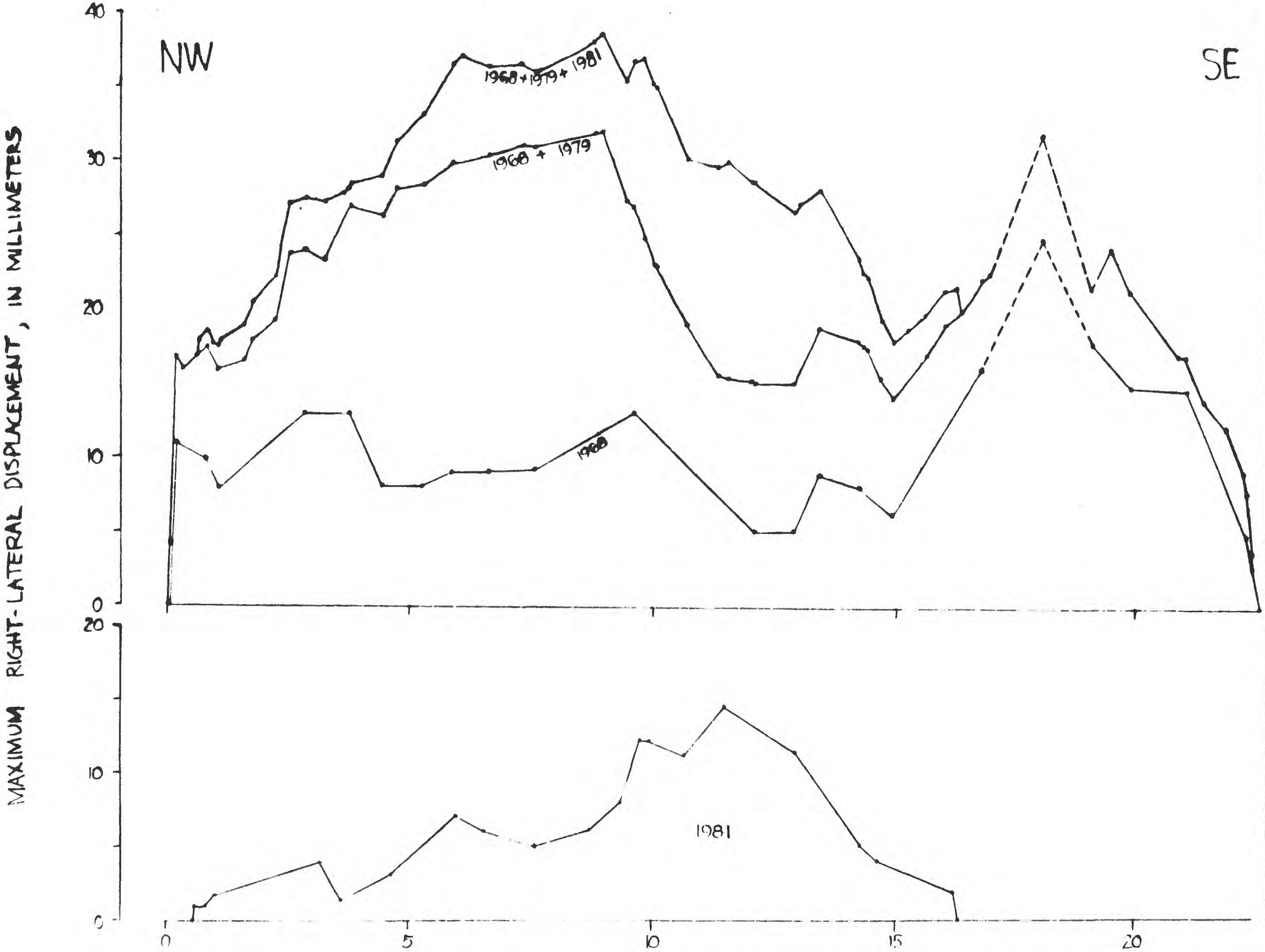

NW
SE
1968+1979+1981
1968 + 1979
1968
1981
MAXIMUM RIGHT-LATERAL DISPLACEMENT, IN MILLIMETERS
DISTANCE ALONG FAULT, IN KILOMETERS
0
10
20
30
40
0
5
10
15
20

