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Shear Zones Formed along Long, Straight Traces of Fault Zones during the 28 June 1992 Landers, California, Earthquake

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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 80 km. The offsets were accommodated generally not by faults—distinct slip surfaces—but rather by *shear zones*, tabular bands of localized shearing. Along simple 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 clearly defined, 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 meters 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. Although these probably are guides to right-lateral fault segments below, the surface rupturing during the earthquake is characterized not by faulting, but by the formation of shear zones at various scales.

Introduction

The most spectacular ground rupturing of any U.S. earthquake yet in this century was produced by the 28 June 1992 M 7.5 earthquake at Landers, California, about 10 km north of Yucca Valley, California (Fig. 1). The ground rupturing was dominated by right-lateral shearing, extended over segments of at least four distinct fault zones, arranged broadly en-echelon and connected through wide step-overs by right-lateral shear zones and tension cracks. The total length of the surface rupture was about 80 km.

The basic structure of the surface rupture at Landers is a narrow shear zone rather than a fault. Whereas a fault is a fracture across which differential displacement is discontinuous (Reid *et al.*, 1913), a shear zone is a tabular zone within which shearing is concentrated but distributed. The differential displacement changes continuously within a shear zone.

Of special interest at Landers is the arrangement of narrow shear zones in broad belts (Fig. 2). 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, with flank faults bounding major landslide masses, and with brittle fracturing sequences in laboratory specimens, will likely recognize the individual narrow shear zones. The belts of narrow shear zones, however, appear to have been undocumented heretofore.

We are documenting belts of shear zones because the way the ground ruptures at the surface may well reflect the way it ruptures in the subsurface. If the shear zones and belts of shear zones we describe herein extend to significant depths, they may be relevant to the mechanics of earthquake rupture along faults at depth. Also, the belts should be documented because they have a bearing on earthquake hazards to engineering structures such as nuclear power plants and dams, and to critical facilities such as schools, hospitals, and fire departments. The great widths of the belts are relevant to California's Alquist–Priolo Act, which is concerned with "setbacks," from active faults of houses, vital utilities, and other structures.

Since the narrow shear zone is the basic element within a belt of shear zones, we begin by describing an example of a narrow shear zone.

Happy Trail Shear Zone

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. A particularly clear example of the internal structure of a narrow shear zone is in the eastern third of the Johnson Valley belt of shear zones, about 100 m south of Happy Trail in Landers. Figure 3a is a view north, along 30 or 40 m of the SW flank of the Happy Trail shear zone, where the shear zone passes through a dirt road. 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 decimetres. The walls of the shear zone (marked roughly by arrows in Fig. 3a) are oriented about N30°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 metres 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 consistent.

The en-echelon fractures started as tension cracks, as indicated by the highly irregular, interlocking traces, in combination with the diagnostic observation that some of the fractures in this set have accommodated opening, but no shear. For example, in a plan view of two of the N–S fractures (Fig. 3b), 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) accommodated left-lateral differential displacement. Its highly irregular trace reflects its tensile origin and the offset reflects the subsequent left-lateral shearing. We call this type of fracture a complex fracture. Individual straight segments of this fracture, oriented roughly N5°W, are open about 2 cm; segments oriented about N30°E are closed. Thus the net differential displacement with respect to ground on the right was about 2 cm in the S30°W direction. Presumably, the complex fracture opened similarly to the fracture on the left and then sheared.

According to our analysis of the formation of left-lateral fractures of this type in a shear zone in the Summit Ridge area of Loma Prieta (Johnson and Fleming, 1993), 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

