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BROAD BELTS OF SHEAR ZONES

THE COMMON FORM OF SURFACE RUPTURE PRODUCED BY THE 28 JUNE 1992 LANDERS, CALIFORNIA, EARTHQUAKE

by

Arvid M. Johnson[1]

Robert W. Fleming

and

Kenneth M. Cruikshank[2]

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[1] Also, Richard H. Jahns Engineering Geology Laboratory, Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, Indiana 47907.

[2] ditto. Now at Department of Geology, Portland State University, Portland, Oregion, 97207.

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ABSTRACT

Surface rupturing during the 28 June 1992, Landers, California earthquake, east of Los Angeles, accommodated right–lateral offsets up to about 6 m along segments of distinct, en echelon fault zones with a total length of about 80 km. The offsets were accommodated generally not by faults—distinct slip surfaces—but rather by *shear zones,* tabular bands of localized shearing. In long, straight stretches of fault zones at Landers the rupture is characterized by telescoping of shear zones and intensification of shearing: broad shear zones of mild shearing, containing narrow shear zones of more intense shearing, containing even–narrower shear zones of very intense shearing, which may contain a fault. Thus the ground ruptured across *broad belts* of shearing with subparallel walls, oriented NW. Each broad belt consists of a broad zone of mild shearing, extending across its entire width (50 to 200 m), and much narrower (a few m wide) shear zones that accommodate most of the offset of the belt and are portrayed by en echelon tension cracks. In response to right-lateral shearing, the slices of ground bounded by the tension cracks rotated in a clockwise sense, producing left lateral shearing, and the slices were forced against the walls of the shear zone, producing thrusting. Even narrower shear zones formed within the narrow shear zones, and some of these were faults. Although the narrower shear zones probably are indicators to right–lateral fault segments at depth, the surface rupturing during the earthquake is characterized not by faulting, but by zones of shearing at various scales. Furthermore, understanding of the formation of the shear zones may be critical to understanding of earthquake faulting because, where faulting is associated with the formation of a shear zone, the faulting occurs late in the development of the shear zone. The faulting occurs after a shear zone or a belt of shear zones forms.

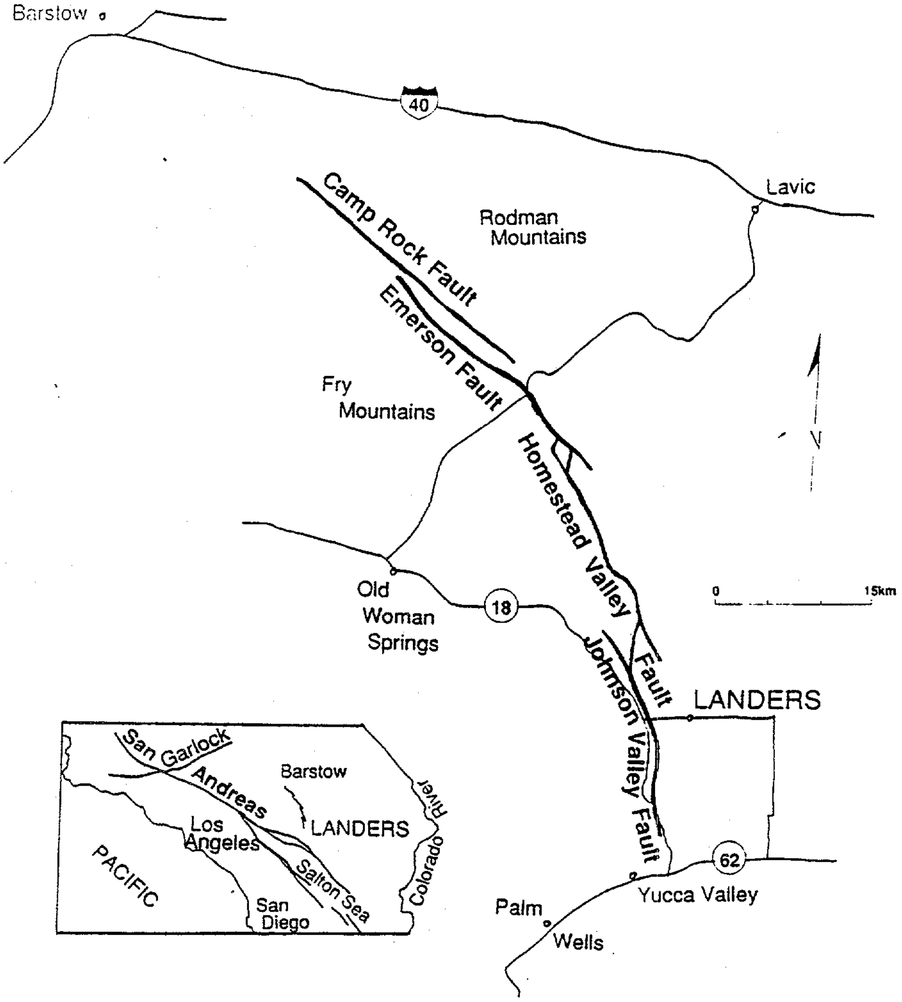

Figure 1. Location map, showing en echelon fault zones, the Camp Rock and Emerson fault zones in the north and the Homestead Valley and Johnson Valley fault zones in the south that ruptured during the 1992 Landers, California earthquake. Epicenter of main shock was near Landers. Inset figure identifies some of the major faults in southern California.

INTRODUCTION

The most spectacular ground rupturing of any earthquake yet in this century was produced by the June 28, 1992, M 7.5 earthquake at Landers, California, about 10 km north of Yucca Valley, California (Figure 1). One reason for the severity of ground rupture may be that the earthquake's hypocenter was very shallow, only one to three kilometers deep. Another reason is that it formed in the desert, where details of ruptures are preserved and the patterns of rupturing are relatively unaffected by houses and roads. The ground rupturing, which was dominated by right–lateral shearing, extended over segments of at least four distinct faults arranged broadly en echelon. The faults were connected through wide transfer zones by stepovers, consisting of right–lateral fault zones and tension cracks. The total length of the surface rupture was about 80 km.

There are several important reasons for deriving a detailed description of the ground rupture during the Landers earthquake. The Landers earthquake is the largest to occur in the United States since the Great Alaskan, Good Friday Earthquake of 1964, and it produced surface rupture reminiscent of the 1906 San Francisco earthquake. To put the Landers earthquake into perspective, consider: The maximum differential, right–lateral displacements at Landers, possibly up to 6 m, are comparable to the maximum value, 5.4 to 6.4 m, in the 1906 San Francisco earthquake; they are much larger than in the 1971 San Fernando and 1989 Loma Prieta earthquakes, [1 or 2 m]; the 1964 Borrego Peak and Managua Nicaragua earthquakes, [2 or 3 dm]; or the 1966 Parkfield earthquakes, [5 to 8 cm], (Gilbert, 1907; Lawson, 1908; Bonilla and others, 1971; Brown and others, 1967, 1973; Clark, 1972; Kamb and others, 1971; Sharp, 1975). The Landers earthquake is also the largest since the revolution of plate tectonics theory and the inception of the National Earthquake Hazards Reduction Program. It has been the most extensive since adoption of many types of hazards criteria for the siting of major engineering structures such as nuclear power plants and dams, and critical facilities such as schools, hospitals, and fire departments. It is the largest and most disruptive earthquake since development of ideas about "capable" faults and segmentation, and since enactment of California's landmark Alquist-Priolo Act, which is concerned with "setbacks" of houses, vital utilities, and other structures from active faults. The extensive surface rupture at Landers will have major implications for future regulations about earthquake hazards, including the hazards of rupturing of containment structures of nuclear waste and other extremely toxic waste. For all these reasons, the Landers earthquake, and the ground rupture associated with it, are scientifically important.

Detailed descriptions of ground breakage are forthcoming from many investigators with the U.S. Geological Survey, the California Division of Mines and Geology, and various consulting companies and universities. Although we have not yet finished our investigations, we are going to document some of our observations here because they might provide a basis for understanding less-completely preserved fault ruptures. In particular, we want to express our amazement that the ground breakage is so feebly described by the terminology, *fault* and *fault zone*, so commonly used to characterize ground rupture during an earthquake. Anyone accustomed to studying faults that formed relatively deep in the earth's crust is in for a shock; ground breakage during the Landers earthquake is quite different from classical ideas of faulting. Investigators familiar with ground breakage during major earthquakes, or familiar with flank faults bounding major landslide masses, will likely recognize many of the structures we describe herein. Heretofore, these structures appear to have been largely ignored. They are so spectacularly developed at Landers, however, that their significance can be interpreted. The purpose of this paper is to exhibit these structures for general consideration.

The basic structures that we observe at Landers are *shear zones.* The concept of *shear zone* is sometimes included with the generalized concept of the fault, and some investigators use shear zone and fault zone interchangeably. There are two, distinct structures, though, and we must differentiate between them. *Fault,* according to Reid and others (1913), is a *fracture* across which the differential displacement of blocks of rock on either side has been approximately parallel with the *walls* of the fracture[1]. The blocks of rock are bounded by walls of the fault and the differential displacement of the two walls in the local plane of the fault surface is the *slip.* A *fault zone* is a zone that contains several closely spaced faults. A shear zone is *not* a fracture[2]. A *shear zone* is a tabular zone within which shearing is *concentrated* compared to the rocks outside either wall of the zone, but within which shearing is also *distributed* (Ramsay and Graham, 1970). A shear zone is described locally in terms of the spacing of its walls (thickness), the attitude of its walls, and the three components of differential displacement across the shear zone. The resultant components of differential displacement accommodated by the entire thickness and acting parallel to the walls of the shear zone is termed the *shift.* The normal component of differential displacement may be significant in a shear zone, so a shear zone can accommodate both shift and *dilation* (Hobbs, Means and Williams, 1976, p. 300). A *belt of shear zones* is analogous to a fault zone; it may contain the traces of several distinct shear zones. Thus, we follow traditional practice and recognize the following distinctions between the concepts of faults and shear zones: There is a displacement discontinuity between the walls of a fault, whereas, in a shear zone, differential displacement changes continuously, although deformation is localized. The net differential displacement in the plane of a fault is local; in a shear zone, it may well include dilation, as well as shearing distributed across the zone. In the limit, as the amount of shift remains finite and the thickness of the shear zone approaches zero, a shear zone becomes a fault, so a fault is a special case of a shear zone. Nevertheless, it is important not to mix the notion of a planar discontinuity of shearing (a fault) with that of a tabular zone of localized shearing deformation (a shear zone).

Shear zones and attendant structures are well–displayed throughout much of the 80–km rupture at Landers and, because the differential displacements are so large, the structures are exaggerated. One can see virtual *cartoons* of deformation patterns in the field. The scarcity of vegetation, the aridity of the area, the firmness of the alluvium and bedrock, and the relative isotropy and brittleness of surficial materials collaborate to provide an almost–unique display of simple cracks, fractures, faults, and shear zones that define the earthquake rupture zone. The difficulty is not in finding a place to describe, but in finding the place to best invest one's descriptive energy, given the relatively limited time available before the structures fade and vanish.

This paper focuses on surface fractures produced along long, linear segments of the fault zones during the earthquake. There are plenty of fascinating examples of complications at Landers, but we purposefully avoided those in order to characterize the rupture of *simple fault zones.* We use the term simple fault zones or long, linear fault zones for fault zones where the fault traces are straight for considerable length and the

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[1] Actually, we use the term *fault* in two, quite different ways. First, we follow the traditional usage, wherein *fault* is defined, by Reid and others (1913), as a type of fracture. Second, we use the term as a proper name for a geological discontinuity of shearing—broad or narrow—between disparate blocks of rock. In this usage we refer to the San Andreas fault zone, or the Johnson Valley or Emerson faults.

[2] *Fracture* is a general term for a discontinuity that severs a soil or rock body into two parts and which consists of two walls and, if finite, a periphery. Faults, tension cracks, and joints are examples of fractures. A *tension crack* is a fracture across which the greatest component of differential displacement of the fracture walls is approximately *normal* to the walls (mode I in the parlance of fracture mechanics), whereas a fault is a fracture that has accommodated mode II or mode III shearing (shearing normal or parallel to the periphery of the fracture; Pollard and Segall, 1987).

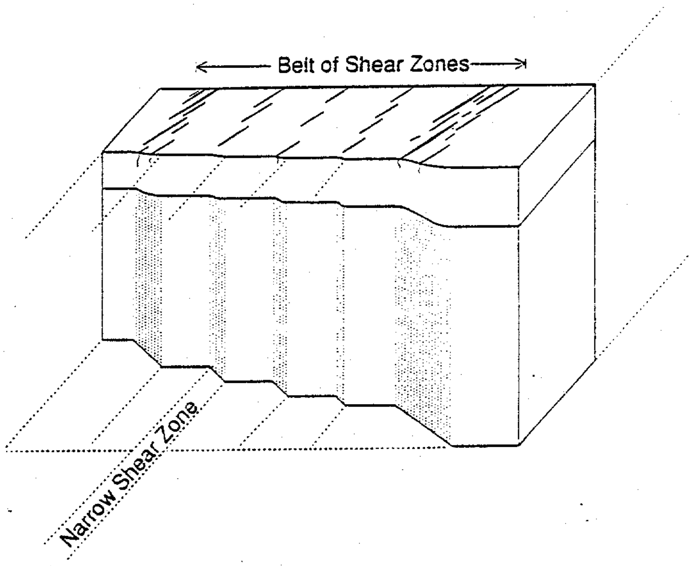

Figure 2. Idealization of a belt of shear zones of the type recognized at Landers. The entire width of the belt consists of a zone of mild shearing which is responsible for broadly distributed tension cracks oriented north-south. Within the belt, though, are narrower shear zones that accomplish most of the shearing across the belt. One of the bounding narrow shear zones, at an outer wall of the belt, accommodates 2/3 to 4/5 of the total shearing of the belt.

principal differential displacements are predominantly right–lateral. Furthermore, complexities are absent; there are no major stepovers, the fault traces are not arranged en echelon, and there are no active ridges or sags. We selected one area on the Emerson fault zone and another on the Homestead Valley fault zone (Figure 1) where we could also determine the right–lateral component of relative displacement of man–made linear features such as roads, fences, off–road vehicle paths, and rows of power poles. The rupture segments were neither right– or left–stepping nor interacting with tectonic ridges. Only for the study area along the Emerson fault zone was the rupture segment even mildly interacting with another fault zone (Camp Rock) in the same valley. We were so surprised by what we found during the detailed mapping that we examined the ground rupture on either side of the map areas to ensure that our maps are typical, at least for the simple segments we describe here.

We mapped the rupture segments at a scale of 1:200, using a total–station theodolite to survey coordinates of control points. After the points were plotted, we reoccupied the fpoints in the field to draw the fractures and disrupted ground. Ultimately compiled and reduced several map sheets to produce the maps published here. Except for the detailed maps of a few areas of ground breakage during the Parkfield earthquakes by Robert Wallace (Brown and others, 1967) and from the 1989 Loma Prieta earthquake along the Sargent and San Andreas fault zones (Aydin and others, in review; Martosudarmo and Johnson, in review), detailed documentation of surface ruptures on a fracture–by–fracture basis is lacking.

HAPPY TRAIL SHEAR ZONE

The rupture zones we studied along the Johnson Valley, Homestead Valley, and Emerson fault zones at Landers all consist of broad belts of shearing, with narrow shear zones within the belt (Figure 2). A narrow shear zone has a characteristic pattern of fracturing, including long en echelon tension cracks and left–lateral fractures oriented about 20° clockwise to the walls, thrust faults at one or both walls, and very narrow right–lateral shear zones trending parallel to the walls of the narrow shear zone. The narrow shear zones were widely recognized along the San Andreas fault during the 1906 San Francisco earthquake (Gilbert, 1907; Lawson, 1908), and the rupture of the ground by the diagonal cracks was termed *splintering* (Reid, 1910, p. 35). A particularly clear example of the internal structure of a narrow shear zone is found 100 m south of Happy Trail, near the coalescence of the NE wall of the Johnson Valley fault zone and the SE wall of the Kickapoo stepover (Figure 3, locality C). There, the ground surface is a compacted dirt roadway, and the material at the ground surface had wonderful tendencies to fracture and preserve minute details of the fractures. We will describe the Happy Trail shear zone as, essentially, an example of a narrow shear zone.

Before proceeding with our description, though, we need to explain why we speak of shear zones when, in fact, we observe fractures. Perhaps the most important, and least appreciated, concept of fracturing and other types of deformation associated with earthquake faulting is that *most of the fractures or other structures one observes at the ground surface are merely guides to deformation that is occurring below.* It was this concept, above others, that allowed us to interpret the enigmatic left–lateral fractures at Loma Prieta (Johnson and Fleming, in review). This concept is a key at Landers, also. It is no simple matter to interpret the ground surface deformation that characterizes large earthquakes. Over the years, though, geologists have accrued many insights into the translation of the superficial phenomena of surface ruptures into viable models of deformation at depth.

Guide fractures[3] *indirectly reflect* the deformation and, possibly, the structure occurring beneath the ground surface,

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[3] This term derives from Chapter 12 of Hugh McKinstry's textbook, Mining Geology (1948), called "Fracture Patterns As Guides." McKinstry also used the

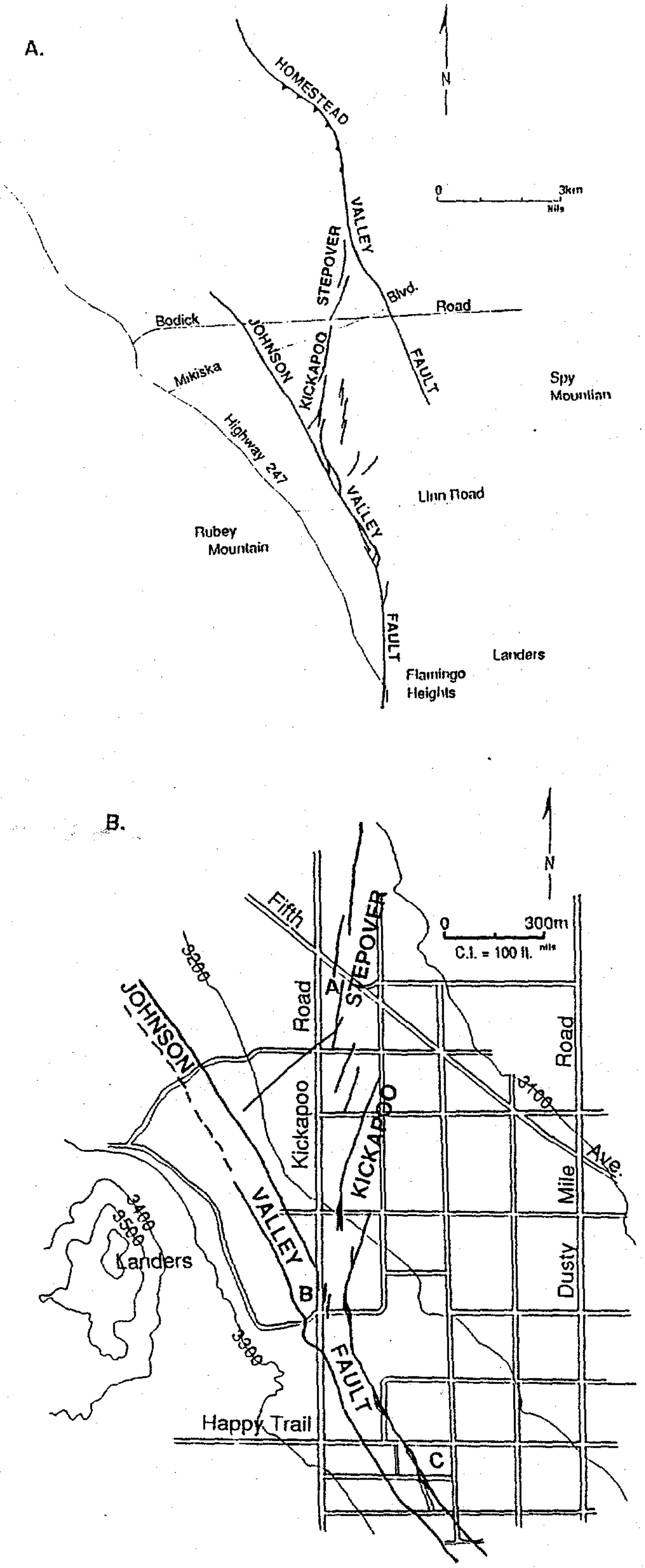

Figure 3. General configurations of ruptured fault zones near Landers. A. Gross geometry of the stepover area between the Homestead Valley fault zone and the Johnson Valley fault zone. Kickapoo stepover connects the two fault zones. Bodick Road study area near location *A*. Happy Trail study area south of location *B*. B. More detailed views of fault zones where Kickapoo stepover joins Johnson Valley fault zone. Johnson Valley fault zone is a broad belt (about 100 m wide) of shear zones. Kickapoo stepover is set of en echelon narrow shear zones. Happy Trail narrow shear zone is near eastern edge of Johnson Valley belt of shear zones at location *C*.

generally through the stress state, but also through differential displacements generated by the structure below (Pollard and Johnson, Chapt. 14, in prep.). Guide structures include en echelon cracks above strike–slip faults, fault segments, and thrust faults and folds (Fleming and Johnson, 1989), with the most familiar being *en echelon tension cracks*. These cracks occur at the ground surface above the termination of a strike–slip fault or narrow shear zone below (Pollard and others, 1982), and they generally form in a band of relatively–uniform width. Traces of individual cracks are generally inclined 30 to 45° to the trend of the strike–slip structure below (Fleming and Johnson, 1989; Olson and Pollard, 1991). Because their formation is relatively well understood, en echelon tension cracks are excellent guide fractures. The width of the band of en echelon cracks reflects the width of the shear zone below, and the orientations provide information about the stress state at the time of formation.