Figure 10

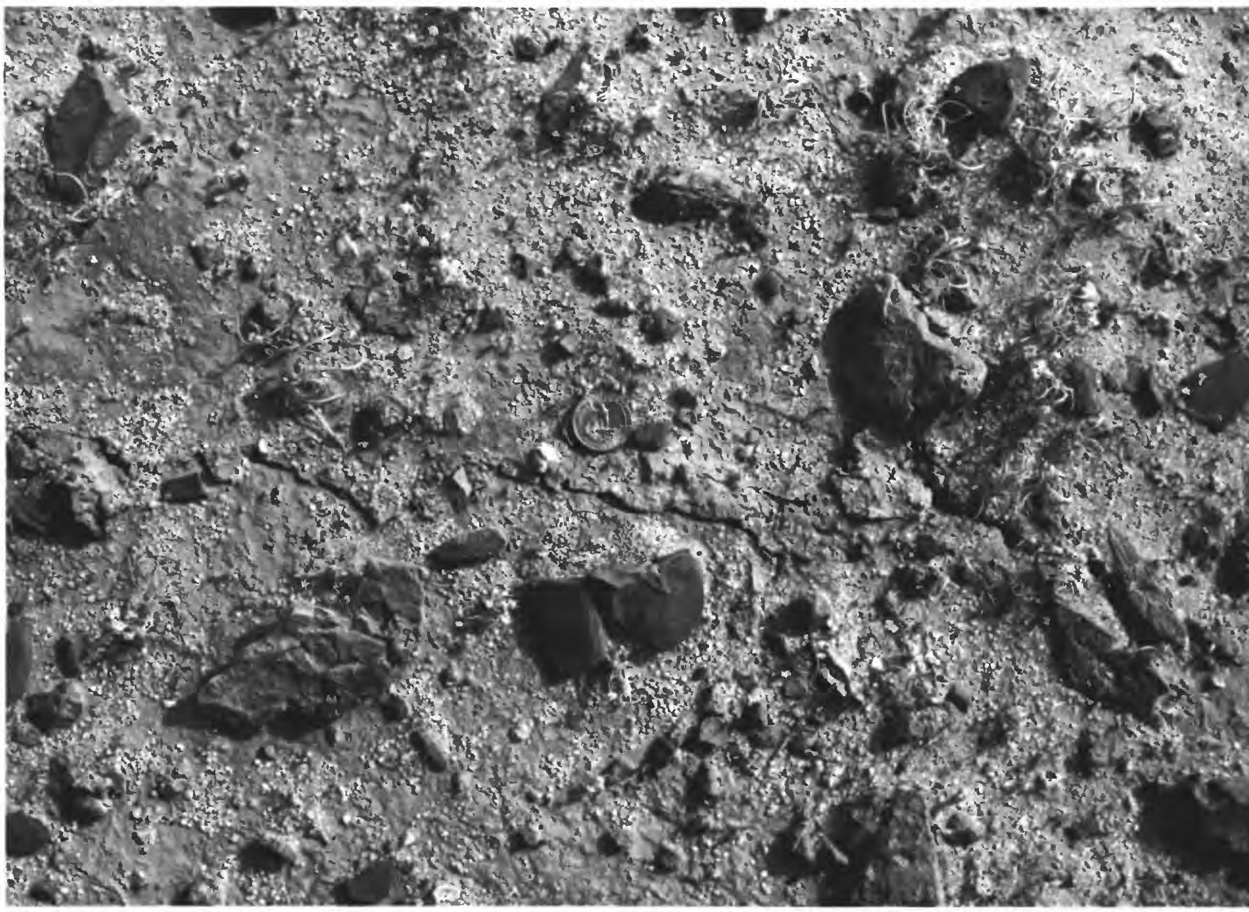
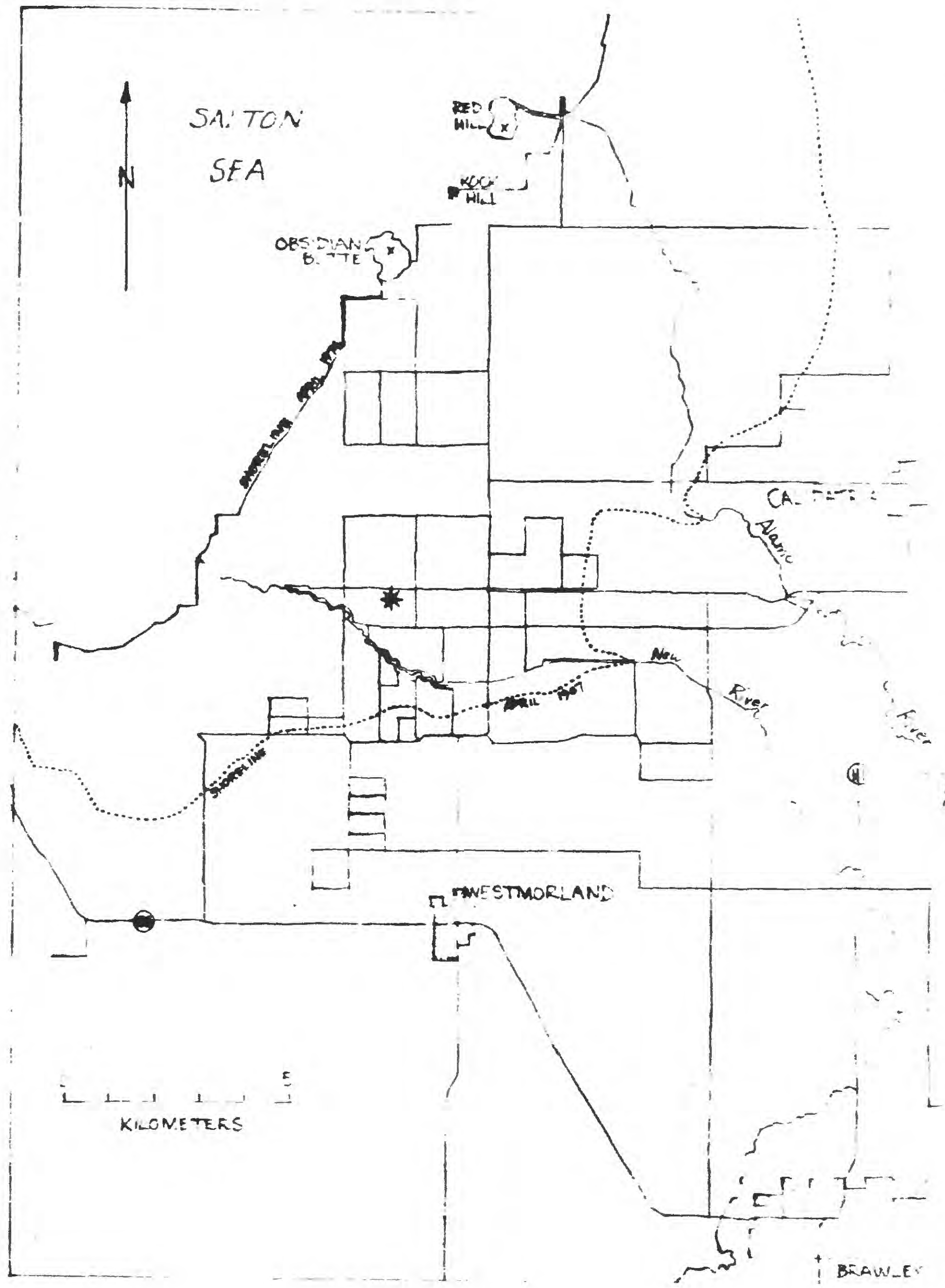