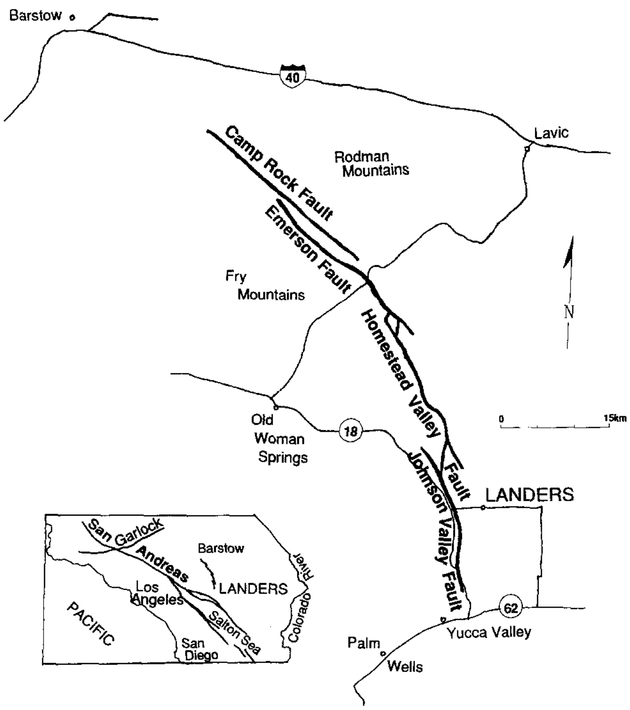

Figure 1. Location map, showing en-echelon fault zones, the Camp Rock and Emerson fault zones in the north, and the Homestead Valley and Johnson Valley fault zones in the south that ruptured during the 1992 Landers, California, earthquake. Epicenter of mainshock was near Landers. Inset figure identifies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

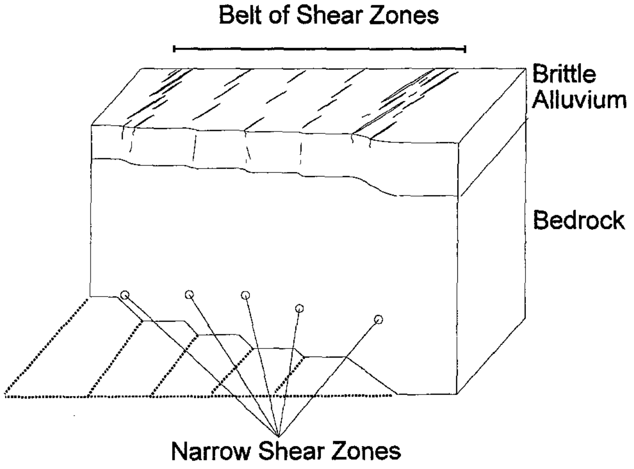

Figure 2. Idealization of a belt of shear zones of the type recognized at Landers. The entire width of the belt consists of a zone of mild shearing which is responsible for broadly distributed tension cracks oriented N–S. Within the belt, though, are narrower shear zones that accomplish most of the shearing across the belt. One of the bounding narrow shear zones, at an outer wall of the belt, accommodates two-thirds to four-fifths of the total shearing of the belt.

physical properties of the ground being sheared, and immediately begin to act as discontinuities bounding rectangular elements of ground. The rectangular elements rotate in a clockwise sense as a result of right-lateral shear, and differential displacement between adjacent elements produces the left-lateral offsets. Furthermore, as the elements rotate, they are jammed against the ground on either side of the shear zone, producing small thrust faults and buckles (Fig. 3a). These structures give rise to the forms called "mole tracks" in descriptions of many rupture zones (e.g., Armijo *et al.*, 1989, p. 2795; Brown *et al.*, 1967; Wallace, 1990; Clark, 1972).

Within the Happy Trail shear zone there is a very narrow, 0.1- to 0.5-m-wide, right-lateral shear zone that represents more intense shearing locally (small arrows in upper right part of Fig. 3a). The narrower shear zone itself is composed, in part, of short en-echelon tension cracks, stepping left and defining a zone 0.1- to 0.5-m wide. 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 at