The details of the Happy Trail shear zone are illustrated in a series of photographs in Figure 4. Figure 4A is a view NW, along 30 or 40 m of the SW flank of the Happy Trail shear zone, where the shear zone passes from a parking area (in the foreground), through the dirt road (in the distance), in front of the large bush visible on the horizon to the left. The width of the shear zone, about 4 m, is marked by the width of en echelon fracturing; the right–lateral shift accommodated across the shear zone is a few decimeters. The ground within the shear zone has been thrusted upward about 1 dm with respect to ground to the SW (left). The soil in the foreground is sandy and soft, so the fracturing is relatively poorly developed and preserved. Even here, though, we can recognize many of the elements. We see en echelon fractures, with highly irregular traces, oriented roughly N–S. We see thrusted or buckled ground along the left side, where the blocks of ground bounded by the en echelon fractures have been pushed toward the south.

The rest of the photos show the compact soil in the roadway, in the background in Figure 4A. Figure 4B is a view about N.15°W., along the SW wall of the shear zone. The walls of the shear zone (marked roughly by arrows) are oriented about N.30°W. One flank of the shear zone, in the foreground, is well defined by thrusting and buckling, which has broken the surficial materials into piles of soil chips. The thrusted blocks are bounded by long, N–S oriented en–echelon fractures. These extend for several meters and their far ends define the ragged, opposite (NE) flank of the shear zone. Although the traces of these fractures vary considerably, and many are highly irregular, the average trace is remarkably straight. Figure 4C, a closer view of one trace, shows offset of the irregularities along the walls of the fractures, indicating that the fractures accommodated left–lateral shearing, as well as opening.

The highly irregular, interlocking traces of the en echelon fractures, in combination with the observation that some of the fractures in this set have accommodated only opening, but no shear, is diagnostic evidence for an origin in tension. For example, in a plan view of two of the N–S fractures (Figure 4D), the fracture on the left is a tension crack with opening deformation only. The net opening of this fracture was about 1 cm. We call this a *simple fracture*. The fracture on the right (east), however, has also accommodated left–lateral differential displacement as shown by the arrows in Fiugre 4D. This fracture first opened and then sheared (and perhaps opened further). Individual straight segments of this fracture, oriented roughly N.5°W., are open about 2 cm; segments oriented about N.30°.E are closed. Thus the *net* differential displacement was about 2 cm of left-lateral shift in the N.30°E. direction. For reasons given above, the fracture almost certainly formed as a tension crack. We call this type of fracture a *complex fracture*[4]. Assuming that the complex fracture opened

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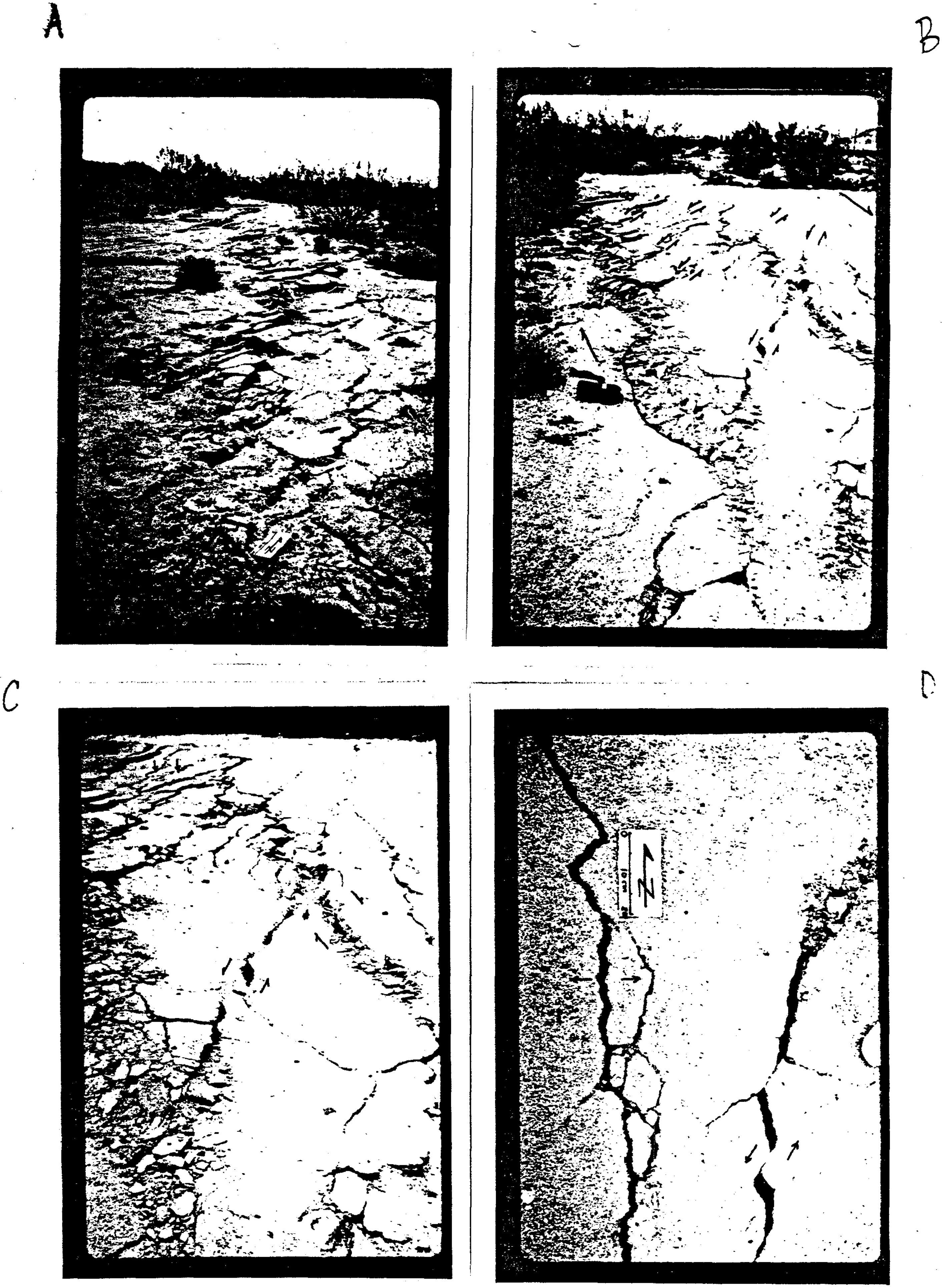
idea in sections on stratigraphic and lithogic guides, and contacts and folds as guides to the location of ore bodies.

[4] A *complex fracture* is a fracture that forms in one kinematic regime and stress state, then accommodates a different kind of deformation in a subsequent kinematic

Figure 4. A narrow shear zone, the Happy Trail shear zone, within the Johnson Valley belt of shear zones. **A**. View N. 30° W. along SW wall of narrow shear zone. Shear zone about 4 m wide accommodated a few decimeters of right–lateral shift. In foreground, soil is soft and sandy and fractures are poorly developed. In background, shear zone crosses firmly compacted dirt road, where fractures are well developed as shown in following photos. **B**. View N.15° W. diagonally from SW side to NE side of shear zone, at dirt road, in upper part of A. Width of shear zone indicated by right–lateral arrows on far left and far right of photo. SW wall of shear zone in foreground. En echelon cracks oriented N-S about 20° clockwise from view. Most cracks them have been transformed into left–lateral fractures, as indicated by arrows. Thrusts (one shown) all along SW wall mark where blocks of ground, bounded by N–S, en echelon fractures, have been pushed laterally during rotation of blocks. The ground in the toes of the thrusts is highly broken and seen as piles of soil chips. **C**. View north along one of en echelon fractures shown in B. Note pull–apart near left–lateral arrows. Offset of irregularities, pullaparts, and thrusts indicate that fractures have accommodated left–lateral shift. Right–lateral arrows near midwidth of shear zone depict a narrow right–lateral shear zone of more intense shearing within the broader zone. **D**. Plan view of a left–lateral fracture and a tension crack at locations of double vertical arrows shown in the upper left part of C. Traces of both fractures are highly irregular and interlocking, indicating that fractures started as tension cracks. Fracture on west (left) side is a tension crack. The tension crack probably is younger than the tension crack/left–lateral fracture.

Fig. 4



similarly to the fracture on the left (1 cm) and then sheared, the second, left–lateral differential displacement was about 1.7 cm toward the north; that is, pure left–lateral shift across the open tension crack. Of course, we have *assumed* that the crack opened 1 cm when it formed, so the second deformation may well have been a combination of opening and shearing. All we observe is the net differential displacement, which is a combination of dilation and shearing.

According to our analysis of the formation of left–lateral guide fractures of this type in a shear zone (Johnson and Fleming, in review), the fractures originate as tension cracks in response to shearing (and perhaps dilation). As a result of their very formation, though, they change the gross physical properties of the ground being sheared, and immediately begin to act as discontinuities bounding rectangular elements ("dominos") of ground. The "dominos" rotate in a clockwise sense as a result of right–lateral shear, and differential displacement between adjacent "dominos" produces the left–lateral offsets. Therefore, although we have described the formation of the left–lateral fractures in two stages, they actually are expressions of a single, continuous, right–lateral deformation.

In summary, the fracturing (Figure 4A) in the Happy Trail shear zone originated as tension cracks generally trending N–S, that was caused by right–lateral shift across a shear zone 3 to 5 m wide. Most of these simple cracks subsequently became complex tension cracks/left–lateral fractures by shifting in a left–lateral sense in response to the right–lateral shearing[5]. Furthermore, as the separated blocks rotated, they were jammed against the ground on either side of the shear zone, producing small thrust faults and buckles (Figure 4B). We saw such structures forming in shear zones bounding and separating landslide elements in Utah (Fleming and Johnson, 1989). These structures give rise to the forms called "mole tracks" in descriptions of many rupture zones (for example, Armijo and others, 1989, p. 2795; Brown and others, 1967; Wallace, 1990; Clark, 1972).

Finally, there is a very narrow, 0.1 to 0.5 m wide, right–lateral shear zone that represents more intense shearing locally within the Happy Trail shear zone (upper right quadrants of Figure 4B and 4C). The narrower shear zone itself is composed, in part, of short en echelon tension cracks, stepping left and defining a zone perhaps 0.5 m wide (as shown to the left of the right–lateral arrows in Figure 4C) and in part by a much narrower rupture zone, perhaps 1 dm wide (as shown in the right–hand side of Figure 4C). The tension cracks within this narrower shear zone are oriented N–S just as they are in the broader, Happy Trail shear zone, but are much shorter and more closely spaced. This *narrower shear zone offsets* the long N–S tension cracks/left–lateral fractures of the Happy Trail shear zone by perhaps 1 dm, indicating that it formed later in the development of the Happy Trail shear zone. It may be a guide to a fault within the shear zone below. It is clear in this case that the narrower shear zone, or fault, appeared after the shear zone appeared.

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regime and stress state. Faults that have formed during a prior deformation regime and subsequently slip along the same break, perhaps in the opposite direction, are examples of complex fractures. Examples of tension cracks that subsequently accommodated oblique differential displacements were documented in landslides in Utah (Fleming and Johnson, 1989), but examples of tensile fractures—joints—that become faults, and of faults that become joints, are common also (e.g., Segall and Pollard, 1983; Cruikshank and others, 1991b; Zhao and Johnson, 1992).

The complex fractures that occurred at Summit Ridge during the 1989 Loma Prieta earthquake were quite confusing (e.g., Ponti and Wells, 1991). There, long fractures with highly irregular and interlocked traces clearly reflect tension at the time of formation. Subsequent to opening, though, many of the fractures accommodated left-lateral shearing as well as further opening (Johnson and Fleming, in review).

[5] The vector sum of the net slip along fractures within a shear zone does not equal the net shift across the belt. In fact, the sense of slip on individual fracures may even be *opposite* to the sense of shift across the shear zone.

The Happy Trail shear zone therefore illustrates in one view the complex internal structure of a narrow shear zone. The sequence of events we can identify is: 1) Formation of the simple fractures, the long tension cracks (N–S) that extend across the entire width of the Happy Trail shear zone; 2) transformation of the tension cracks into complex fractures by subsequent left lateral shift and, perhaps, further opening across the tension cracks. The left lateral shift and the formation of thrusts at the ends of the blocks bounded by fractures are results of *rotation* of the blocks. Additional tension cracks probably form even as blocks rotate; 3) formation of much narrower, right–lateral shear zone within Happy Trail shear zone. The narrower zone contains more intense en echelon cracking and offsets earlier–formed complex fractures. The narrower zone may be a fault a short distance below the ground surface.

We would comment that we have observed the same set of fractures of different kinds at various scales within broader belts of shear zones. There the direct evidence of sequence of events is lacking. Perhaps one can propose that the same sequence of events pertains on the basis of similarity or fractal arguements. However, one can also argue logically: We see shear zones without faults but the faults occur within shear zones and we never see a fault without a shear zone. The fault occurs after the shear zone.

SURFACE RUPTURE ON HOMESTEAD VALLEY FAULT ZONE

The surface rupture on the Homestead Valley fault zone is manifest in *belts of shear zones* (Figure 2) of the type at Happy Trail. The belts are well expressed at several places on long, straight segments of the Johnson Valley, Homestead Valley, and Emerson fault zones. As described above, we refer to these belts as "simple" to distinguish them from places where a fault zone is curving, stepping, or interacting with a geologic structure in some complicated way.

Broad Shear Zone

The widest, long, linear belt of shear zones that we identified is along the Homestead Valley fault zone, at Bodick Road between Acoma Trail and Shawnee Road (Figure 5), about 10 km north of Landers (Figure 3A). The long, linear belt extends along strike for about half a kilometer NW and at least a kilometer SE of the area we mapped. Figure 6 is a summary map of the larger structures immediately NW of Bodick Road. The long dimension of the map, oriented SW–NE, is the width of the belt; the short dimension, oriented NW–SE, is a 100–m stretch along strike of the belt. The belt of shear zones at Bodick Road consists of a broad shear zone, encompassing the entire width of the belt, and several narrower zones of more intense shearing within the belt. The broad shear zone is about 180 m wide; 0.5 km to the NW of Bodick Road it is 120 m wide, about 0.5 km SE it is about 200 m wide, and at Bodick Road it is 180 m wide.

Tension Cracks

Wherever we examined the broad shear zone, it contained both abundant tension cracks and some short fractures with right– or left–lateral shift. The tension cracks are the most widespread structures and were the first fractures to form as the ground was deforming. They are particularly well developed here in highly compact Pleistocene alluvium (Dibblee, 1967) that cracks much like "Stresscoat"[6] in response to very small strains. The cracks are

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[6] The relation between guide structures and the deformation in the subsurface during faulting is similar to the relation between tiny cracks in a material, "Stresscoat," and the strain in the member below (see Wu and Pollard, 1992, for a supplier of "Stresscoat"). "Stresscoat" is painted on a member but, when it dries, is so brittle that, relatively insignificant strains developed in the member will produce myriad cracks in the Stresscoat. The compact alluvium in the Landers area serves as nature's "Stresscoat" for the

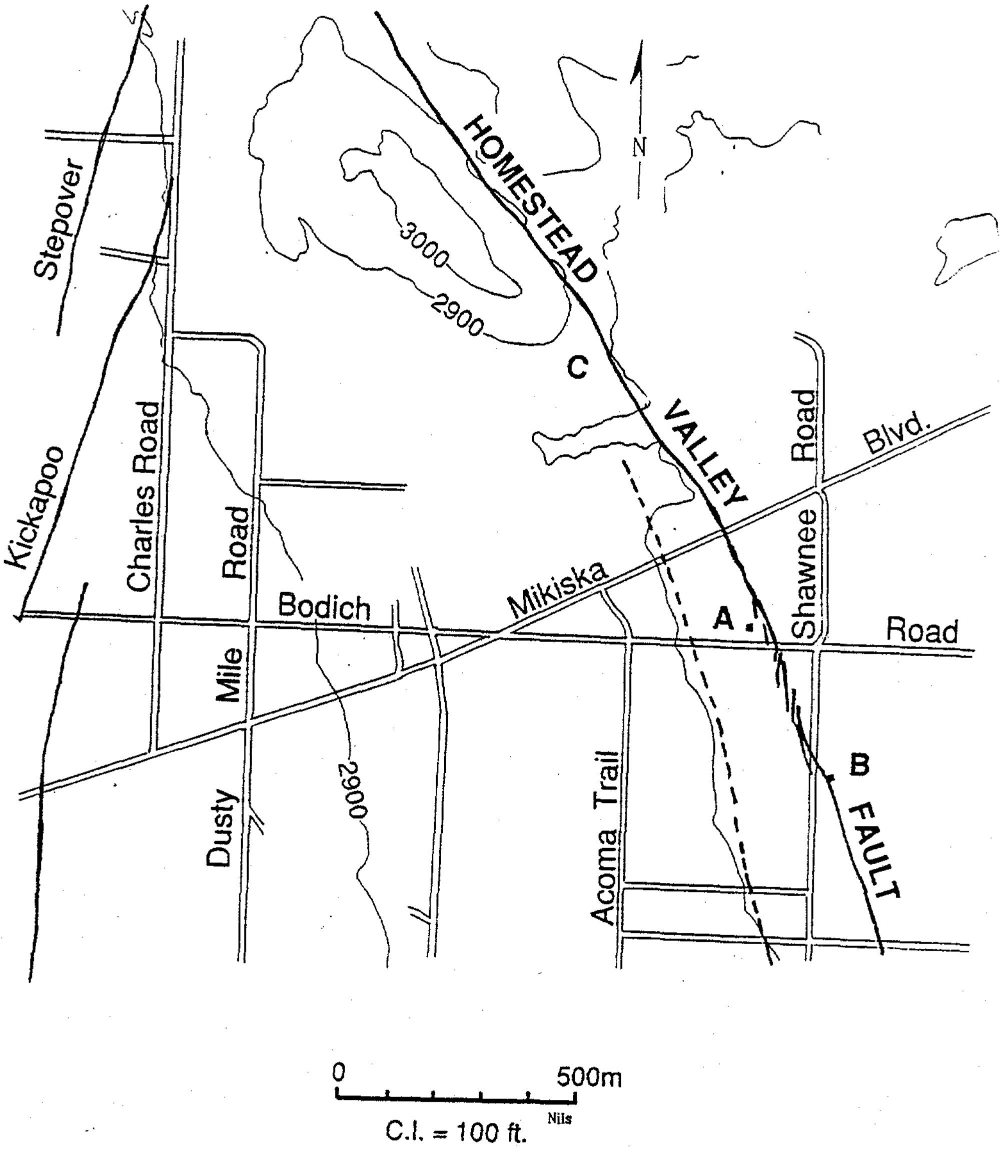


Figure 5. Approximate locations of narrow shear zones bounding walls of belt of shear zones along Homestead Valley fault zone. Location of shear zone on NE wall well known. Location of shear zone on SW wall only approximate in most places. Width unknown at C. Detailed maps made at A. Shear zone breaks down into left-stepping en echelon shear zone segments between A and B.