Figure 11



SALTON
SEA
N
RED HILL
ROCK HILL
OBSIDIAN BUTTE
CALIPATRIA
Alamo
New River
WESTMORLAND
KILOMETERS
5
BRAWLEY

Figure 12

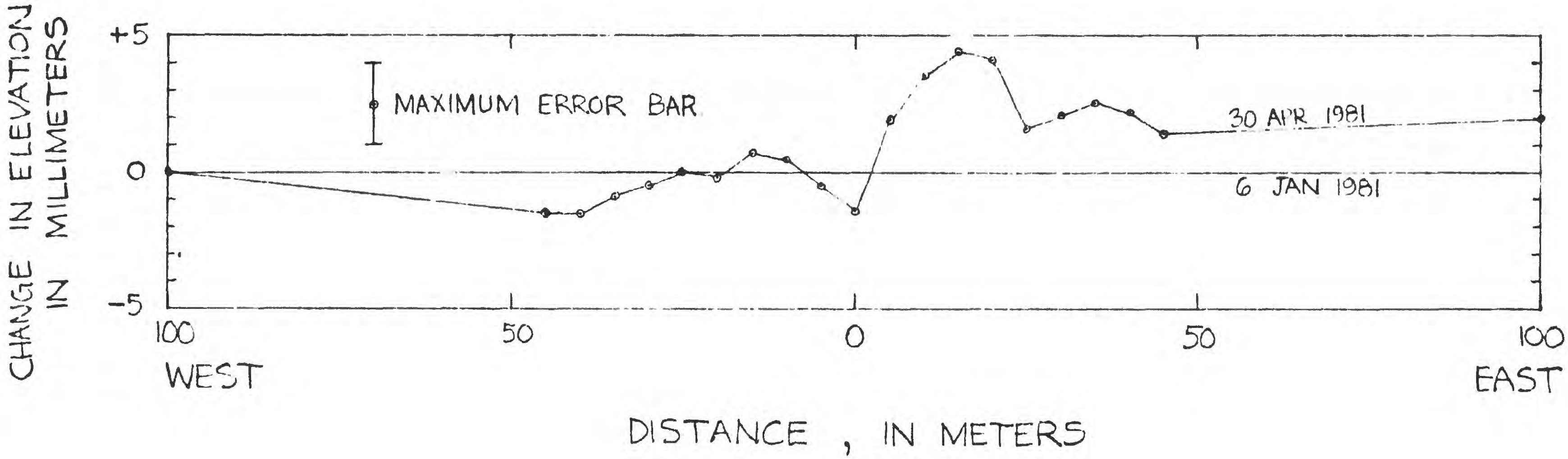

CHANGE IN ELEVATION, IN MILLIMETERS
+5
0
-5
MAXIMUM ERROR BAR
30 APR 1981
6 JAN 1981
100
50
0
50
100
WEST
EAST
DISTANCE , IN METERS

Figure 13