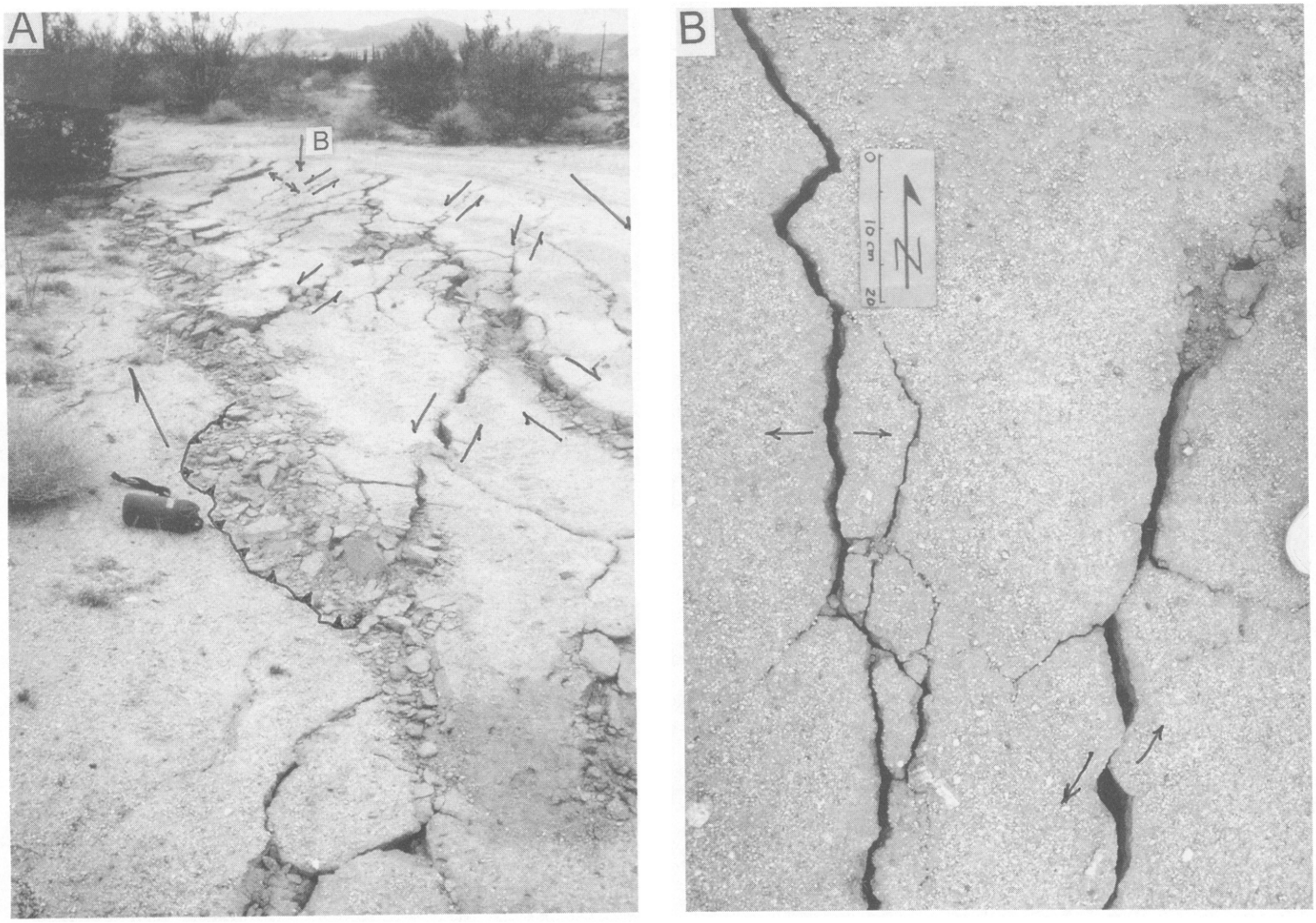

Figure 3. A narrow shear zone, the Happy Trail shear zone, within the Johnson Valley belt of shear zones. (a) View N15°W diagonally from the SW side to the NE side of shear zone. Width of shear zone, about 4 m, indicated by right-lateral arrows on far left and far right of photo. The SW wall of shear zone in foreground. En-echelon cracks oriented N–S about 20° clockwise from view. Most of them have been transformed into left-lateral fractures, as indicated by arrows. Thrusts (one shown) all along this 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 represented by piles of soil chips. (b) Plan view of a left-lateral fracture and a tension crack. 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.

a later stage in the development of the Happy Trail shear zone. It may be a guide to a fault within the shear zone below.