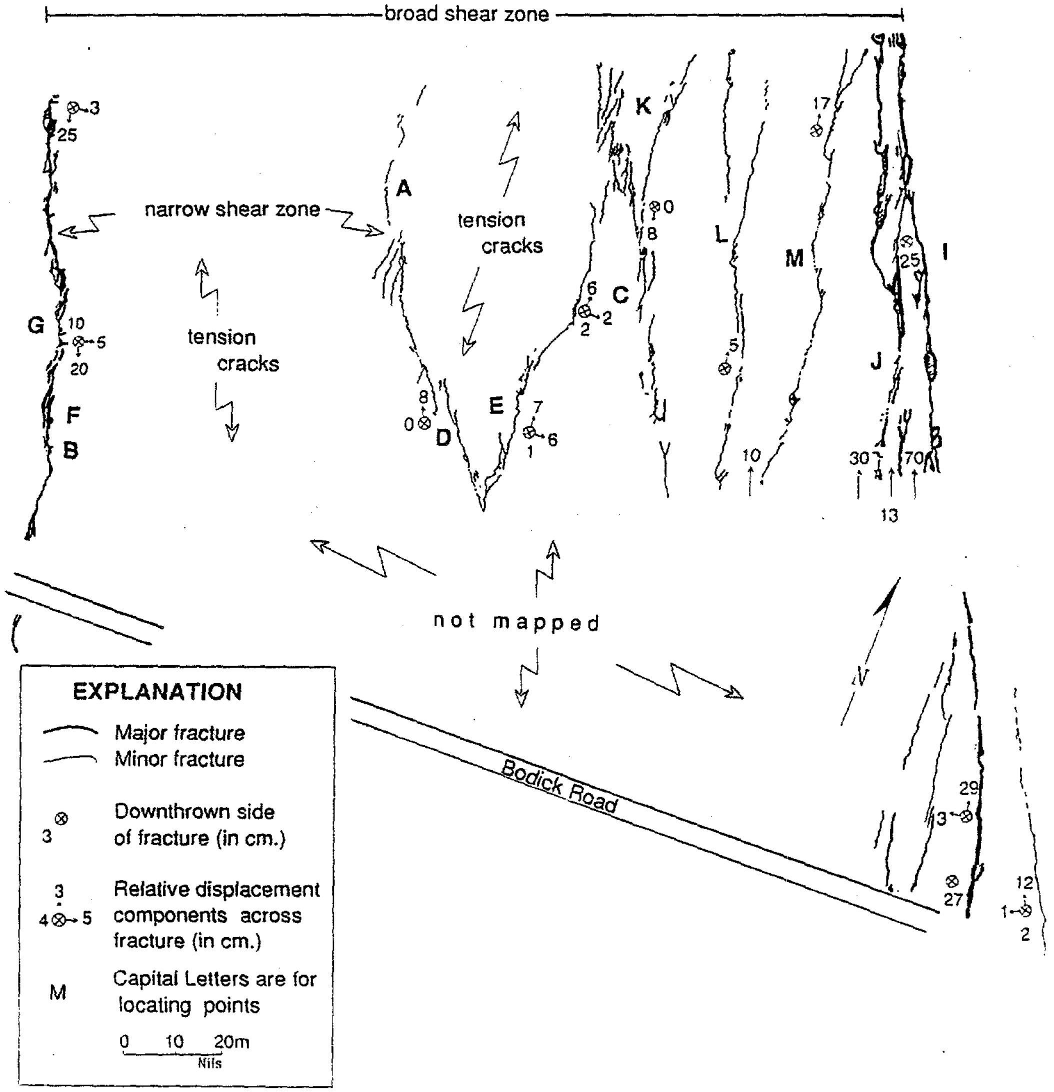


Figure 6. Synoptic map of broad belt of shear zones defining rupture at "Two Ranches" study area, along Homestead Valley fault zone in northern part of Landers (Location A, Figure 5). Belt consists of about seven narrow shear zones here, six right-lateral and one left-lateral. Fractures at several locations, A, B.....M, described in text and shown in more detailed maps and in photographs. Shear zone on NE side accommodated about 0.78 m of offset. Shear zone on NW side accommodated about 0.25 m Differential displacement across other shear zones generally 0.1 m, or less.

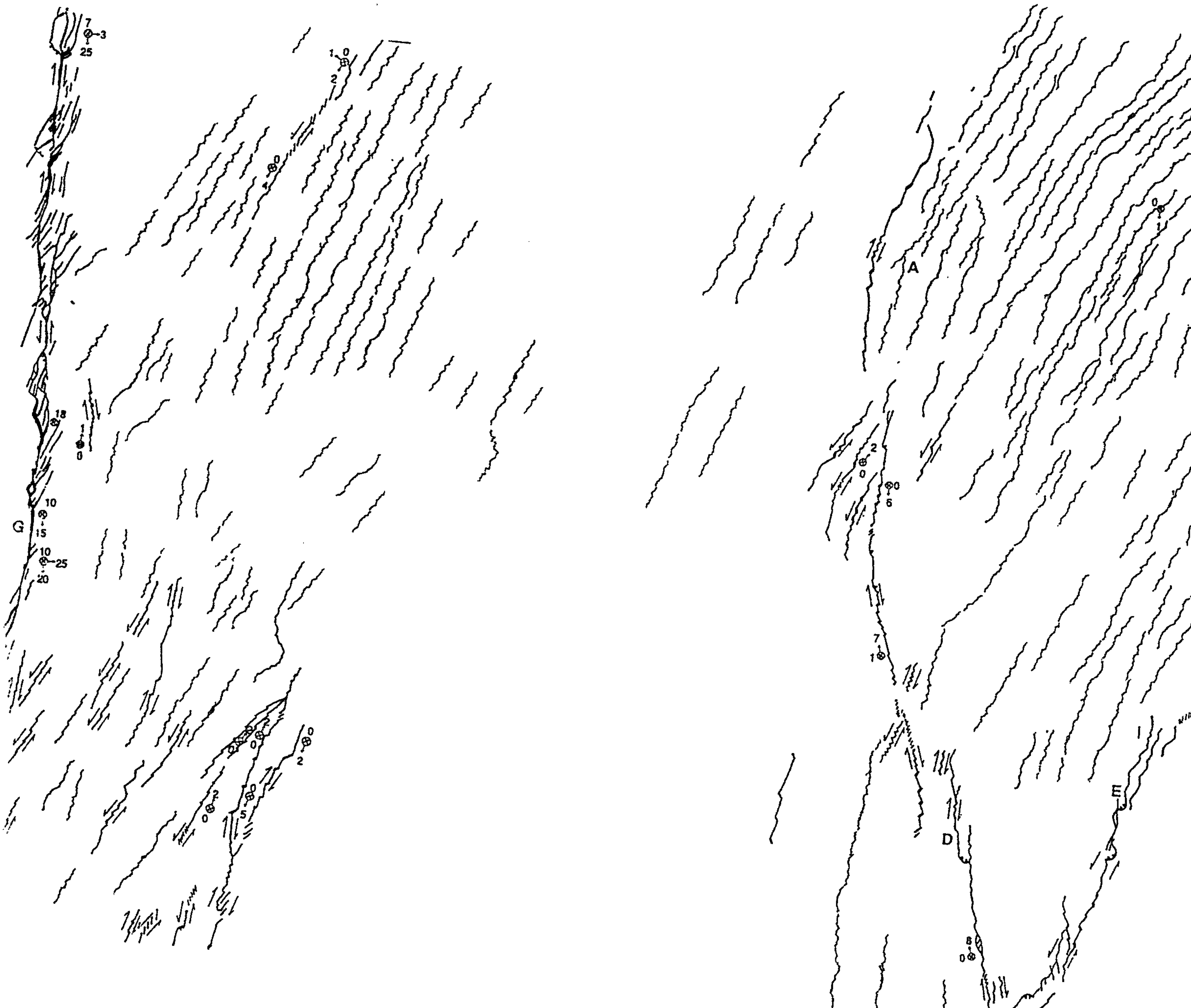
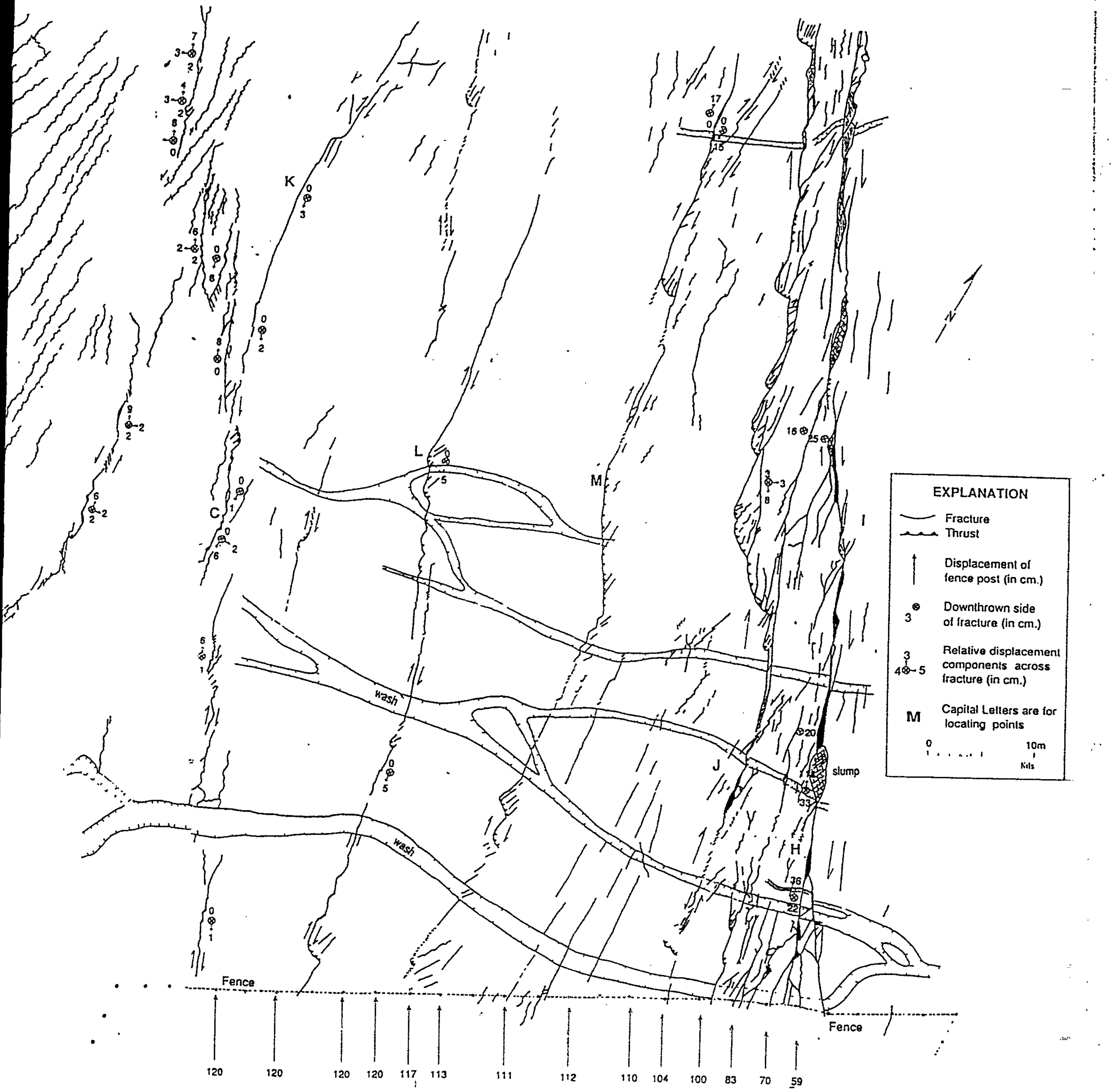


Figure 7. Detailed, analytical map of tension cracks, small faults, and right– and left–lateral narrow shear zones along the Homestead Valley fault zone, near the intersection of Bodick Road and Shawnee Trail. Shapes of individual tension fractures shown schematically with dotted pattern, but lengths, distributions, and orientations are accurate. Some of the fractures that formed as tension cracks subsequently slipped to produce the characteristic open and closed fracture segments that reflect right– or left–lateral shearing. At SW wall is a shear zone up to 5 m wide that has accommodated 1.5–3.0 dm of right–lateral shift. The band of tension cracks within the broad zone, adjacent to the SW wall, is about 30 m wide. Much of central third of the belt of shear zones is also characterized by tension cracks oriented roughly N–S. At the NE wall of the belt is a shear zone that accommodated more than half of the right–lateral shearing of the entire belt. This shear zone is complex and is up to 12 m wide, generally widening from NW to SE. Its east side is marked by a scarp, up to 3 dm high, and its west side is marked by thrusts. Within the zone are tension cracks and left–lateral fractures oriented N–S, and right–lateral fractures generally oriented about N.30°W. Components of differential displacement normal to fence line indicated along base of diagram.


EXPLANATION
Fracture
Thrust
Displacement of fence post (in cm.)
3 Downthrown side of fracture (in cm.)
3 4 5 Relative displacement components across fracture (in cm.)
M Capital Letters are for locating points
0 10m
N
K
L
M
C
J
H
I
slump
wash
wash
Fence
Fence
120
120
120
120
117
113
111
112
110
104
100
83
70
59

remarkably narrow for their lengths, with length–to–width ratios of 500 to 1000.

The shapes of individual tension cracks are too convoluted and ornate to show precisely, even at the 1:200 scale of our mapping, so the traces are shown symbolically in the analytical maps (Figure 7 ,. Nevertheless, the locations, spacing, lengths, and trends of tension cracks are shown accurately in the analytical maps. Where tension cracks were absent on the ground, they are absent on the map. The tension cracks are notably absent in ground on either side of the belt of shear zones, although we found one long fracture, trending subparallel to the belt, about 100 m NE of the belt, along Shawnee Road (Figure 5).

Characteristically, the orientation of tension cracks throughout the area is N–S (see, for example, Figure 7). The tension cracks are scattered throughout the width of the shear zone, but are most common in two areas. One area is a belt parallel to the SW edge of the broad shear zone (Figure 7). The other is a wedge shape near mid-width in the shear zone (Figure 7). Traces of individual tension cracks extend irregularly for 1 to perhaps 10 m (Figure 8A). Although variable, their apertures are generally a few millimeters to perhaps a centimeter. They have rough walls—characteristic of tensile failure—and their traces are extremely irregular (Figure 8B). In many ways the tension cracks resemble cracks in a tile floor, where the crack works its way across the floor, turning left or right through large angles, and generally following the mortar between tiles. In this case the tension cracks follow soil peds, older shrinkage cracks or other vertical, prismatic structures in the dense sedimentary deposits and create characteristic zig–zag paths. We infer that the highly irregular fracturing we see at the ground surface is merely *guide fracturing* related to straighter tension cracks below the ground surface. The overall trend of the traces of the irregular cracks are remarkably consistent throughout the shear zone, and individual fractures can be traced for many meters. There are very few examples of tension cracks whose average trace wanders significantly (Figure 7).

Small Faults

Scattered throughout the broad shear zone, and not obviously related to any throughgoing structures within the belt of shear zones, are tension cracks that subsequently shifted and thus became *complex fractures*. We have shown many of the complex fractures in the analytical maps, Figure 7.

In places they are shown only schematically, being represented by sawtooth forms, with one limb of the fracture having a wider aperture than the other. These crudely resemble the actual fractures. For example, Figure 9A shows the trace of a highly irregular fracture with an average trace trending about N–S, about 5 m from the SW edge of the shear zone (location B, Figure 6 and Figure 7). The plan view of the fracture (Figure 9B) shows that segments of the fracture trending about N.30°E. are closed, whereas segments of the fracture trending N–S to N.30°W. are wide open. The net differential displacement is 1 to 2 cm. The direction of net differential displacement across this fracture (including both the opening that occurred when it formed *and* the subsequent movement) is N.15° to 20°E.. With respect to the walls of the shear zone that trend N.30°W., the net differential displacement on the fracture was dilational. Most of the tension cracks/left–lateral fractures within the broad shear zones are similar to that shown in Figure 9. They are left–lateral (and dilational) and apparently formed by, first, dilation and then left–lateral slip (or perhaps a combination of left–lateral slip and further dilation).

Although the openings along the small faults we have described formed very differently from the openings that characterize en echelon tension cracks over a shear zone (and

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deforming rocks below, and the directions and spacing of tension cracks in the compact alluvium are guides to the tension and extension of the ground below.

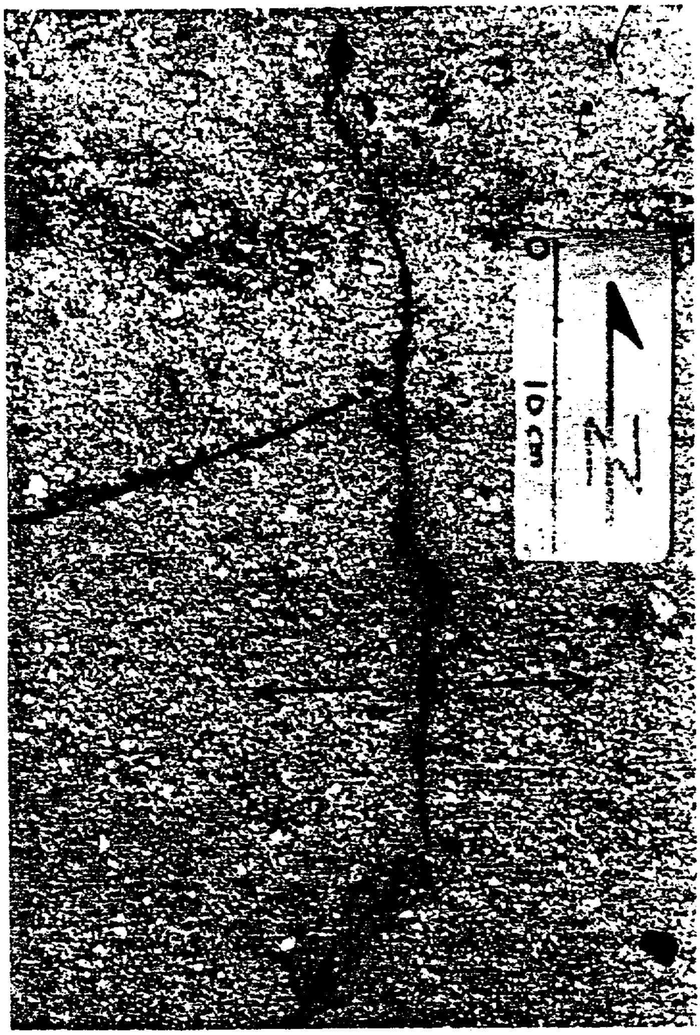

Figure 8. Detailed views of tension cracks shown schematically in figure 7. *A*, View north along traces of several tension cracks at locality A (figs. 6 and 7), near midwidth of the broad shear zone at Bodick Road. Zig–zag, roughly sawtooth pattern of interlocking elements in walls of tension cracks is characteristic. Strong overall trend suggests a straighter crack beneath ground surface; *B*, Closer plan view showing irregularities in trace. Dark line on left is a twig, not a crack.