The Happy Trail shear zone therefore illustrates superbly the complex, but quite understandable, internal structure of a narrow shear zone. The sequence of events we can identify is as follows. (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 and, perhaps, further opening across the tension cracks. Simultaneous rotation of blocks bounded by complex fractures and formation of thrusts at ends of blocks. Additional tension cracks probably form even as blocks rotate. (3) Formation of much narrower, right-lateral shear zone within Happy Trail shear zone, containing more intense en-echelon cracking, and offsetting earlier-formed complex fractures.

Rupturing on Homestead Valley Fault Zone

Now we will describe the kind of rupture zone that characterizes long, straight traces of fault zones at Landers. Along all of these we typically observed a broad belt of shear zones, on the order of 50- to 200-m wide, within which all the ground had been sheared, but some parts much more than others. Elsewhere, we have described examples of the rupture zones in five areas along the Johnson Valley, Kickapoo step-over, Homestead Valley, and Emerson faults (Johnson *et al.*, 1993). Here we describe the belt along the Homestead Valley fault zone, at Bodick Road between Acoma Trail and Shawnee Road (Fig. 4). The belt extends along strike for more than a kilometer NW and SE of the area we mapped. The NW extension is largely in bedrock. We selected this belt because it shows most of the characteristics of belts at Landers. It has a well-developed broad shear zone.

Broad Shear Zone

The belt of shear zones 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. The trend of the belt is about N30°W.

Tension cracks occur throughout the width of the belt of shear zones. They are notably absent in ground on either side of the belt. The cracks are remarkably narrow for their lengths, with length-to-aperture ratios of 500 to 1000. Although variable, their apertures are generally a few millimeters to perhaps 1 cm. Individual fractures can be traced for 1 to perhaps 10 m. They have rough walls—characteristic of tensile failure—and their traces are extremely irregular (e.g., Fig. 3b), but their average direction is remarkably consistent throughout the shear zone. Characteristically, the orientation of tension cracks throughout the area is N–S (Fig. 5). The tension cracks are most common in a belt parallel to the SW edge of the broad shear zone and in a wedge-shaped area near mid-width in the shear zone.

The widespread distribution of the tension cracks throughout the broad shear zone, and their absence in ground on either side, indicates that the ground within the shear zone was subjected to localized deformation vis-à-vis the ground on either side of the shear zone. The cause for the localization is unknown. The orientation of the tension cracks is N–S, regardless of the proximity of oblique narrow shear zones within the belt.

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 most of them on the map (Fig. 5), although 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 resemble the actual fractures (e.g., see Johnson *et al.*, 1993; Figure 9a). They are left lateral (and dilational)

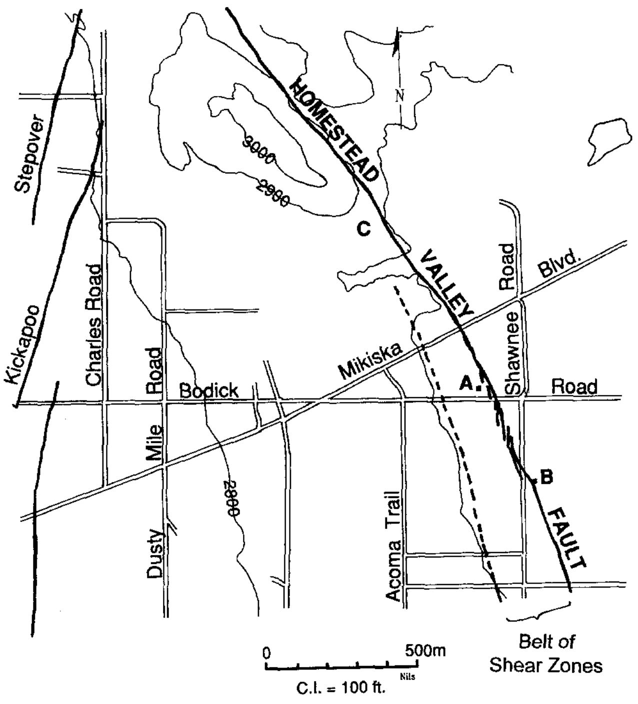

Figure 4. Approximate locations of narrow shear zones bounding walls of belt of shear zones along Homestead Valley fault zone. Location of shear zone on NE wall well known. Location of shear zone on SW wall only approximate in most places. Width unknown at C. Detailed maps made at A. Shear zone breaks down into left-stepping en-echelon shear zone segments between A and B.

and formed by first dilation and then left–lateral slip (or perhaps a combination of left–lateral slip and further dilation) like those in the Happy Trail shear zone (Fig. 3b).

Thus, as shearing began at Bodick Road, 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 maximum tension within the shear zone 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, 1993). The primary fractures in the broad shear zone, then, are the tension cracks, not the small left-lateral fractures.

Shear Zone Model. The deformation within the belt responsible for the tension cracks was not pure shear 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 have been 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 (Cruikshank *et al.*, 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 (Fig. 6a) 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 interpretation of a single fault at depth (e.g., Reid, 1910; Tchalenko and Ambraseys, 1970). Our observations that closely tie faults to shear zones (Aydin and Johnson, 1978, 1983; Johnson and Fleming, 1993; Johnson, 1994a, b, c) have made us positively disposed toward shear zones at Landers. According to the conceptual model (Fig. 6), a combination of shearing and dilation in a shear zone at depth produces 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. In this way we can explain the orientation of the tension cracks.

In summary, what we suggest is that the combination of pure shear and dilation normal to a broad shear zone at depth is responsible for the stress state and the resulting orientations of tension cracks 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 a shear zone. While clearly beyond the scope of our observational study of surface fracturing, this is an interesting question (Johnson, 1994a, b, c).

Internal Narrow Shear Zones

Within the broad belt are several narrow shear zones. They are 3- to 10-m wide and closely resemble the one at Happy Trail. A narrow, right-lateral shear zone near mid-width of the belt (loc. C, Fig. 5) accommodated 5 to 8.5 cm of right-lateral shift of the fence line at the SE end of the mapped area, so it accommodated a small part of the 1.8 m of right-lateral shift across the entire