A.

Figure 9. Fracture that started as tension crack and then slipped in left-lateral sense near bounding, right-lateral shear zone at SW wall of belt of shear zones (locality B, figs. 6 and 7). *A*, View north along trace. Trace highly irregular, just like tension cracks, but fracture here slipped in left-lateral sense.

B.

B, Plan view of same fracture, showing left-lateral and dilational movement. Segments trending about N.30°E. are closed, whereas segments trending N–S to N.30°W. are open, reflecting net left-lateral, differential displacement toward NE.

should not be confused with simple en echelon cracks), we can interpret the sense of shearing accommodated by a fracture containing openings just as we do the sense of shearing associated with en echelon cracks. Where the zig-zag tension cracks sheared, the zigs might be closed and the zags opened further, so that the zags appear much like en echelon cracks, allowing one to readily and correctly "read" the sense of shearing along the fractures (Figure 4D, Figure 9B). The openings along the zig-zag fractures step left in right-lateral shear zones, and right in left-lateral shear zones, exactly as do en echelon tension cracks.

Précis

On the basis of our description of the tension cracks and tension cracks/left-lateral fractures within both the narrow Happy Trail shear zone and the broad shear zone in the Bodick Road area, we see the following pattern for the deformation and formation of fractures in a shear zone. As shearing began, the first deformation consisted of a combination of pure right-lateral shearing parallel to the walls and dilation normal to the walls of the shear zone. The shearing and dilation are reflected in the orientations of tension cracks. Here, the maximum tension was oriented E-W. After the tension cracks formed, the mechanical behavior of the ground was changed profoundly, and it sheared readily. As shearing continued, some blocks of ground bounded by tension cracks rotated in a clockwise direction, causing left-lateral offsets across the fractures and changing some of the fractures into left-lateral faults (Johnson and Fleming, in review).

Thus, the primary fractures in the broad shear zone are the tension cracks, not the small left-lateral fractures. The distribution of the tension cracks throughout the broad shear zone, and their virtual absence in ground on either side, indicates that the ground within the shear zone was subjected to *localized deformation* vis a vis the ground on either side of the shear zone. While the cause for the localization is unclear, much can be learned about the deformation by interpreting the orientations of the tension cracks. The average trends of the irregular tension cracks, approximately N-S, is remarkably uniform throughout the area (Figure 7). The walls of the broad shear zone in this area (Figure 6) are oriented N.30°W., so the tension cracks are oriented about 30° clockwise from the walls of the shear zone.

Shear Zone Model

Although the magnitudes of the principal stresses within the belt of shear zones are unknown, the magnitudes of the principal stresses are unknown, of course. We do know, however, that the deformation responsible for the tension cracks was not pure shear oriented parallel to the walls of the shear zone, as we commonly associate with simple shear along a fault zone. In that case the tension cracks would be oriented 45°, not 30°, from the walls of the shear zone. Rather, the orientations of the tension cracks are consistent with a stress state of pure shear plus additional tension oriented NE-SW, normal to the walls of the shear zone. The strong preferred orientation of the tension cracks indicates that the direction of crack propagation parallel to the ground surface was stabilized, further indicating that the principal stress parallel to the fractures was either zero or compressive (Cottrell and Rice, 1980; Cruikshank and others, 1991, p. 875). The pure shear would provide the necessary compression.

Our reading of the stresses near the ground surface, plus the observation that the tension cracks are localized within a distinctive zone, about 200 m wide, and are absent in ground on either side of the zone, suggest a conceptual model (Figure 10A) in which the ground surface at Bodick Road was subjected to localized shearing plus dilation by a broad shear zone, about 200 m wide, at greater depth. This model is closely related to that which we proposed to explain structures consisting of en echelon cracks and thrusts along strike-shift shear zones within the Twin Lakes landslide in Utah (Fleming and Johnson, 1989). At that time, though, we were not attuned to evidence for a zone of combined dilation and shearing, accepting instead the traditional

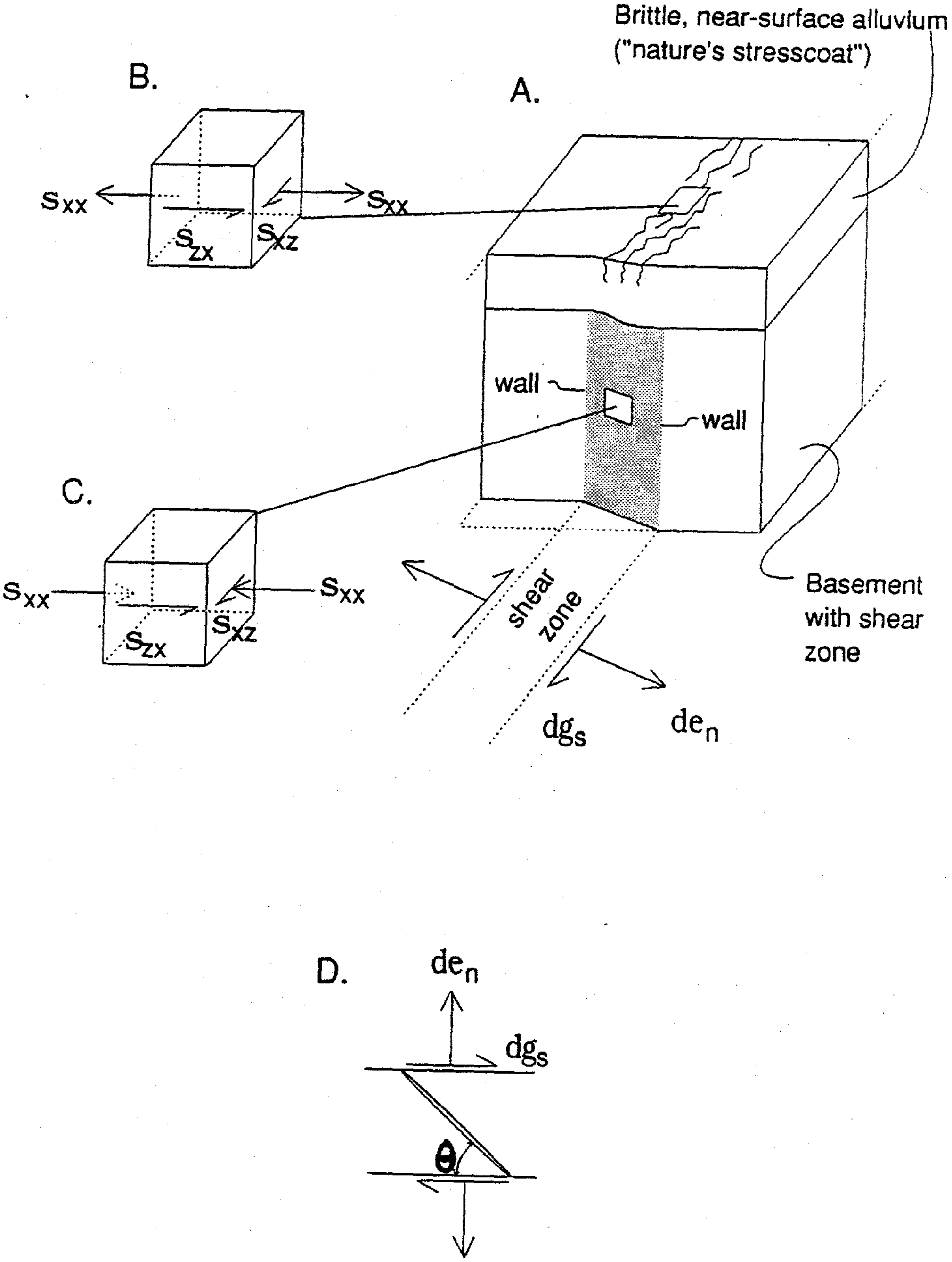

Figure 10. Idealization of the subsurface conditions responsible for the formation of tension cracks within shear zone at ground surface. A. Brittle, near-surface alluvium layer overlies rock or alluvium below that contains a shear zone. Shearing and dilation within the shear zone produce tension normal to zone and shearing parallel to zone in brittle alluvium. B. Nonzero stresses in zone near ground surface including shear stress parallel to walls and tension normal to walls, causing cracks to form at clockwise angle less than 45° to walls. C. Stresses in shear zone at depth including shearing parallel to walls and compression normal to walls. D. Relation between incremental simple shear parallel to walls and normal dilation normal to walls and orientation, θ, of tension crack in brittle crust.

interpretation of a single fault at depth (e.g., Reid, 1910). Our observations that closely tie faults to shear zones (Aydin and Johnson, 1978, 1983; Johnson, in review a,b,c; Pollard and Johnson, Chapt. 14, in prep.) have made us positively disposed toward shear zones at Landers.

The conceptual model predicts that a combination of shearing and dilation in a shear zone at depth would produce shearing and *tension* in brittle, near–surface alluvium, so that the tension cracks would tend to be oriented at angles of less than 45° to the walls of the shear zone. There is compression normal to plane of the shear zone below (Figure 10C), and tension normal to the shear zone above (Figure 10B). The change in normal stress is a result of the tendency for the shear zone to dilate and the brittle alluvium to prevent dilation. Since the material in the shear zone is coupled to the overlying brittle alluvium, their deformations and stress states are compromised via shear stresses generated at the interface between the shear zone and the brittle alluvium (Figure 10). In this way we can understand the orientations of the tension cracks resulting from a combination of shear stress (which would produce cracks at 45° to the walls of the shear zone) and tension (which would produce cracks parallel to the walls of the shear zone), causing net orientation between 0 and 45°. Thus the conceptual model explains the orientation of the tension cracks.

Two other phenomena explained by the conceptual model of a shear zone below and brittle alluvium above are the presence of *numerous* tension cracks at the ground surface between the walls of the belt and the *total absence* of tension cracks on either side of the belt. External loading from the sides of the shear zone at the ground surface—loading by blocks of ground on either side of the shear zone—would produce only a few tension cracks because the growth of a single tension crack (or a few cracks) would relieve the applied stresses throughout the zone. We imagine that the near–surface materials behave much like a layer of "Stresscoat" overlying a shear zone below. Since the normal stresses are generated by the gradient in the horizontal shear stress (σ_{yx} in Figure 10C) applied to the base of the brittle alluvium by the shear zone, though, the normal stresses would be relieved only locally by the formation of tension cracks. To visualize this, note that the horizontal shear stress vanishes at the ground surface, and that it is the gradient in horizontal shear stress that induces the tension in the brittle alluvium; one can verify this even qualitatively by examining the three–dimensional differential equation of equilibrium for the x–direction in terms of stresses (e.g., Johnson, 1970). Because of this coupling of the shear zone to the base of the brittle alluvium through an interface, a single tension crack will relieve the tension only locally; and the brittle crust nearby remains in tension, transmitted via a shear stress gradient from the interface to the ground surface. For this reason, many tension cracks can form, side by side. Using the same arguments, but in counterproof, we explain the lack of tension cracks in ground outside the walls of the belt in terms of insignificant shear stress gradient in that ground because the shear zone is lacking beneath it.

In summary, what we suggest is that the combination of pure shear and dilation normal to a shear zone at depth is responsible for the stress state and the resulting orientations of tension cracks within what we have called a *broad shear zone* at the ground surface. The stress state near the surface at the time the tension cracks formed consisted of N–S compression and E–W tension. One then wonders how the deformation becomes concentrated in the shear zone at depth. While beyond the scope of our observational study of surface fracturing, this is an interesting question (Johnson, in review, a,b,c).

We can proceed one step further, and compute the ratio of the increment of normal strain and the increment of simple shearing, $\delta\varepsilon_n/\delta\gamma_s$, within the shear zone, below, responsible for the orientation of the tension cracks in nature's "Stresscoat", above. As shown elsewhere, the ratio of strain increments can, in some circumstances, be related to the *angle of dilatancy*, δ, of the material in the shear zone (Johnson, in review a). In dilatant shearing (Figure 10A), the increment of simple shearing, $\delta\gamma_s$, and the increment of normal strain perpendicular to the shear zone, $\delta\varepsilon_n$, are related through the angle of dilatancy (Johnson, in review, a),

$$\tan(\beta) = \delta\varepsilon_n / |\delta\gamma_s| \qquad (1).$$

Because the increment of normal strain parallel to the dilatant shear zone, $\delta\varepsilon_t$, is zero, however (Figure 10A), the orientation of the principal extension in the shear zone is,

$$\tan(2\theta) = \delta\gamma_s / \delta\varepsilon_n \qquad (2).$$

In these equations, θ is the clockwise angle between the walls of the shear zone and the trace of the plane across which extension is maximized (Figure 10D), $\delta\gamma_s$ is positive if right–lateral, and $\delta\varepsilon_n$ and β are positive if dilative (negative if contractive). Combining these results, we can determine the orientation of maximum extension in the shear zone at depth in terms of the angle of dilatancy:

$$\tan(2\theta) = \cot(\beta)\ \mathrm{sgn}[\delta\gamma_s]$$

or

$$\beta = [(\pi/2) - 2\theta\ \mathrm{sgn}(\delta\gamma_s)] \qquad (3)$$

in which $\mathrm{sgn}[\delta\gamma_s]$ is +1 if the shearing is right–lateral, and –1 if the shearing is left–lateral.

Thus, if we assume that the maximum tension in the near–surface alluvium corresponds to the maximum extension in a broad shear zone below, then for the Bodick Road area, we have $\mathrm{sgn}[\delta\gamma_s] = +1$ and $\theta = +30°$, and therefore, the angle of dilatancy is +30° for deformation in the broad shear zone. Based on estimates of dilatancy fom other structural problems, this is a reasonable value (Johnson, in review, a, b).

Narrow Internal Shear Zones

Within the broad belt of shear zones shown in Figure 6 are five narrow internal shear zones, which closely resemble the one described earlier that cut across the fractured blocks at the Happy Trail shear zone. The narrow shear zones are 3 to 10 m wide and consist of a concentration of fractures relative to the ground on either side. For example, Figure 7 shows a narrow shear zone near mid-width of the belt near location C. This shear zone accommodated 5 to 8.5 cm of right-lateral shift of the fenceline at the SE end of the map area. Many of the fractures in the narrow shear zone are complex; they began as tension cracks and then transfomed into right- or left-lateral faults. Fractures are typically 8 to 15 m long and form a clockwise angle of about 15° to 30° to the general trend of theshear zone. Although they are identical in appearance to individual complex fractures that occur throughout the borad zone, those along the narrow shear zones are marked by their en echelon arrangement, stepping left along the right-lateral shear zone, by their spacing, and by their concentration in a narrow band of consistent orientation.

The fractures in a narrow right-lateral shar zone are of two types: complex fractures that are primarily right-lateral fault segments and en echelon tension cracks. The complex fracturs have an irregular trace and rough fracture surfaces, indicating that they formed in tension. The pattern of opening and closing along the irregular trace of the tensile fracture reveals that the fracture was later offset in a right-lateral sense. These right-lateral frault segments degenerate locally into narrow bands of en echelon tension cracks that make a small clockwise angle with the right-lateral fault segments.

The right-lateral fault segments and the tension cracks apparently are guides to very narrow shear zone segments or fault segments below the ground surface. For example, Figure 11 shows the appearance of a fracture at location C (Figure 7) that is about 10 m long and has accommodated about 6 cm of right–lateral, 2 cm of dilation, and essentially zero vertical relative displacement.

A.

Figure 11. Right-lateral fractures. *A*, Fracture with right-lateral shift within right-lateral shear zone near midwidth of belt of shear zones at Bodick Road (locality C, figs. 6 and 7). Average trend about N.20°W. Components of differential displacement are 6 cm right lateral, 2 cm dilational, and 0 cm vertical. Rough break at surface suggests failure in tension. However, a few centimeters below surface, fracture is straight rather than zig-zag, as appears to characterize tension cracks (figs. 8 and 9).

Figure 11. *B*, Fracture in right–lateral shear zone trending N.45°W. near midwidth of belt of shear zones at Bodick Road (locality D, figs. 6 and 7). View S.30°E. of compound fracture consisting of shorter elements, 1–3 m long and stepping left.

Figure 11. *C*, Plan view of the fracture in *B*. The shorter elements are open where the right–lateral shift steps right. The steps are compressed and, in places, folded or thrusted.

The average trend of the fracture is N.10° to 20°W. and the direction of differential net displacement is about N.20°W.. The roughness of the walls of the fracture suggests that it originated as a tension crack, at least within a few centimeters of the ground surface. The fracture is *compound*[7], however; a few meters along trend to the NW, it becomes oriented N.30°W. Over a few meters of its length it consists of en echelon tension cracks oriented N–S to N.10°E. and the NE ends of the blocks bounded by tension cracks have been thrusted (Figure 7). About 10 m farther NW along the shear zone, at location C (Figure 7), the central part of the shear zone is dominated by another compound fracture, about 15 m long, trending N.30°W. Over part of its length, it consists of a combination of tension cracks and thrusts. As shown at the Happy Trail shear zone, all these fracture patterns are consistent with right-lateralshift across a narrow shear zone.

A particularly clear example of the kind of compound structure that forms over a narrow shear zone is shown in Figure 12 in a sketch made by Robert Sharp (in Clark, 1972, p. 62) of fractures, buckles, and thrusts in a playa deposit of Benson Lake. The en echelon fractures in Figure 12 originated as tension cracks bounding blocks of sediment, of unknown depth, about 3 dm wide and 5 dm long. Compressional features—thrusts and chevron buckles—formed at the ends of the blocks in a thin veneer ("Stresscoat") of the deposit. The upper parts of the tension cracks then served as transform faults, of left– or right–lateral senses, accommodating the compression near their ends. Thus, each compound structure consists of a transform fault and a buckle, or a transform fault and a thrust fault, and the en echelon fractures themselves have accommodated left–lateral or right–lateral shearing, consistent with their roles as transform faults between the compressional structures (Clark, 1972, fig. 29).

Similarly, 10 m SE of the fracture, at location C (Figure 7), is a compound fracture at least 35 m long that extends to the fence line. Along part of its length it consists of en echelon tension cracks (left–stepping), and near location C it accommodated 6 cm of right–lateral, 2 cm of dilation, and 1 cm of vertical (downthrown on SW) differential displacements. The associated thrusts are missing there.

A different shear zone, also near the center of the 180 m wide belt of shear zones, trends about N.55°W. near location D (Figure 6 and Figure 7). It accommodated about the same amount of right–lateral shift as the zone near location C. Also, although there are left–lateral fractures associated with this zone, the trend of the zone is defined more by right–lateral than by left–lateral fractures. Some of the elements themselves are composed of en echelon, left–stepping tension cracks oriented about N–S, but much of the shear zone is defined, grossly, by elements of compound fractures that trend about N.40°W., range in length from 5 m to 20 m, and step left. One shown near location D (Figure 7) has a thrust at the left step. Each of these fractures is composed of smaller, similar fractures, trending about N.30°W.

One of the difficulties in interpreting en echelon fractures is that fault segments arranged en echelon can superficially resemble tension cracks arranged similarly (Fleming and Johnson, 1989). For example, *en echelon tension cracks* tend to form in a left–stepping array along a right–lateral shear zone. Indeed, such

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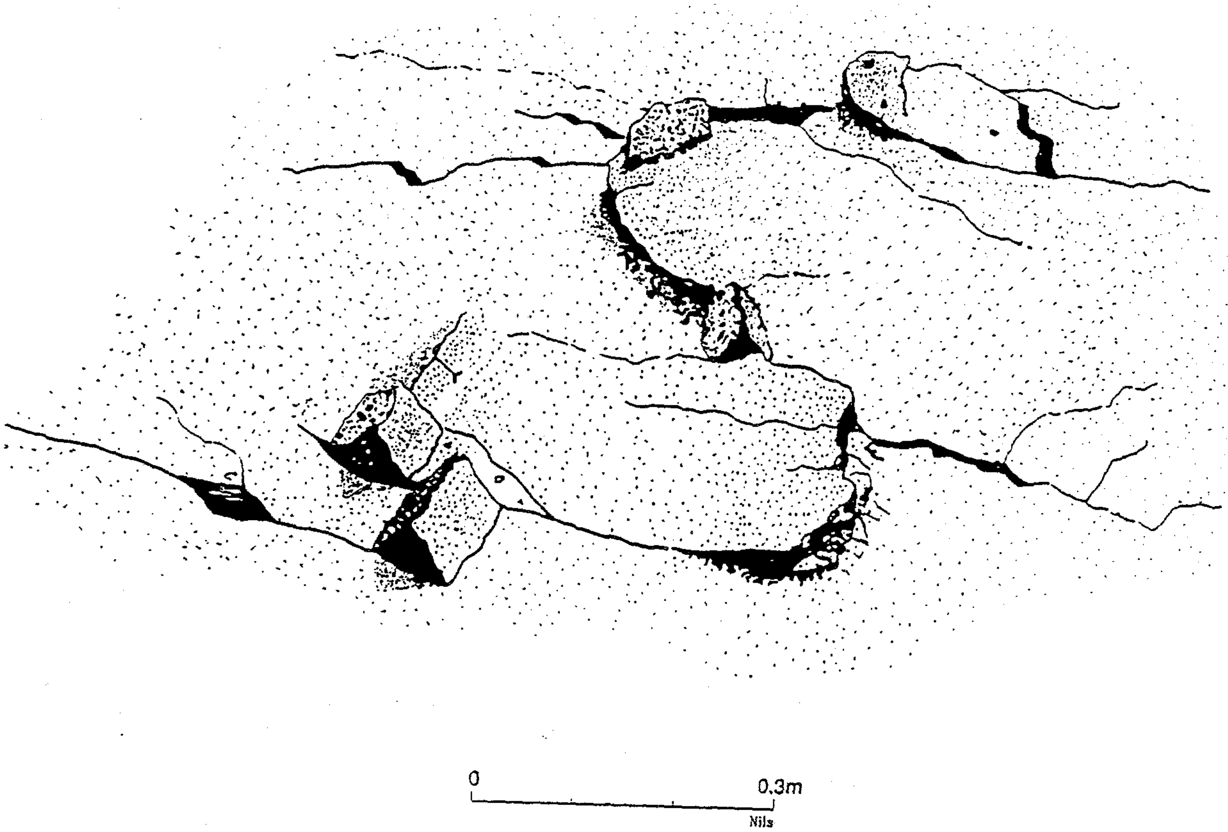
[7] A *compound fracture* is a fracture that changes local kinematic character along its trend. Because the orientation of the fracture changes, however, the fracture accomplishes throughout its length the same kind of differential displacement of adjacent blocks or plates of ground. Well-known examples are the combination of spreading ridges and a transform fault in plate tectonics, a head scarp and flank faults of a landslide, and steps that produce ramp folds along thrust faults (Fleming and Johnson, 1989). Malcolm Clark (1972) described examples of what we call compound fractures that formed within a shear zone along the Coyote Creek fault that ruptured during the 1968, Borrego Peak earthquake in southernmost California. Robert Wallace described similar compound structures at Parkfield (in Brown and others, 1967). The rupture zones were composed of en echelon fractures inclined about 30° clockwise to the general trend (N.30° to 40°W.) of the rupture zones with a few decimeters of shift. In many cases en echelon tension cracks formed compound structures with compressional features.



Original sketch by Robert Sharp

Figure 12. Compound guide structure formed along rupture zone of Coyote Creek fault during the 1968 Borrego Peak earthquake. Sketch by Robert Sharp (Clark, 1972, p. 62). Left-stepping en echelon fractures began as tension cracks. Subsequent slippage along fractures produced buckles in thinly laminated, brittle playa deposit between ends of fractures. The structures are compound because they are of different types yet they formed together and represent the same movement of the block on one side of the shear zone relative to the block on the other.

an array is practically diagnostic of right–lateral shearing. It is perhaps less well known that strike–slip faults that have broken through incompletely to the ground surface often are expressed as fault segments, arranged en echelon, and that the sense of stepping is the same for tension cracks and fault segments (Fleming and Johnson, 1989; Wallace, 1990; Cruikshank and others, 1991). These stepping fault segments are also practically diagnostic of the sense of shearing, which is read the same as for tension cracks. The orientations of fault segments and tension cracks, however, reflect quite differently the orientations of the principal stresses in a shear zone. According to our experience, tension cracks tend to form at 45°±15° and fault segments at 15°±10° to the walls of the shear zone (Fleming and Johnson, 1989), *but the orientations, themselves, are not diagnostic of the tensile or shear origin of the fracture* (see Pollard and others, 1982, for discussion of orientations of en echelon tension cracks and Johnson, in review a, b, c, for discussion of orientations of shear zones and faults.) Thus, it is important to have independent methods of recognizing tension cracks and fault segments. A characteristic that distinguishies a fault segment from a tension crack is the surface texture of the walls of the fracture below the ground surface. Fracture walls with high roughness indicate that the fracture formed as a tension crack, whereas fracture walls that are smoother, and possibly grooved or striated, indicate that the fracture originated as a fault (Fleming and Johnson, 1989). In the case of the fractures near location D (Figure 9), the origin of the fault segments or very narrow shear–zone segments oriented about N.40°W. is suggested by the evidence of primary shear along the fractures (en echelon tension cracks) and the orientation of the segments. Most of the en echelon right–lateral fractures at Landers probably are right–lateral fault segments or very narrow shear–zone segments at shallow depths below the surface.

A left–lateral shear zone (location E, Figure 6 and Figure 7) connects the two right–lateral shear zones at C and D. The fractures trending along the axis of the shear zone have accommodated about 6 to 9 cm of left–lateral, 2 cm of dilation, and 2 cm of vertical (downthrown on E) movement. Much of the length of the shear zone appears to be coalesced tension cracks, oriented about N–S. The fracture elements over part of the length of the shear zone are en echelon tension cracks (with individual cracks oriented N.30° to 40°W), suggesting a left–lateral shear zone or fault at depth. Figure 13A (location E) shows two long elements of the left–lateral shear zone viewed toward the south. The element in the foreground is about 3 m long, and that in the background is about 7 m long. The elements step right, and between them is a thrust, partially obscured by vegetation in the photograph, but shown on the map at location E (Figure 6). Figure 13B shows the northern element near the thrust. It consists of closed segments, trending N–S, and open segments trending more westerly, reflecting the left–lateral slip. The overall pattern of this left–lateral shear zone suggests coalesced fractures with orientations ranging from N.20°E. to N.20°W.

The total assembly of surface fractures—ranging from the tension cracks in the overall broad zone of weak shearing, to zones of more complex fracturing in narrow shear zones of small shift, and yet further to intensive surface rupture where the shift amounts to a few dm—convinces us that the intensity of fracturing is displacement–dependent.

Bounding Narrow Shear Zones

The broad belt of shear zones along the Homestead Valley fault zone at Bodick Road contains both a broad shear zone of weak deformation extending across the belt and several narrow zones of concentrated shear within the belt. Together, the broad zone of shearing and the internal shear zones that we have described thus far accommodated about 0.3 m of right-lateral shift. The total right-lateral shift for the entire belt of shear zones is 1.8 m as determined by sighting down the line of power poles along Bodick Road. Therefore, the internal shear zones and the broad

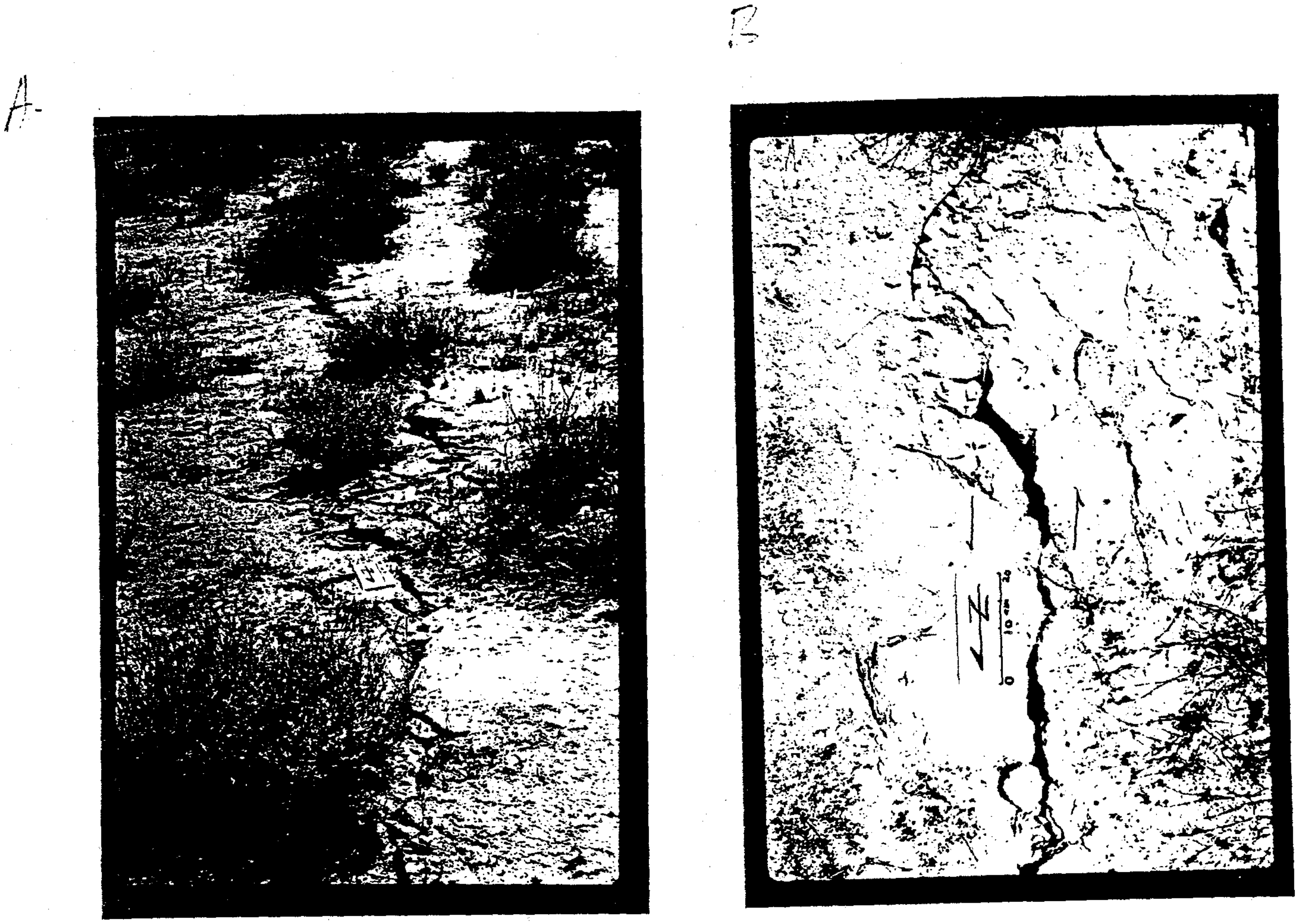


Figure 13. Fractures in N-S, left-lateral shear zone connecting right-lateral shear zones near midwidth of belt of shear zones at Bodick Road. Location E, Figure 6 and Figure 7B. A. View south along fracture, showing fracture segments that step right. Vegetation obscures a thrust connecting the two fractures. B. Plan view of one of fractures, showing closed segments trending N-S and open segments trending up to N30W.

zone of shearing accommodated only about 1/6 of the total differential displacement across the belt.

Most of the differential displacement was concentrated in narrow shear zones along the boundaries of the belt of shear zone at Bodick Road. The zone bounding the belt on the NE has 1.2 m of right–lateral shift, while that on the SW has 3 dm. The observation of relatively intense shearing along the walls of the belt of shear zones is somewhat curious in light of the observation that, outside the belt of shear zones, farther SW than the shear zone on the SW side of the belt and farther NE than the shear zone on the NE side of the belt, the ground is practically undisturbed and devoid of cracks.

We would also comment that, if the kinematics of the interior fractures are not recognized as due to shearing, the belt of shear zones might be misinterpreted as two separate faults. Indeed, an observation of this type was made along the Johnson Valley fault zone, several kilometers south of this area, and led to the incorrect assumption that there is a "double fault" there (Engineering and Science News, 1992).

Shear Zone on SW Side

The SW bounding shear zone accounts for about one–sixth of the total shift of the 180-m-wide belt, roughly the same as the combined shift accommodated by shearing across the broad zone and the several internal shear zones. In the bounding shear zone, differential displacements are contained in many diagonal, en echelon fractures some of which have opened to become gaping cracks and many of which have accommodated the left–lateral shift that we described at Happy Trail and interior shear zones that accommodated smaller offsets here. Within the bounding shear zone are scarps up to 1 dm high that face NE. Deformation is so highly concentrated that the scarps resemble faults (Figure 14B), but rather than right-lateral fracturing in the zone, there are small thrusts and closely spaced tension cracks. The fracture damage is so great in this bounding shear zone that in many places the senses of offset across fractures are difficult to recognize. In other places the diagonal fractures bound blocks of ground that end in thrust faults at either edge of the shear zone (Figure 14A). Only the orientations and the general relationships relative to the shear zone and the associated thrusting remain to identify the origins of these fractures. These fractures all occur within a rupture zone ranging in width from 1 m to perhaps 5 m. The differential displacements across the narrower parts of the bounding shear zone range from 26 cm right–lateral, 3 cm dilation and 7 cm vertical (downthrown on NE side) at the NW end of the map area, to 10 to 15 cm right–lateral, less than 5 cm dilation and 10 cm vertical (down on NE) near mid-length (Figure 7).

Shear Zone on NE Side

Most of the shift on the Homestead Valley fault zone during the Landers earthquake was accomplished within a narrow shear zone along the NE wall of the broad belt of shear zones (Figure 6 and Figure 7). Our measurements of deformations of the fence surrounding the ranch along Bodick Road document the concentrated shearing (Figure 15). The northern corner of the fence (shown in foreground in Figure 16) is on essentially unbroken ground. The belt of shear zones begins about 14 m SW of the fence corner. The bases of the first four fence posts from the corner provide a datum for measuring *lateral* components[8] of the

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[8] Only one component of differntial displacement can be measured with this fence along the NW side of the ranch. The differential displacements between fence posts (shortening or lengthening of distances between posts) could not be measured because the fence was being stretched by ground deformation and the fence itself strongly resisted stretching. However, the component of differential displacement we could measure along this fence line must be a large fraction of the total differential displacement because: 1) the fence line is roughly perpendicular to the walls of the belt of shear zones, and 2) measurements of differential displacement vectors of the fence along the SE side of the ranch (Figure 15) indicate about the same total differential displacement.

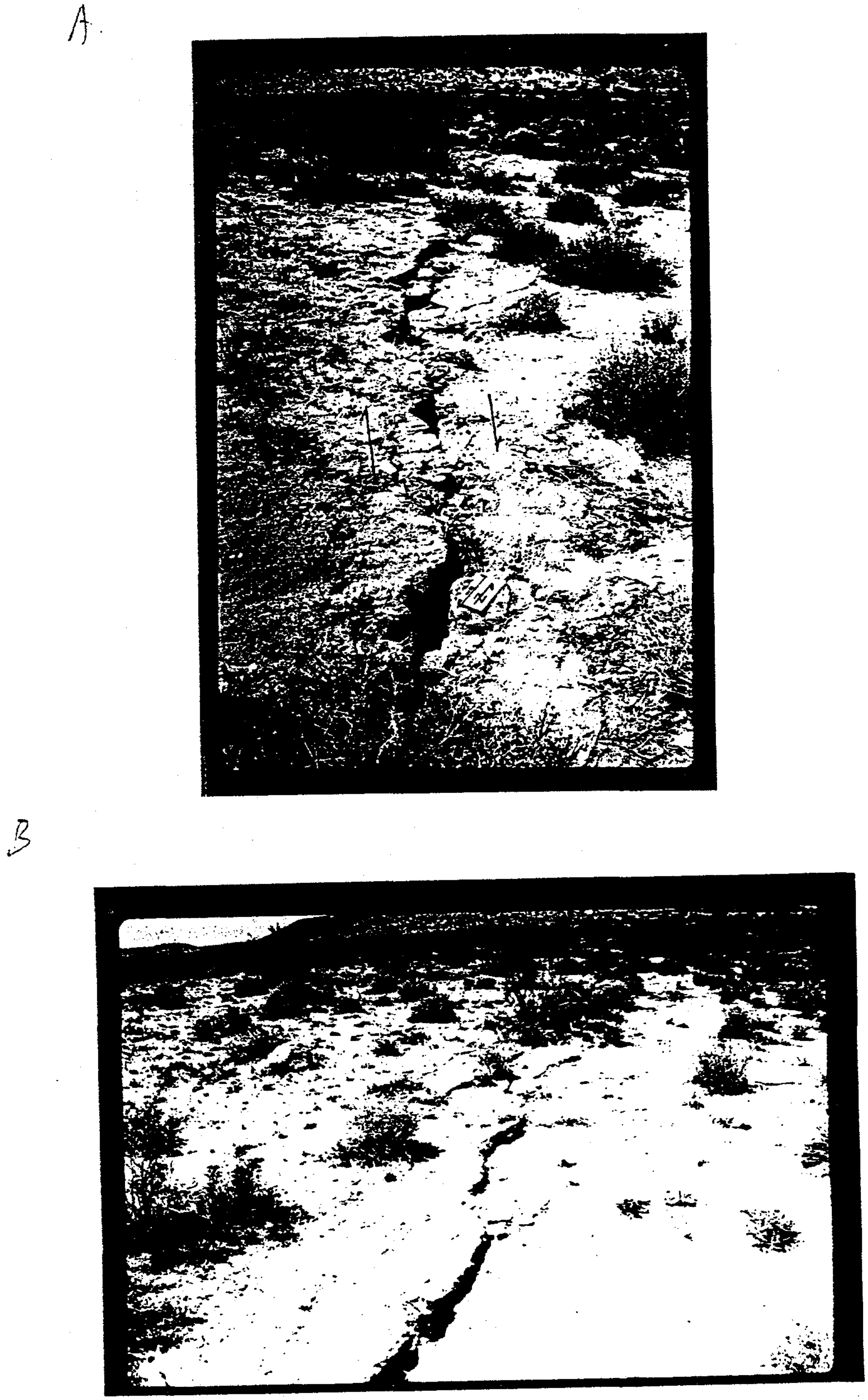

Figure 14. Narrow shear zone bounding SW side of band of shear zones. A. View about N30W at location G, Figure 6 and Figure 7A. The broad shear zone is on the right in the view. Narrow shear zone is essentially a fault, accommodating 1.5 dm right lateral and 1 dm vertical components of differential displacement. B. Oblique view N40W along bounding, narrow shear zone along SW wall of belt of shear zones. Location F, Figure 6 and Figure 7A. In the middle distance is a set of en echelon, or overlapping fractures trending N-S. Right-lateral shift 13cm, opening 3 cm and downthrowing of NE side about 5 cm.