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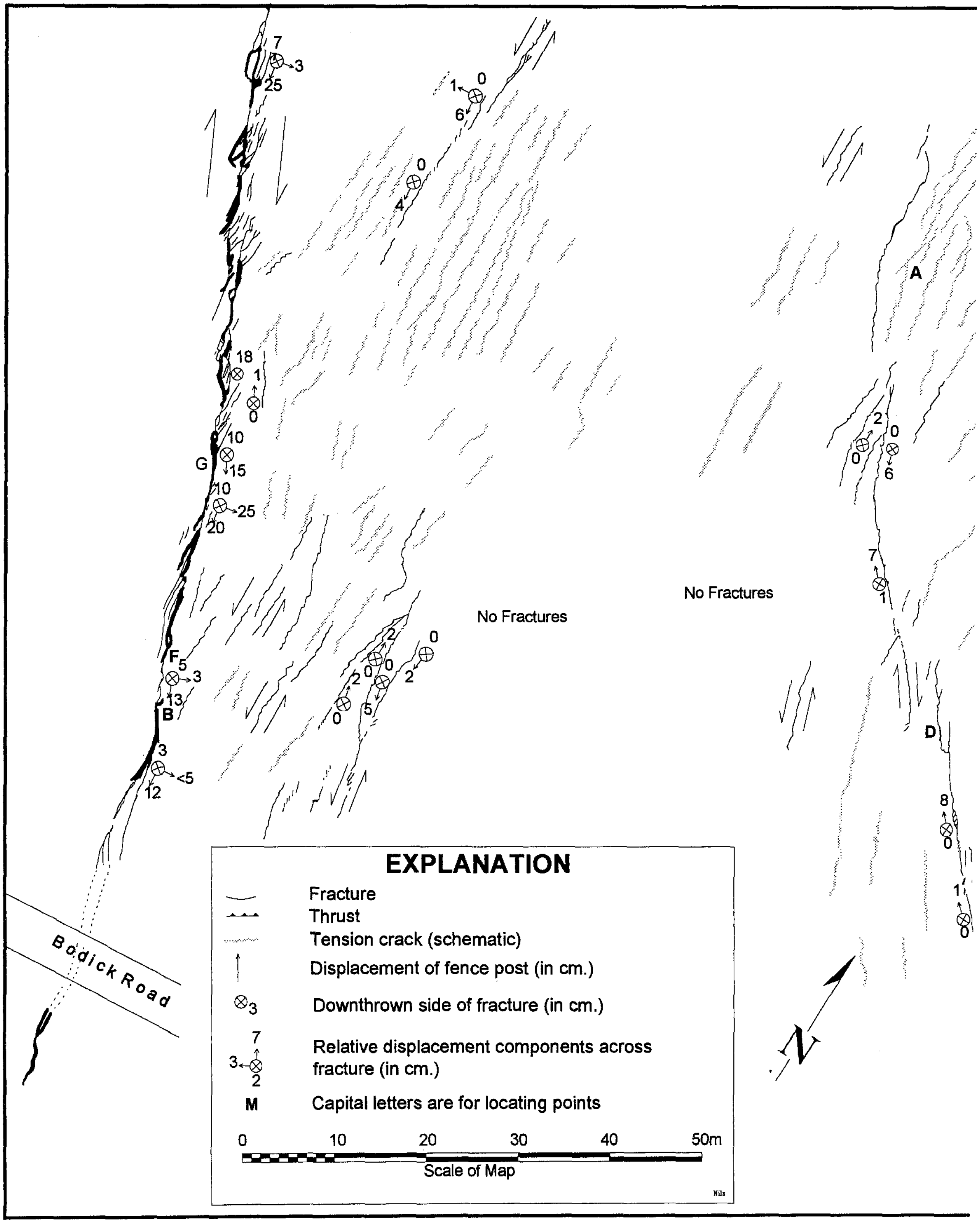
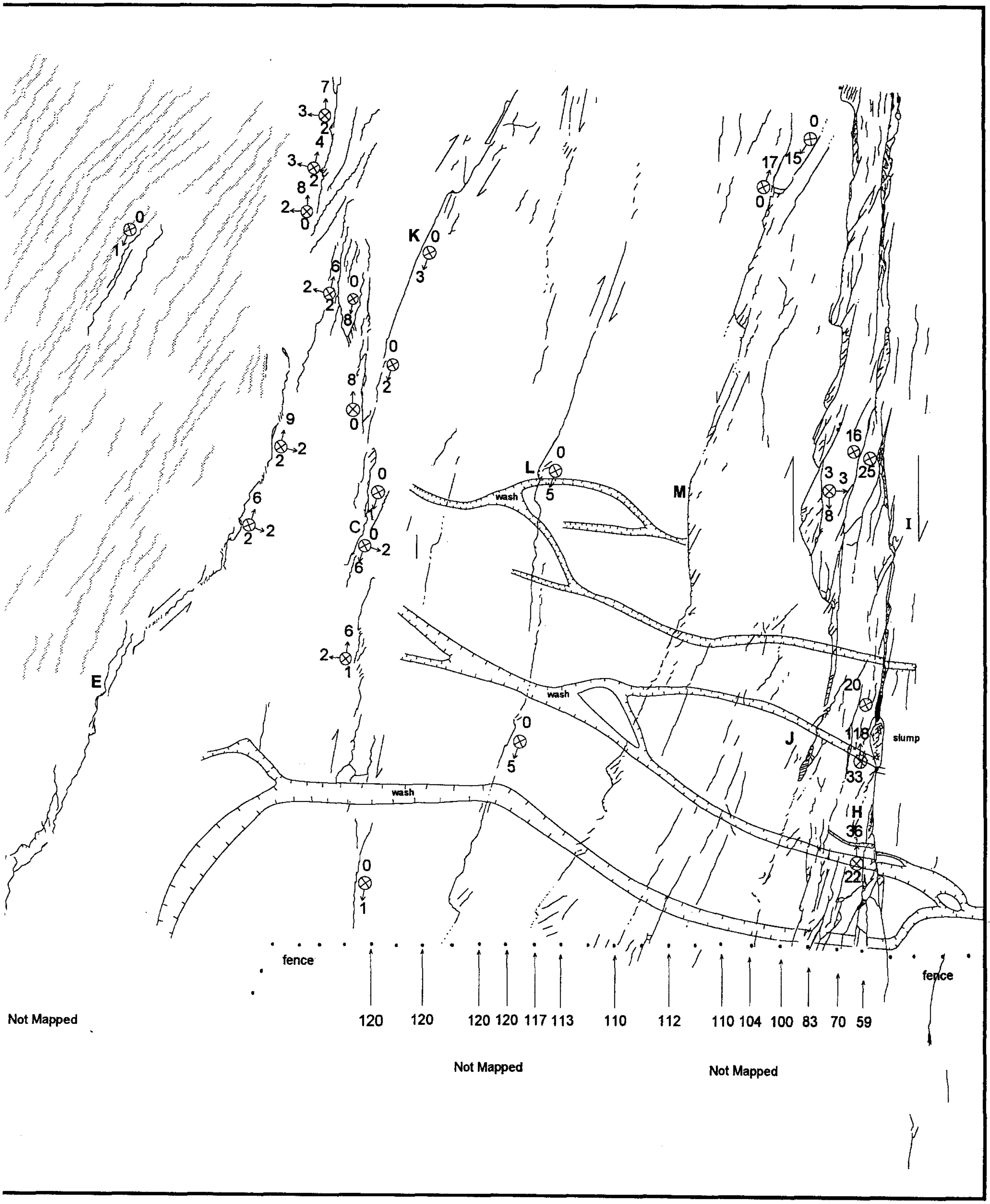
Figure 5. Detailed, analytical map of tension cracks, small faults, and right- and left-lateral narrow shear zones along the Homestead Valley fault zone, near the intersection of Bodick Road and Shawnee Trail. Shapes of individual tension fractures shown schematically with dotted pattern, but lengths, 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 the SW wall is a shear zone up to 5-m wide that has accommodated 1.5 to 3 dm of right-lateral shift. The band of tension cracks within the broad zone, adjacent to the SW wall, is about 30-m wide. The NE edge of the map is another narrow shear zone that accommodated a few decimeters of right-lateral shearing. Much of the central third of the belt of shear zones is characterized by tension cracks oriented roughly N–S. Shear zone on the right (*east*) side is along the NE wall of the belt of shear zones and 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 N30°W. Components of differential displacement normal to fence line indicated along base of diagram.