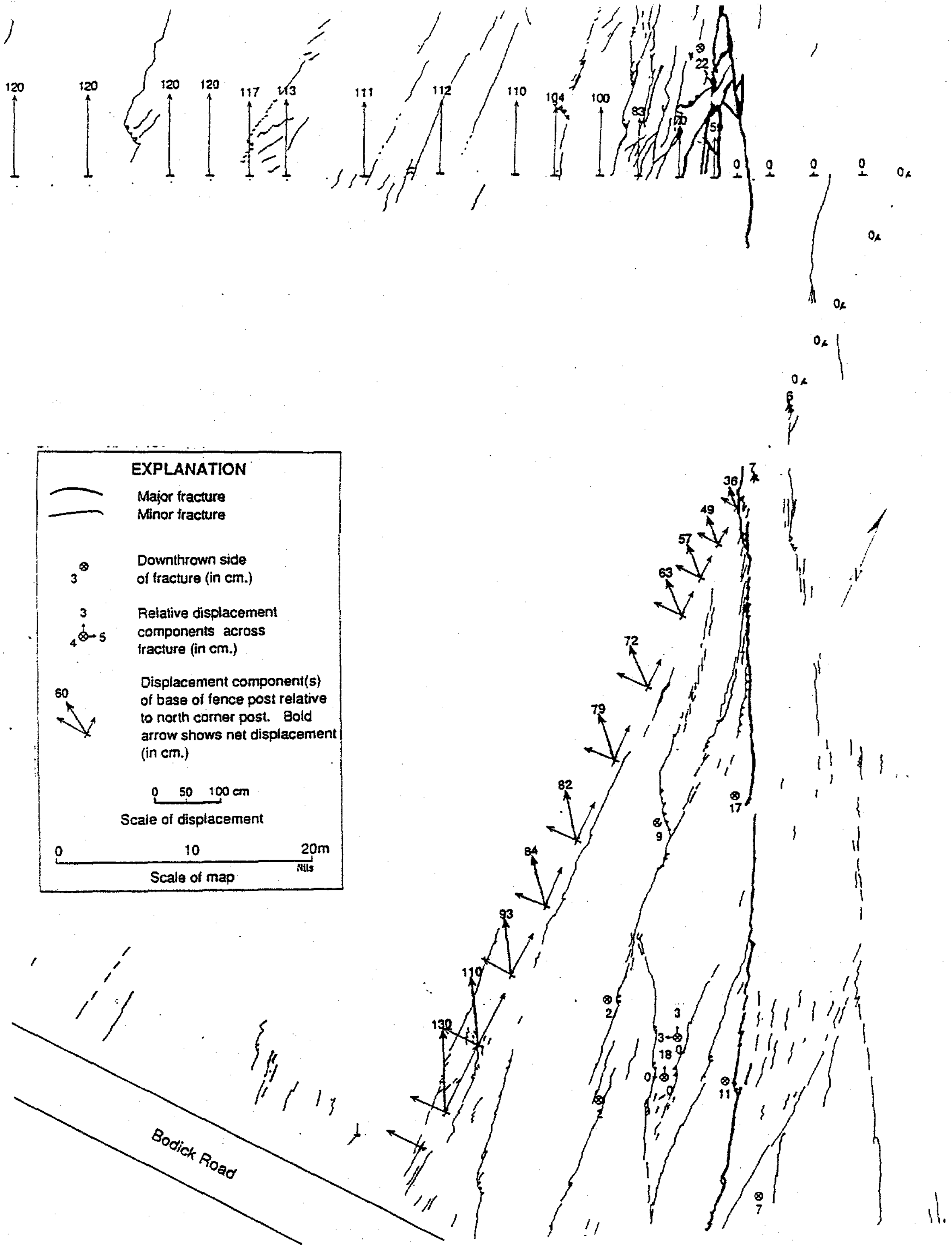

Figure 15. Differential displacements across NE half of belt of shear zones in Two Ranches area as indicated by offset of fence lines. Total displacements shown in N-S fence, NW components shown in SW-NE fence. Most of differential displacement accommodated by shear zones within a few metres of the NE wall of the belt of shear zones.

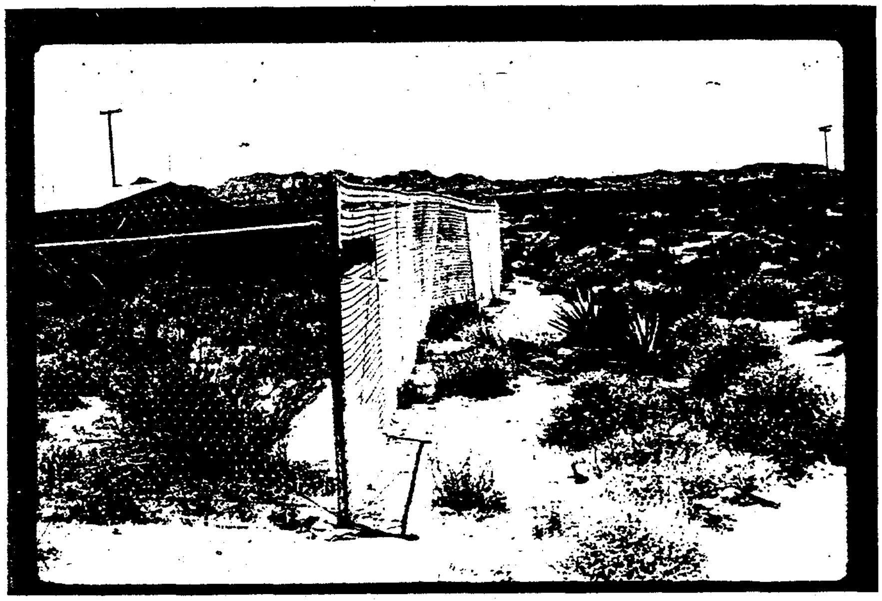

Figure 16. View SW along fence line at SE end of Figure 15, showing large offset (0.6 m) between 5th and 6th fence posts and total offset of 1.2 m across broader zone.

differential displacement recorded by the fence along the NW side of the ranch property. Figure 16 is a view toward the SW, along the fence, and shows the boundary shear zone in mid-view. Only the corner posts and those next to them, in each direction, are tied by horizontal bars; the other posts are free–standing. In the following discussion, we will assume that the total differential displacements are indicated by theoffsets of the fence line along the NW side of the ranch.

As indicated in Figure 15, between the fifth fence post, about 0.5 m NE of the flank, and the sixth fence post, 3 m to the NW, within the shear zone, the right–lateral component of the differential displacement is 0.59 m. Of the two fractures we mapped in this ground (Figure 7), the one bounding the shear zone apparently accommodated most of the offset. In one length of about 6 m, between the sixth and seventh posts, we found three fractures that accommodated an additional 0.11 m of offset, so the net is 0.7 m. The seventh and eighth posts are in ground crossed by three fractures, and the offset increases a further 0.13 m (Figure 15), so the total is 0.83 m. Between the eighth and ninth posts, over a total width of about 12 m, there is only one large fracture and the additional offset is about 0.7 m. The 10th fence post is at the inner boundary of the bounding shear zone and it is offset about 1.04 m. Thus this bounding shear zone, about 12 m wide, accommodated more than half of the total of 1.8 m of shift of the entire belt of shear zones.

Thus, measurements of the fence line indicate that, within the NE third—about 70 m—of the belt of shear zones, the right–lateral component of the total differential displacement was about 1.2 m, or two-thirds of the total for the belt of shear zones. Within a 12 m wide zone along the NE wall fully 1 m of differential displacement occurred in ground that contains seven or eight fractures. Within a very narrow shear zone immediately along the NE wall of the belt, a large fracture, or a fault accommodated one-third of the total differential displacement, 0.6 m.

The narrow zone of intense shearing within about 12 m of the NE wall of the broad shear zone is a commanding structure (Figure 6 and Figure 7). It can hardly be overlooked in the field. If any of the structures in the broad belt were to be identified as "the fault," it would certainly be this structure. It includes a vertical scarp, 2 to 3 dm high, along its outer edge, facing the center of the belt of shear zones (Figure 17B)[9]. Elsewhere, the scarp is bounded by a wedge–shaped mass of loose soil chips (Figure 17A).

The inner edge of the narrow shear zone, along the NE wall of the belt of shear zones, is more irregular, consisting partly of narrow thrust blocks bounded by fractures oriented N–S (Figure 7). The N–S fractures apparently originated as tension cracks and then accommodated left–lateral shearing. Along part of the inner boundary of the narrow shear zone, 14 m from the bounding fractures, are gaping fractures that have accommodated right–lateral offsets. The component of right–lateral differential displacement across this part of the narrow shear zone was about 0.04 m; farther NW it was about 0.1 m.

En Echelon Shear Zones

The NE half of the belt of shear zones at Bodick Road is somewhat complicated because the style of shearing changes within the entire map area, as shown in Figures 7 and 15. At the NW end of the area, the belt of shear zones is bounded in the NE (Figure 7) by a relatively simple shear zone. At the SE end (Figure 15), though, the belt of shear zones is bounded by a set of en echelon, right–lateral shear zone segments, oriented about N.10° W. and stepping left. Along Bodick Road, the NE wall of the belt of shear zones becomes diffuse. Fractures are subparallel to the NE wall, outside the boundary of the bounding shear zone with 6

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[9] The smaller shear zone at the SW wall of the belt also has a scarp facing the center of the belt, so the belt is an extremely shallow graben, with a width to depth ratio of 1000:1.

dm offset (Figure 15). Thus the Bodick Road map area contains a transition between a fully developed, en echelon fracture zone to the SE and a fully developed, long, linear fracture zone to the NW. We traced a zone of left–stepping shear–zone segments for about 300 m SE of Bodick Road, to Shawnee Road, where it again becomes a long, linear shear zone (Figure 5). For about 100 m NW of the map area, the SE wall is a simpler zone of intense shearing.

The shear zones oriented about N.10° W., within the NE third of the belt of shear zones (at K, L and M, Figure 6), appear to be incipient, right–lateral segments forming at the NW end of the en echelon shear zones. Apart from differing in orientation from the bounding shear zone by about 20° clockwise (N30W), they are unremarkable. These shear zones have accommodated only small amounts of right–lateral differential displacements—perhaps up to 1 or 2 dm—making them comparable in this respect to the other narrow shear zones we described above. They generally contain many N–S oriented fractures, which apparently originated as tension cracks, and thrusting occurs at the ends of blocks bounded by N–S fractures, as we have observed elsewhere.

The net shift across the en echelon zone was determined from the section of the fence line oriented N–S (Figure 15) in the SE part of the Bodick Road area. We measured the slack[10] in the fencing between posts and the lateral displacement of fence posts, so that we measured orthogonal components of the displacement vector at each post. The net displacement, about 1.3 m, is roughly the same as the strike shift, 1.2 m, measured along the other alignment of fence posts in the central part of the area, where the en echelon pattern is only starting to develop (Figure 7). Thus, the two different expressions of rupture in a shear zone produced the same net shift. The causes of the change in form of surface rupture is unknown.

LONG, LINEAR BELT OF SHEAR ZONES ALONG EMERSON FAULT ZONE

A second location where we mapped surface rupture is at a site crossed by the Emerson fault zone. The site is at the intersetion of the fault zone with a line of steel towers for electrical transmission. This site should not be confused with another place, about 2 km NW, where the fault zone crosses two more powerlines. The area is in the northern part of the segmented fault zones activated during the Landers earthquake (Figure 1). Farther southeast, the rupture zone becomes complicated by a fascinating system of active ridges, but we will describe that area elsewhere (Fleming and others, in prep.). We selected the powerline site because the rupture zone was simple and straight for at least 2 km to the NW and 1 km to the SE (Figure 18).

Shift on the Emerson fault zone nearly caused collapse of a high–voltage transmission tower because its legs straddled the largest break in the belt of shear zones. Using the distances between the legs of the deformed tower, and the corresponding distances between the legs of a neighboring, undeformed tower, (the sides of both originally measuring about 7.3 to 7.8 m), we calculated that the largest break accommodated 2.7 m of right–lateral differential displacement along, and 2 to 7 cm of dilation normal to the trace of the shear zone within the base of the tower. Actually, we suspect that 2 to 7 cm of dilation is well within the limits of inherent error caused by assuming that the deformed and undeformed towers originally had the same shape at their bases, and so we would have to further suspect that the dilation was not

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[10] The measurement of lateral displacement of the fence posts was simple. One merely establishes the original orientation of the fence line and measures offsets. The measurement of slack is somewhat less straightforward. First, this method works only if the fence line is oriented so that it is becoming slack, and the fence posts are not braced to resist changes of spacing. Second, fences are of course built with a certain amount of slack. We tested the slack of the fence line outside the belt of shear zone to determine thebackground slack. Our measurements indicate about 2 cm of slack in the original fence.

detectable. By sighting along the towers of the powerline we determined that an additional 2.1 dm of right–lateral relative displacement occurred to the SW of the deformed tower. An additional 6 dm of displacement to the NE of the deformed tower accounts for the entire right–lateral component of differential displacement, 3.5 m, accommodated by the belt of shear zones.

The deformed tower is at the middle of the map area showing the powerline shear zone (Figure 19). The belt of shear zones here is about 70 m wide. The entire width is shown in the SE end of the map, whereas only the NE half is shown in the NW end of the map. The ground in this area is sandier and softer than that in the Bodick Road area along the Homestead Valley fault zone, and there was a great deal of disturbance from repair vehicles and visitors to the site. As a result, the tension cracks were not as well preserved here as at the sites at Bodick Road and Happy Trail.

Tension Cracks Within Shear Zone

The same types of structures occur in the broad shear zones at the Bodick Road and the powerline areas. In the powerline area, the broad shear zone is oriented N. 45° to 50° W.. Tension cracks, oriented at clockwise angles from about 30° to 45° (N–S), occur sparsely throughout the width of the broad shear zone (Figure 19), and a few of them have some left–lateral shift. Their relative scarcity, as compared to the Bodick Road area, almost certainly reflects the lower degree of brittleness of the near–surface alluvium and soil in the powerline area. The tension cracks that formed at about 45° to the walls of the broad shear zone (location *E*, Figure 20) seem to reflect only simple shear, without dilation, across a shear zone at depth. Those oriented at 30° (e.g., locations C and *F*, Figure 20 and Figure 21) seem to reflect a combination of shear and dilation, as we discussed for the Bodick Road area.

Narrow Shear Zones

There are a few, narrow, right–lateral shear zones within the broad shear zone in the NW part of the single–tower powerline area (Figure 21). One of these extends about 20 m and trends N. 45° W., about 10 m SW from and parallel to the larger, bounding shear zone to the NE (location C, Figure 21). Three other, nearby shear zones, trending around N. 30° W., extend from the bounding shear zone for about 10 m to 15–20 m, then disappear (location D, Figure 21). In this NW section, tension cracks are lightly scattered over the area, which was not mapped, between the edge of the mapped ground and a bounding, narrow right–lateral shear zone about 40 m to the SW. The narrow shear zone is a continuation of the one mapped in the SE part of the single–tower powerline area (Figure 19), showing that the broad shear zone actually extends through the entire single–tower powerline map area, indeed, continuing to the north and south of the region (Figure 18).

Most of the right–lateral shift was accommodated by narrow shear zones bounding either side of the broad shear zone. The narrow shear zone along the SW wall accommodated about 2 dm of right–lateral and 0 to 10 cm of vertical (downthrown on NE side) relative displacement (Figure 20). For much of its length, it consists of N–S oriented fractures, several meters long. The blocks of ground between the fractures typically end in low thrusts, directed toward the center of the broad shear zone. It is quite analogous to the narrow rupture zone ("mole track") along the SW boundary of the Bodick Road belt of shear zones.

The narrow shear zone (or "mole track") along the NE wall dominates the belt of shear zones. It ranges from perhaps 0.5 m wide, at places in the NW section of its trace (Figure 21), to 10 m wide in the SE section (Figure 20), and it has a beaded, or pinch–and–swell structure, which is particularly noticeable in the NW section. The very narrow segments—the pinches—are a few dm wide; they contain narrower grooves in the ground surface, around one dm deep and wide, along parts of their spans, perhaps representing a fault surface not far below the ground. The broader

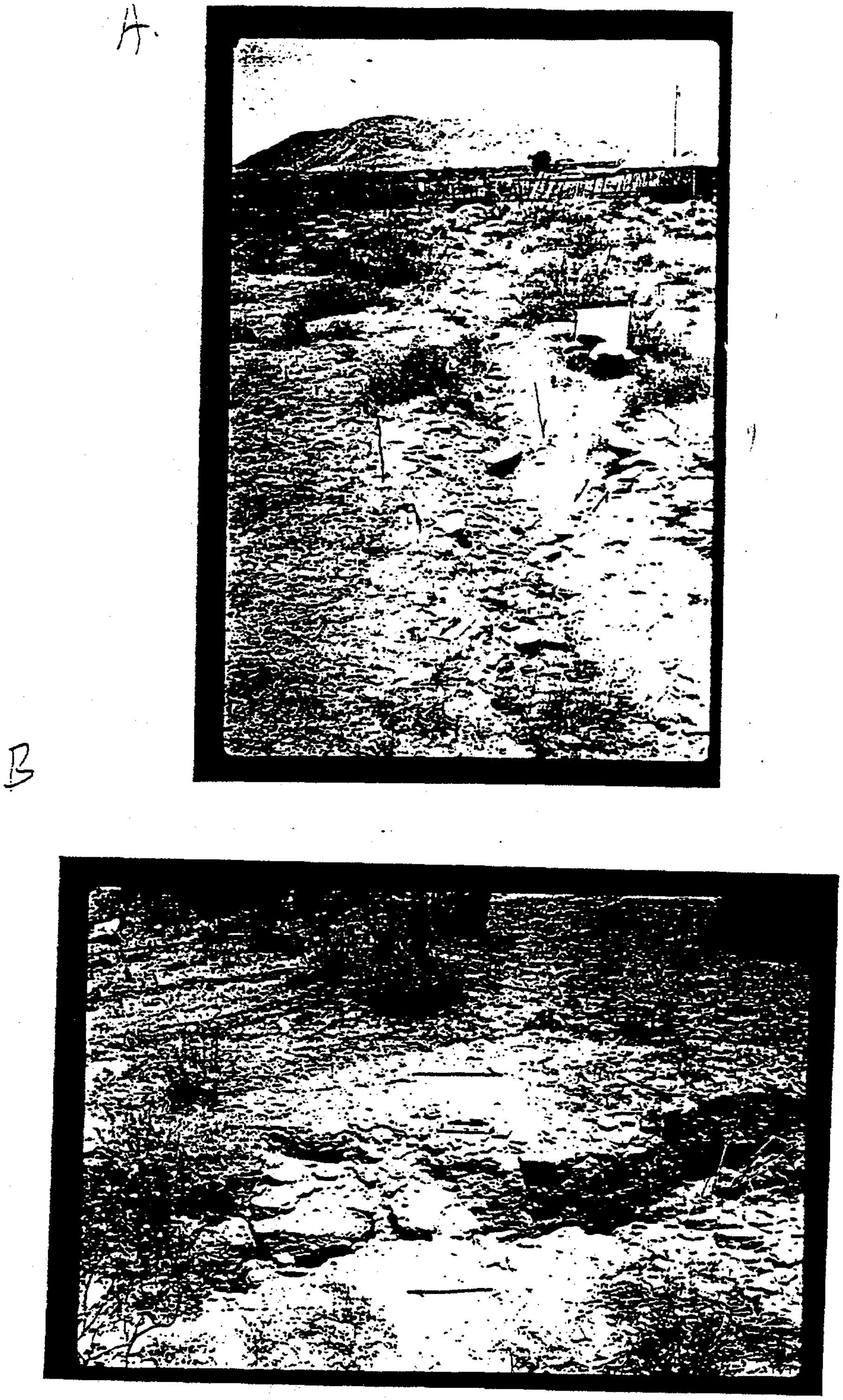

Figure 17. NE wall of belt of shear zones. Fractures here accommodated about 6 dm of right-lateral offset. A. View SE along scarp on NE side of shear zone that forms wall of belt of shear zones. Belt of shear zones to right, unfractured ground to left. N-S tension crack/left-lateral fracture identified with arrows. The scarp here is marked by wedge-shaped mass of loose soil chips (location I, Figure 6 and Figure 7C). In background is ranch and fence shown in Figure 15 and Figure 16. B. View NE of vertical scarp about 4 dm high facing SW at location H, Figure 6 and Figure 7C, at the NE wall of the belt of shear zones at Bodick Road. Scarp defined by zone of subparallel fractures and here is essentially a fault. Small crack, marked c, visible several m NE of belt of shear zones. Small crack shown in map, Figure 7C, loc. H.