No Fractures
No Fractures
A
B
D
F
G
Bodick Road
N
EXPLANATION
Fracture
Thrust
Tension crack (schematic)
Displacement of fence post (in cm.)
Downthrown side of fracture (in cm.)
Relative displacement components across fracture (in cm.)
M Capital letters are for locating points
0 10 20 30 40 50m
Scale of Map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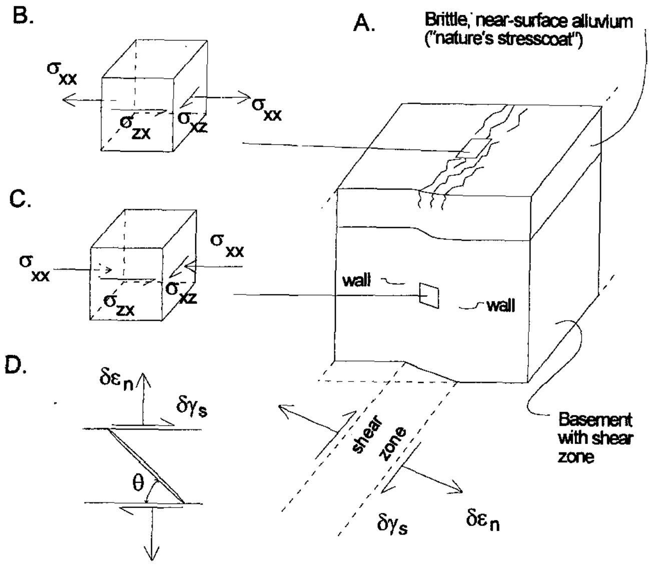