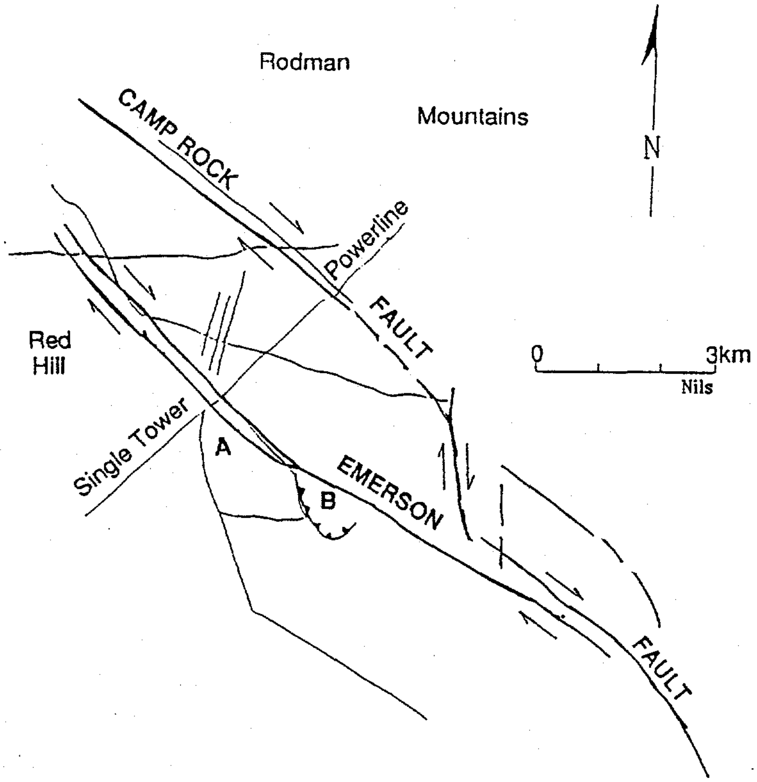

Figure 18. Approximate traces of faults that ruptured in the northern part of the area of the June, 1992 Landers, California, earthquake. Location A is area of detailed study where single tower powerline crosses the Emerson fault zone. Cracks extending about N20E toward the Camp Rock fault zone appear to be part of stepover structure between the two rupture zones.

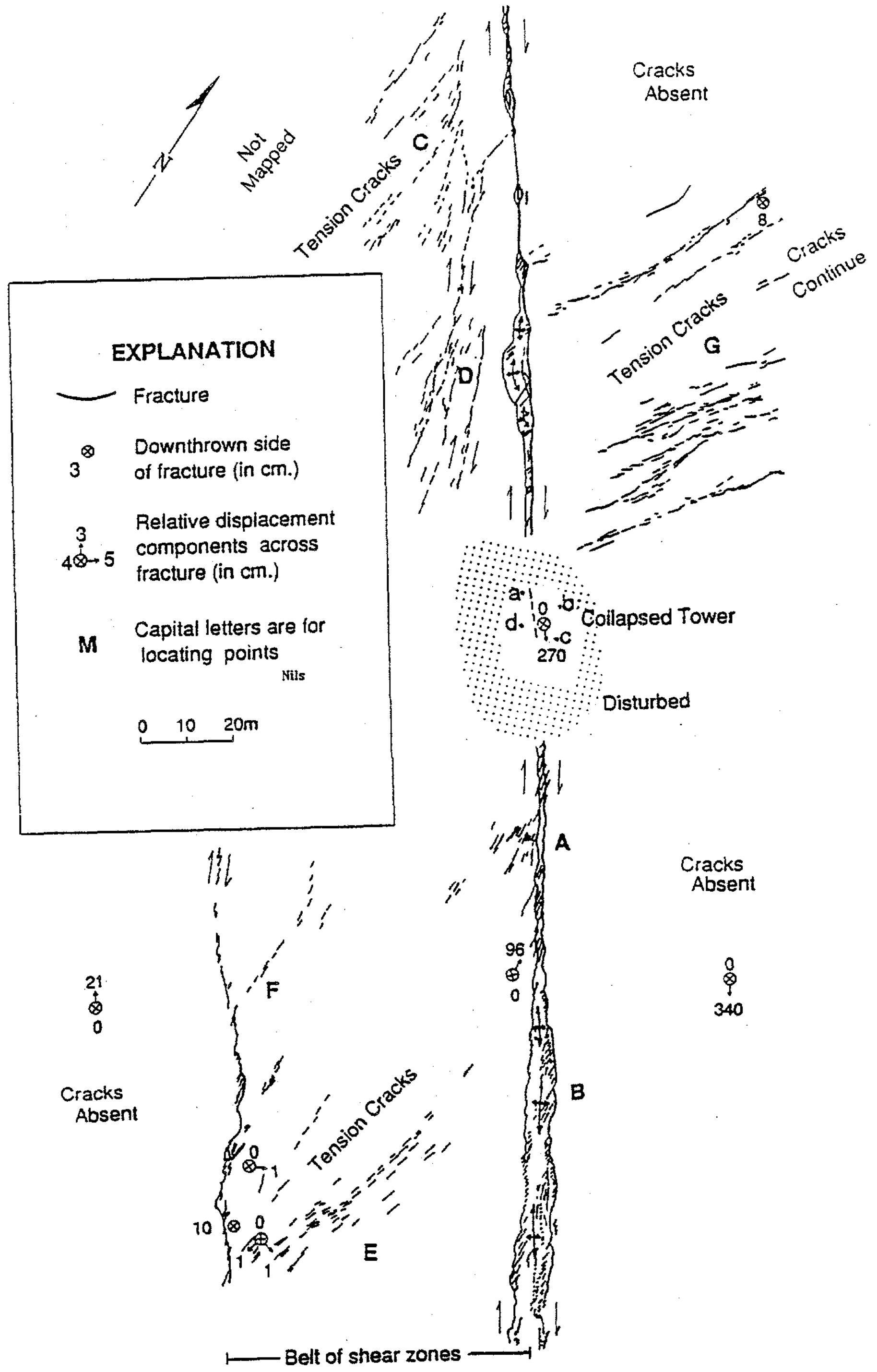

Figure 19. Synoptic map of fractures that define the rupture zone along the Emerson fault where the single-tower powerline crosses the fault (Figure 17). Overall shift across belt about 3.6 m. Belt of shear zones about 60 m wide here (compared to 160 m at Two Ranches). Each side of belt defined by relatively straight, narrow shear zones. Narrow shear zone on right (NE) side accommodated about 2.7 m of right-lateral shifting, according to analysis of deformed legs of tower that straddled this shear zone, shown at midlength of map. Tension cracks within belt of shear zones generally oriented about N-S to N10E, whereas tension cracks outside NE side of belt, which apparently are part of a stepover structure with the Camp Rock fault zone, are oriented about N30E to N40E.

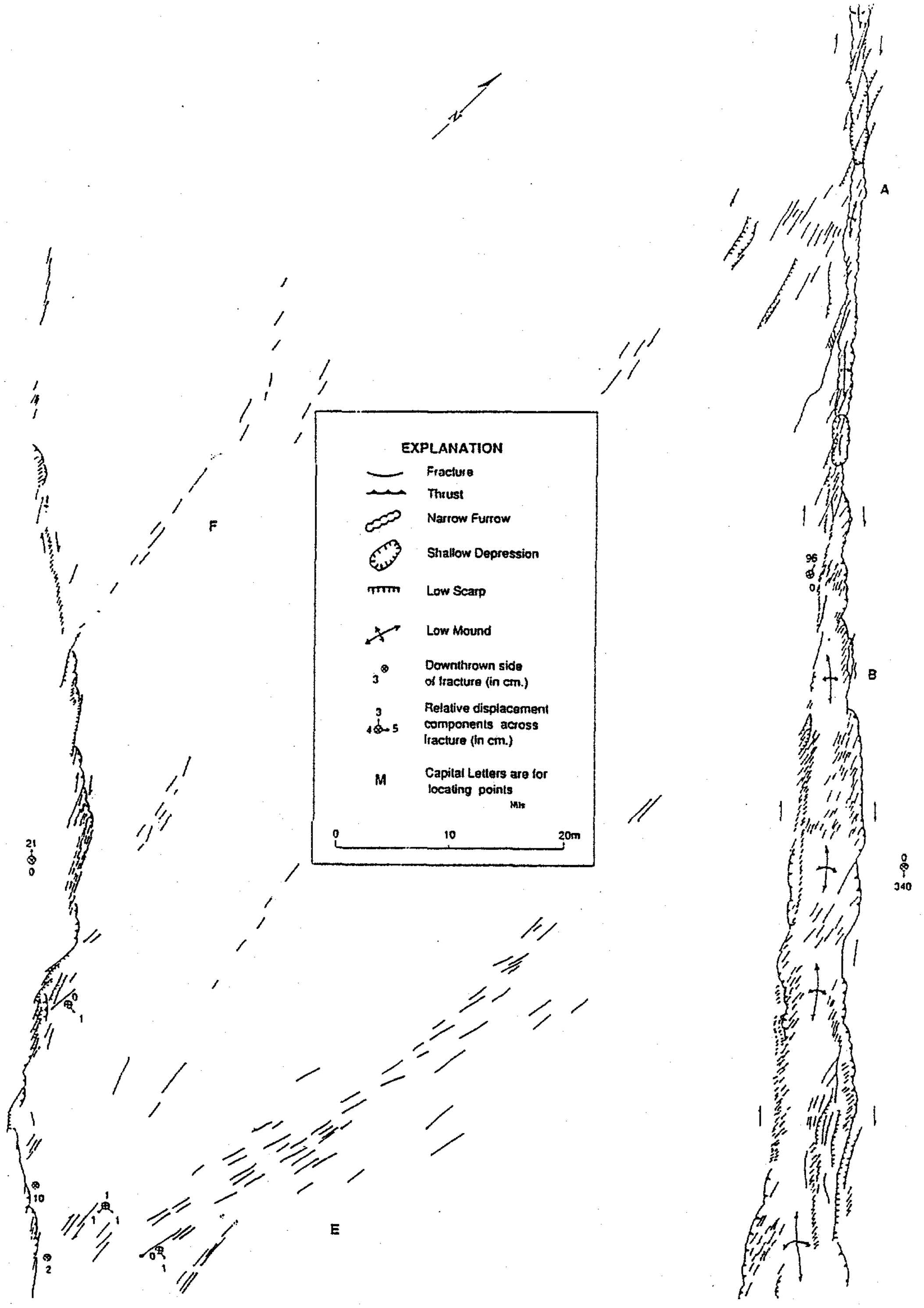

Figure 20. Analytical map of fractures in SE part of single-tower powerline area. NE wall of belt marked by narrow shear zone or "mole track" that broadens from a few dm to 2 m in NW to about 8 m in SE. This narrow shear zone offset the ground about 2.5 m. It is marked by en echelon fractures, thrusting on one or both sides, and series of low domes and shallow basins along its trace. Only south end of SW wall of belt of shear zones was mapped, although it was traced to NW and SE of area mapped, as shown by double lines in Figure 18. The SW wall is also marked by a narrowshear zone, but the shear zone accommodated only about 2 dm of offset, it is irregular, and appears to be composed of en echelon shear zone segments. Shear zone about 0.5 to 3 m wide and dominated by long en echelon fractures, thrusts and occasional right-lateral fractures and narrow bands of en echelon cracks. A few zones of tension cracks, oriented roughly N-S (N15W to N15E), are scattered across the belt of shear zones.

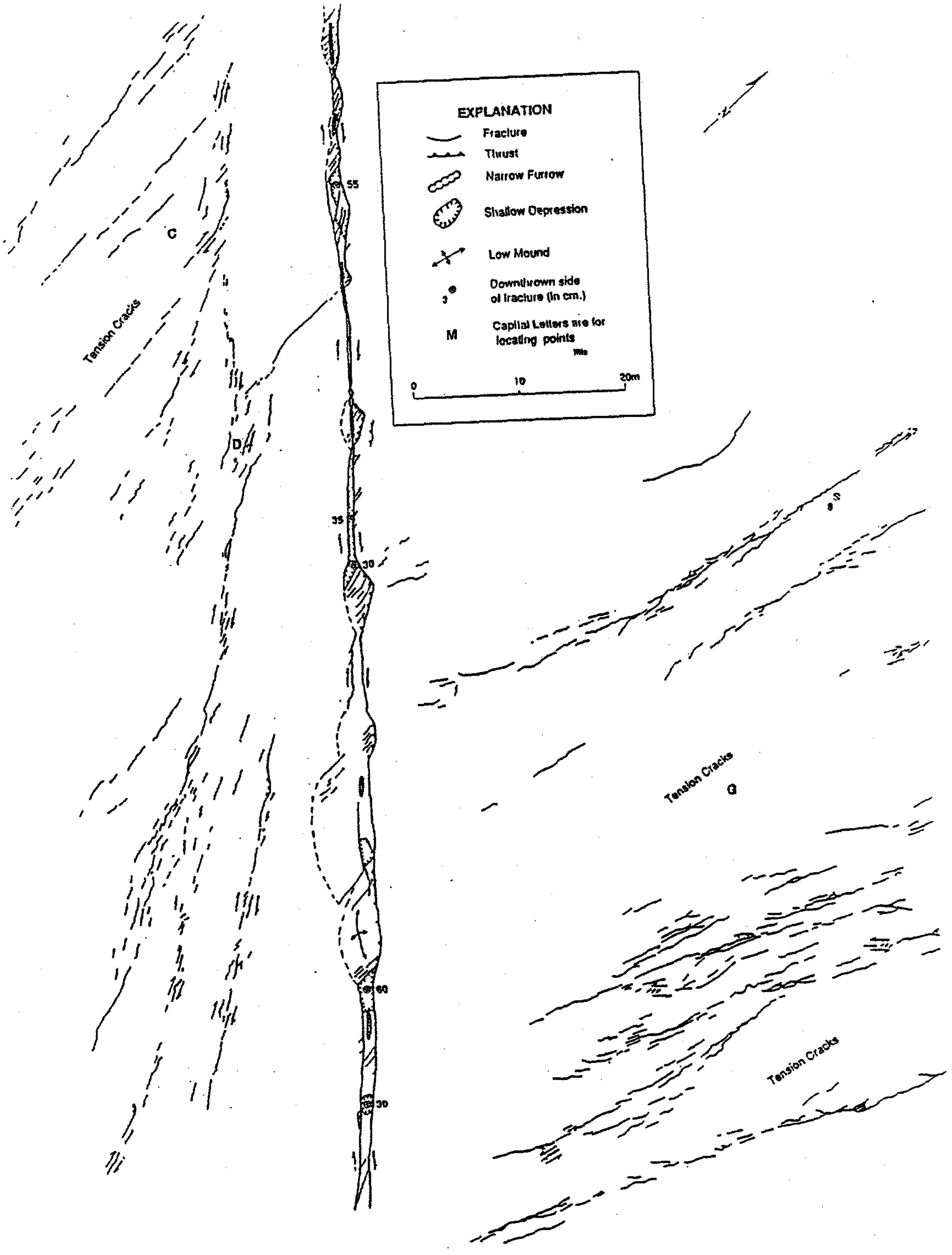

Figure 21. Analytical map of fractures in NW part of single-tower powerline area. Only the ground near the NE wall of the belt was mapped there (Figure 18). Near the NE wall, there are a few narrow zones of right-lateral shearing (C and D) subparallel (inclined at a small clockwise angle) to the walls of the shear zone. The narrow shear zone along the NE wall of belt is a "mole track" that pinches to a width of perhaps 3 dm and swells to a width of 6 m along its length This is the shear zone that offset the ground about 2.5 m. It contains many en echelon fractures and there are thrusts on one or both sides of the zone, and the axis of the shear zone consists of a series of low domes and shallow basins. In a few places there is a very narrow furrow, perhaps marking the trace of a fault below. To the NE of the NE wall of the belt (at G) is a swarm of tension cracks oriented 60 to 70° clockwise from wall of belt. The tension cracks have been traced about 0.5 km to the NE, across the valley. They presumably connect with the Camp Rock fault zone on the NE side of the valley (Figure 18).

segments—the swells—are several meters wide and generally have the kind of internal structure we described in the narrow shear zones at Happy Trail and in the Bodick Road map area. These contain long fractures, oriented at a clockwise angle of about 30° to the trend of the shear zone. The ground has been thrusted at one or both ends of the blocks separated by fractures (Figure 20 and Figure 21). In the NW end of the bounding shear zone in the single–tower powerline area, the thrusting is generally toward the north (Figure 21), whereas in the SE end of that zone, where the narrow zone broadens to about 10 m, the thrusting is in both the north and south directions (Figure 20). Another feature of the narrow shear zone here is that the ground surface is depressed (perhaps up to 2 dm) along some stretches and raised (perhaps an equal amount) along other stretches, so that, along the trend of the narrow shear zone, there will be an elongate basin, then an elongate dome, then an elongate basin, and so forth (Figure 21).

Tension Cracks In Stepover

For the most part, the fractures at the powerline site are the same as at other locations at Landers containing long, linear surface rupture, however, an additional swarm of tension cracks with different orientation occurs outside the belt of shear zones. This swarm of tension cracks occurs in a belt about 50 or 60 m wide, trending N. 20° to 30° E., and extending at least 500 m toward the Camp Rock fault zone (Figure 18 and location G, Figure 21). Although we traced the tension cracks only a few hundred meters across the valley, they probably extend to the Camp Rock fault zone about 1.5 km to the NE. As such, they are an expression of the deformation in the transfer zone, between overlapping segments of the Emerson and Camp Rock fault zones that ruptured during the earthquake. We observed such transfer zones at several other places where fault zones overlap.

The orientations of the tension cracks within the transfer zone are distinctly different, by 20° to 30°, from those of the tension cracks within the broad shear zone along the Emerson fault. The tension cracks in the shear zone are oriented at a clockwise angle of 30° (to as much as 45°) to the walls of the shear zone, whereas those within the transfer zone are typically oriented at a clockwise angle of 60° to 70° to the walls of the shear zone.

An interesting consequence of the two different orientations of tension cracks is the difference in direction of maximum tension within and outside the shear zone. The tension direction was about N. 60° W. within the transfer zone, but about E–W within the broad shear zone. This marked difference in stress state over a relatively short horizontal distance supports our interpretation that the tension cracks within the broad shear zones result from shearing and dilation within a zone of *localized* shearing at depth; because the shearing and dilation are localized below, the stresses generated in the near–surface materials are localized. In contrast, the stresses responsible for the fractures within the transfer zone are a result of *interaction between two relatively widely spaced fault zones*, in this case interacting across the valley (David Pollard, personal communication, 1992). David Pollard and his students (e.g., Segall and Pollard, 1983b; Martel, Pollard and Segall, 1988; Martel and Pollard, 1989) have clearly illustrated and documented the formation of tension cracks in similar transfer zones between interacting faulted joints in granitic rocks. Interestingly, they observe that the traces of tension cracks form at 50° to 90°, perhaps with a strong tendency for angles of 60° to 70°, counterclockwise with respect to traces of parallel, overlapping, bounding, left–lateral, faulted joints. The angle for bounding right–lateral fault zones at the single–tower powerline site is equivalent: 60 to 70° clockwise.

The presence of tension cracks outside the broad shear zone at the single–tower powerline area is understood to be a minor complication, simply a reflection of the transfer of displacement across an area between overlapping fault zones. The conceptual model of a broad shear zone containing superimposed narrow shear zones and collectively defining a belt of shear zones

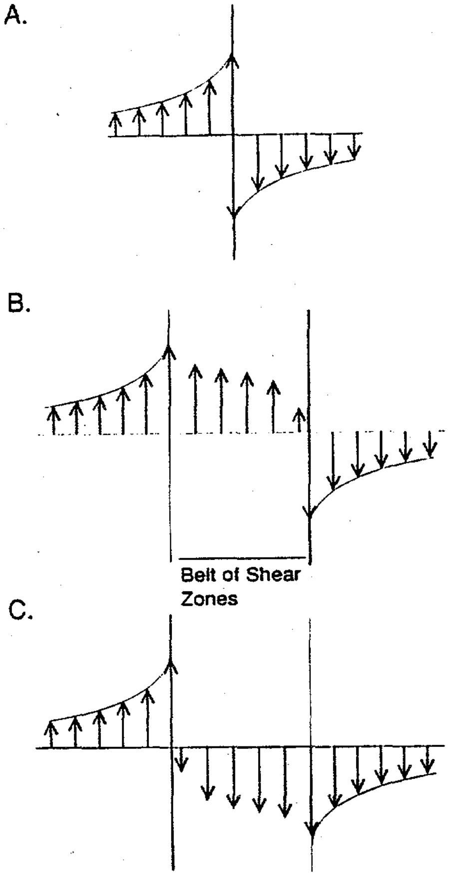

Figure 22. Idealized distributions of relative coseismic shift distributed at the ground surface in the vicinity of a fault or a belt of shear zones. A. Distribution of coseismic shift generally assumed in the vicinity of a ruptured fault, with shift dying out on either side of the fault trace. B. Distribution of coseismic shift assumed to occur in the vicinity of a belt of shear zones. Distribution within belt corrsponds to that observed in broad belts at Landers. Largest shift across a narrow shear zone along right wall of belt. Smaller shift across shear zones within belt. Moderate shift across shear zone along left wall of belt. Distribution of shift outside the belt is hypothetical; it was drawn to match that shown in A. We have no measurements. C. Same as B, except narrow shear zone with maximal shift along left wall of belt.

remains as the characterization of the simplest reaches of ground rupture along the fault zones that activated during the Landers earthquake.

DISCUSSION AND CONCLUSIONS

Summary of Observations at Landers

The display of surface ruptures during the Landers earthquake was extraordinary. The combination of large right–lateral shearing and ideal, highly brittle, surficial materials, in an arid, sparsely vegetated, and nearly unpopulated environment cannot be expected to occur often Documentation of a surface rupture could well provide important insights into problems such as siting and design of critical facilities, the nature of rupture during earthquakes in the upper part of the crust, and could possibly even provide further clues to the generation of earthquakes during faulting. Here, we have described our observations of some long, linear fault ruptures to clarify the essential geometric properties of fracturing and processes of faulting near the ground surface.

Our observations have, frankly, astonished us. Rather than well–defined faults represented by displacement discontinuities (Figure 22A), for the most part, we observed broad zones of disruption, which we describe in terms of belts of shear zones that have accommodated widely–differing amounts of shearing. The displacements within the belt are distributed across its expanse (Figure 22B). In a few locations—in bedrock along the Homestead Valley fault zone and granite bedrock 2 km SE of the single–tower powerline area—we did observe fault surfaces. In general, though, in both compact alluvium and unconsolidated alluvium, we observed shear zones. We also repeatedly observed evidence for shearing over broad zones, ranging from 50 to 200 m, closely resembling what we have described herein, in both alluvium and in bedrock. Thus we tentatively conclude that the characteristic long, linear rupture at Landers is not expressed in faulting, but in the formation of shear zones or belts of shear zones. Whether or not these near–surface phenomena are anything more than murky guides to "real" faulting—slip on single surfaces, at depth—remains to be seen.

Previous Observations

Many of the features of belts of shear zones and broad shear zones that we mapped at Landers had not been described in previous accounts of ground rupture during earthquakes. While some of these features been have described incidentally in previous investigations, they certainly have not received the extensive treatment we present here. There are several reasons for the thoroughness of our descriptions, as compared to those previous. One is that most mapping is synoptic; the type of detailed or analytical mapping, such as we performed, is uncommon, and the critical features are visible only in analytical maps. Another is that we have recently focused on relations between shear zones and faults (Aydin and Johnson, 1983; Johnson, in review a,b,c); previous to this, it was unclear why shear zones might be interesting phenomena unto themselves. Probably the most important reason is that the unique combination of favorable conditions at Landers may have produced an unprecedented, spectacular display of the internal structure of shear zones operating near the ground surface during an earthquake. If that is the case, it is not surprising that shear zones and belts of shear zones have been inadequately documented during previous earthquake investigations.

Of course, there is always the risk that our observations are, somehow, a peculiar result of accidental circumstances and that these features have not occurred in previous earthquakes, although previous fragmentary descriptions suggest that this is unlikely (Reid, 1910; Philip and Meghraoui, 1983; Armijo and others, 1989). We have reviewed descriptions of coseismic earthquake fracturing prepared by some prominent observers—

G.K. Gilbert, Andrew Lawson, and F.E. Matthes on parts of the 1906–San Andreas rupture north of San Francisco; Malcolm Clark on the rupture during the 1968 Borrego Peak earthquake; and Robert Brown and George Plafker on the 1972 rupture in Managua, Nicaragua. Our review suggests that shear zones, or parts of shear zones have been widely recognized, but not singled out for particular emphasis as we have done.

During the 1906 San Francisco earthquake, a segment of the San Andreas fault zone at least 300 km long (about four times the length as at Landers) ruptured with differential right–lateral displacements as large as 6.4 m (Gilbert, 1907, p. 5; Lawson, 1908, p. 2). The rupture was along what was called the *fault–trace,* defined as the manifestation of the "intersection of the fault plane or narrow zone with the surface of the ground" (Lawson, 1908, p. 3). In the following quote, Andrew Lawson describes a broad shear zone, about 100 m wide, as well as a narrow shear zone with long, en echelon fractures at an acute clockwise angle to the walls of the shear zone. The zone of most intense rupture, "the fault–trace or rupture plane" occurred on one side or the other of a shear zone:

> ". . . the surface of the ground was torn and heaved in furrow–like ridges. Where the surface consisted of grass sward, this was usually found to be traversed by a network of rupture lines diagonal in their orientation to the general trend of the fault . . . The width of the zone of surface rupturing varied usually from 3 ft up to 50 ft or more. Not uncommonly there were auxiliary cracks either branching from the main fault–trace obliquely for 100 to 300 ft, or lying subparallel to it and not......directly connected to it. Where these auxiliary cracks were features of the fault–trace, the zone of surface disturbance which included them frequently had a width of 300 ft. *The displacement appears thus not always to have been confined to a single line of rupture, but to have been distributed over a zone of varying width.* Generally, however, the greater part of the dislocation within this zone was confined to the main line of rupture, usually marked by a narrow ridge of heaved and torn sod . . . Nearly all attempts at the measurement of the [differential] displacement were concerned with horizontal offsets on fences, roads and other surface structures at the point of their intersection by the principal rupture plane, and ignore for the most part any [differential] displacement that may be distributed on either side of this in the *zone of movement.*" (Lawson, 1908, p. 53; italics ours).

G.K. Gilbert and F.E. Matthes describe the feature we have termed a "narrow shear zone" as follows:

> "The fault trace is itself in some places inconspicuous . . . where one may walk across it without noticing that the ground had been disturbed. Its ordinary phase, however, includes a disruption of the ground suggestive of a huge furrow, consisting of a zone, between rough walls of earth, in which the ground has splintered and the fragments are dislocated and twisted . . . In many places the fault trace sends branching cracks into bordering land, and locally its effect in dislocation is divided among parallel branches . . ." (Gilbert, 1907, p. 5)

> "[In several places in Sonoma and Mendocino Counties] on fairly level ground, where conditions are simplest and no vertical movement is evident, the sod is torn and broken into irregular flakes, twisted out of place and often thrust up against or over each other. The surface is thus disturbed over a narrow belt . . . Within such a belt there is seldom, if ever, a well–defined, continuous, longitudinal crack . . . Rather, there is a marked predominance of diagonal fractures resulting from tensile stresses . . . " (Matthes, in Lawson, 1908, p. 55).

Esper S. Larsen documented a broad shear zone bounded by a narrow shear zone on only one side by surveying a fence on the Call place, a few kilometers NW of Fort Ross (in Lawson, 1908, p. 64). The offsets of the fence were insensible (less than 3 cm) NE of the main rupture, so the main rupture defined the NE wall of the shear zone. The total offset was about 3.6 m (right–lateral), of which about 2.6 m was accommodated along the main rupture, but of which about 1 m was distributed smoothly over 90 m of the width of the shear zone. Between 91 m and 131 m SW of the main rupture, the fence was displaced laterally 10 cm, indicating that the shear zone was between 91 and 131 m wide. The main rupture was a narrow shear zone about 1.5 m wide. Over a horizontal distance of 25 cm within the narrow shear zone, the main rupture itself accommodated about 2.3 m, or three–fifths of the total offset.

G.K. Gilbert (in Lawson, 1908, p. 70) measured the offsets of two fences on a Mr. E.R. Strain's place, west of Woodville, near the head of Bolinas Bay (Gilbert, 1907, p. 6). The southern fence is crossed by "two visible branches of the fault," represented by short, en echelon tension cracks oriented in the usual way. Each of the branches offsets the fence. Gilbert indicates that, on either side of the branches, the fence is straight, meaning that, here, the shear zone is contained between the two branches. Gilbert indicates that "there is more or less diffused shear in the intervening ground" between the two branches, across a zone about 27 m wide. The total offset here is 4.6 m. At a second fence, north of the first, the SW–bounding branch continues, represented by en–echelon tension cracks, and the shear zone continues, but the NE–bounding branch is absent. Here, the SW–branch accommodated 2.6 m of offset; the rest of the shear zone accommodated the additional 3.4 m of total offset. The shear zone, here, is NE of the narrow rupture zone.

The fault rupture was not represented by a broad shear zone at all locations, though. According to Gilbert (in Lawson, 1908, p. 71), thirteen kilometers north of this area, "at Mr. Skinner's place, near Olema, the entire fault is apparently concentrated in a single narrow zone." Even at Mr. Strain's place, a large branch of the fault was merely a slip surface (Gilbert, 1907, p. 6): ". . . the main branch of the fault trace (which is here divided) crosses the foreground from left to right, touching the dissevered ends of the fence, but the shear is at this point so smooth that its surface trace is concealed by the grass." The fence was offset 2.6 m.

Though less obvious, Brown and others (1973) described some evidence for shearing over broad zones in the magnitude 6.2--Managua, Nicaragua earthquake of 1972. Ground rupturing occurred along a fault zone in the city of Managua, and so was manifested conspicuously in man–made structures. What appears to have developed in the Managua earthquake is: 1) a broad belt of rupturing, about 5 km long, consisting of two shorter shear zones that accommodated negligible shift and, 2) two longer narrow shear zones, accommodating 2.6 to 3.8 dm of left–lateral shift, bounding a broad shear zone, 250 to 500 m wide, within which deformation was generally small. At one site, the researchers show the curbing of a street that has been distorted, and state that the amount ofdifferential displacement was 2.8 dm across a zone about 49 m wide (Brown and others, 1972, fig. 6, p. 11). They also describe several fracture zones scattered *between* the two long, left–lateral rupture zones. We note that the faulting in Managua was left lateral and that the fracture zones scattered across what appears to be a shear zone between bounding rupture zones that accommodated *right–lateral* shifting. If so, the fracture zones are analogous to those we described within the shear zone at Happy Trail and the belt of shear zones in the Bodick Road area at Landers.

The magnitude 6.4--Borrego Mountain, California earthquake of 9 April 1968 caused right–lateral differential displacements up to about 4 dm, an order of magnitude smaller than those of the 190--San Francisco and the 1992--Landers earthquakes. Because the ground around Borrego Mountain provided "Stresscoats" that ranged from fairly good to excellent, the patterns of guide fractures were highly developed at least locally. According to Malcolm Clark (1972, p. 59), most of the rupture zone at Borrego Mountain consisted of en echelon fractures, ranging in length from a few meters to hundreds of meters, occupying a belt ranging in width from 1 m to 100 m. Parts of the rupture zone consisted of two or more distinct breaks within a zone as wide as 100 m, but most consisted of only one, distinct break. Even in the wide rupture zones, most of the differential displacement occurred within narrower belts, generally those less than 20 m wide. According to Clark, ". . . a belt of fractures developed on one side or the other of the principal fractures at different places along the rupture," (Clark, 1972, p. 72).

Discussion of Itemized Conclusions

A clear understanding of the distinctions between *shear zones* and *faults*, *tension cracks* and *faults*, and *belts of shear zones* and *fault zones*, and recognition of the implications of *guide fractures*, *compound fractures* and *complex fractures* are required to decipher the kinematics of surface rupture produced by an earthquake. These concepts, combined with mapping at a scale that shows fractures in their true positions, sizes and shapes (analytical, not synoptic mapping), permit a thorough evaluation of coseismic surface rupture along fault zones. With these definitions and concepts in mind, we have described surface rupture along long, linear traces of faults produced by the Landers earthquake. On the basis of these descriptions, in addition to those at Loma Prieta (Aydin and others, 1992; in review; Martosudarmo and Johnson, in review; Johnson and Fleming, in review), we draw the following conclusions about *long, linear* belts of shear zones:

(1). Earthquake faulting is expressed at the ground surface as shear zones, if not generally, then very commonly. We are suggesting that Landers–type fracturing within shear zones is a product of coseismic surface rupture. Such shear zones were previously obscure to us for several reasons: the shearing was too small; the surficial materials were insufficiently brittle, (ratio of fracture toughness to elasticity modulus too high); structures with high anisotropy, such as roads and buildings deflected, displaced, redirected or concentrated the deformation; or the localized deformation was so large that an associated, mild, broad shear zone was overlooked. A very important reason that shear zones have been overlooked is that we associated most earthquakes with *faults* and had erroneous preconceptions about how faults should appear in the field. We have learned to expect an earthquake to produce deformation that, if not concentrated on a single surface, is at least concentrated in a narrow shear zone—variously called a "mole track," a furrow, or a rift—that we can translate directly into the surface expression of a fault at depth. The shear zones we described at Landers—one along the Homestead Valley fault zone and another along the Emerson fault zone—contained, scattered across their widths, tension cracks and, in some places, small strike–slip fractures that reflect general shearing at depth across a broad zone.

The tension cracks and strike–slip fractures, however, are merely guide structures. Other structures, or simply distributed differential displacements—strain and rotation—could be guides to the deeper–seated shearing that we associate with a shear zone. Indeed, the distortion of fence lines over a broad zone is the primary evidence for a belt of shearing along the San Andreas during the 1906 earthquake. Fracturing, however, can be more sensitive to shearing than is the distortion of fence lines. In the Bodick Road area at Landers, tension cracks, and even narrow shear zones, occurred within the central part of the broad shear zone, reflecting the mild shearing. Because the offset in the fence line in that area (as determined by the misalignment of fence posts) was small enough to be attributable to the fence's construction, though, we could not use the fence line to detect the small amounts of shearing required for the fracturing. Yet we knew from the position, type, orientation and kinematics of the fractures that shear had occurred. In contrast, along the San Andreas in 1906, the ground apparently was so ductile that deformation of fence lines and other structures occcurred in measureable amounts without formation of cracks.

(2). Earthquake faulting occurs within a belt of shear zones, after the belt has formed. The belt of shear zones may contain either a single shear zone, or a broad zone and one, or more, narrow zones of more highly concentrated shearing. It follows, of course, that belts of shear zones may well include complexities that we do not recognize and, perhaps, do not exist in the long, linear belts that we have examined. It also follows, though, that belts of shear zones may be simpler than those we mapped at Landers. A shear zone might, in principle, occur alone, so one should not necessarily expect to see a narrow zone of shearing where earthquake rupture breaks through to the ground surface. Indeed, we suggest elsewhere (Johnson and Fleming, in review) that, during the 1989 Loma Prieta earthquake, the earthquake rupture was expressed largely in a broad zone of shearing along Summit Ridge, which produced tension cracks bounding blocks that rotated to produce the left–lateral fractures which characterized the fracturing there. The same pattern of fracturing apparently occurred in 1906 at Loma Prieta during the San Francisco earthquake. The offsets on right–lateral faults or narrow shear zones at Loma Prieta were small in 1989, on the order of 0.1 or 0.2 m, whereas the offset across the broad shear zone along Summit Ridge appears to have been 1 or even 2 m.

Where faulting is associated with the formation of a shear zone or belt of shear zones, the faulting occurs late in the development of the shear zone. That the faulting occurs after the formation of a shear zone is a matter of observation and logic: At Landers and Loma Prieta, some belts of shear zones occur without faults. Where the sequence has been documented in detail, as at Happy Trail, the fault cross cuts and therefore postdates the formation of other structures within the narrow shear zones. Everywhere at Landers where there is a fault, though, it occurs within a shear zone or a belt of shear zones. It follows, therefore, that the faulting occurs after a shear zone or a belt of shear zones forms.

(3). One or both walls of the belt of shear zones might be loci of narrow zones of concentrated shearing. The statement that one, or both, sides of a belt of shear zones may be bounded by zones of concentrated shearing is a statement of observation. At Landers, both sides of the two shear zones described herein, as well as the Johnson Valley belt of shear zones near Kickapoo Road, are defined by narrow zones of higher shearing. Indeed, in the first two cases the NE side was the locus of two–thirds to three–quarters of the right–lateral shift accommodated by the entire shear zone. Descriptions by Brown and others (1973) of faulting and deformation of man–made structures at Managua, Nicaragua, suggest zones of intense shearing on both sides of a broad shear zone. According to G.K. Gilbert's descriptions of rupturing in 1906 along the San Andreas fault zone north of San Francisco, there may be one or two zones of major rupture bounding a shear zone.

(4). One narrow shear zone, which occurs at one side of the belt of shear zones, may accommodate most of the shearing. The conclusion has been reported for nearly all earthquake ruptures. The distorted fence described by F.E. Matthes shows a broad zone of relatively uniform shearing, bounded on one side by a very narrow zone of intense shearing. This assumption may be related to Atilla Aydin's observation that slip surfaces in porous sandstone occur at the edges of zones of deformation bands in the sandstone (Aydin and Johnson, 1978, 1983). We do not know why this happens, however.

(5). Deformation within shear zones includes both simple shearing and dilation. The orientations of tension cracks within the broad shear zones at Landers suggest a shear zone at some depth below a brittle crust. The orientations could be produced by a combination of shearing and dilation within the shear zone at depth. Indeed, such a shear zone could account for the markedly different orientations of tension cracks inside and outside the broad shear zone in the single–tower powerline map area along the Emerson fault.

(6). Shearing can be transferred from one belt of shear zones to another through stepover or transfer zones. The deformation that occurs within a shear zone is distinctly different from that occurring within a *transfer zone*, between two fault segments, or between two shear–zone segments that are overlapping, arranged en echelon, and stepping. In the single–tower powerline area there is a belt of tension cracks oriented about N.20° E. that extends from near the NE wall of the belt of shear zones toward the ruptured segment of another fault zone, on the northeastern side of the valley. The two faults connect over a broad overlap zone. The right–lateral differential displacement is transferred across the valley, partly through the tension cracks, much as described in fault zones in granite by Segall and Pollard (1983), Martel, Pollard and Segall (1988), and Martel and Pollard (1989). About 1 to 3 km south of the single-tower powerline area, there are right–lateral faults accommodating part of the transfer. These faults, extending diagonally between the Camp Rock and Emerson rupture zones, apparently participated in the transfer in the same way that duplex structures accommodate transfer between two stepping faults (e.g., Cruikshank and others, 1991b).

(7). Fault rupture zones should be described. One reason we are publishing this paper as soon as possible, is to suggest how ground rupture might be described so that we can thoroughly document the character of the surficial fracturing before the record has vanished. In describing the fault rupturing at Landers, we should use terms, diagrams, and maps that, as clearly as possible, portray the actual structures there, rather than terms, cartoons, spot measurements, and map symbols that merely reflect our preconceptions of faulting. We should use extreme care in describing these beautifully displayed structures that have inspired our admiration and wonder. As Ken Lajoie said in the field, "Superstition Hills was a geophysicists' earthquake. Landers is a geologist's earthquake."

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