Figure 6. Idealization of the subsurface conditions within shear zone responsible for the formation of tension cracks at ground surface. (a) Brittle, near-surface alluvium layer overlies rock or alluvium below that contains a shear zone. Shearing and dilation within the shear zone produce tension normal 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 dilation normal to walls and orientation, θ, of tension crack in brittle crust.

belt. The shear zone is largely expressed through fractures at the ground surface, which we assume to be guides to shearing across a zone a few meters wide at depth. Many of the fractures are complex; they began as tension cracks and transformed into left-lateral faults. Some appear to be fault segments. The fractures are generally 8- to 15-m long, arranged en-echelon, and form a clockwise angle of about 5° to 30° to the general trend of the narrow shear zone. For example, the fracture shown at location C (Fig. 5) is about 10-m long, and has accommodated about 6 cm of right-lateral, 2 cm of dilation, and essentially zero vertical relative displacement. The average trend of the fracture is N10° to 20°W and the direction of differential net displacement is about N20°W. The orientation of the fracture suggests that it is a fault segment. The fracture is said to be compound, because it changes character along its length (Fleming and Johnson, 1989; Johnson *et al.*, 1993). A few meters along the trend to the NW, it becomes oriented N30°W, and over a few meters of its length it consists of en-echelon tension cracks oriented N–S to N10°E and the NE ends of the blocks bounded by tension cracks have been thrusted.

A different shear zone, also near the center of the belt, trends about N55°W near location D (Fig. 5). 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 N40°W, range in length from 5 to 20 m, and step left. One shown near location D has a thrust at the left step. Each of these fractures is composed of smaller, similar fractures, trending about N30°W. We would suggest that the right-lateral fractures along the narrow shear zone near location D reflect stepping segments of shear zones or fault segments in the subsurface. The fractures are highly localized, presumably reflecting high localization of shearing at depth.

A left-lateral shear zone (loc. E, Fig. 5) connects the vicinities 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 east) shift. 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 N30° to 40°W), suggesting a left-lateral shear zone or fault at depth.

Bounding Narrow Shear Zones

The belt of shear zones along the Homestead Valley fault zone at Bodick Road contains both a broad shear zone of mild deformation extending across the belt and several narrow zones of concentrated shear within the belt. These shear zones have accommodated a few decimeters of right-lateral offset in the interior of the belt, but most of the shift is concentrated in shear zones along its boundaries. The zone bounding the belt on the NE has 10 dm of right-lateral shift, while that on the SW has 3 dm, so most of the total shift of 1.8 m for the belt of shear zones, determined by sighting down the line of power poles along Bodick Road, occurred along these two boundary shear zones. Incidentally, the bounding shear zones have been reported by others but not recognized as such; those along the Johnson Valley fault zone are called "double fault" (Engineering and Science, 1992).

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. Thus, these bounding shear zones abruptly border the belt. For these reasons, the bounding shear zones are special.

Shear Zone on SW Side. The SW bounding shear zone accounts for about one-sixth of the total shift across the belt. The width of the bounding shear zone ranges from about 1 to 5 m (Fig. 5), so it is similar in size to the Happy Trail shear zone. The shear zone contains small thrusts and closely spaced tension cracks. The differential displacements across the narrower parts of the shear zone range from 15- to 25-cm right-lateral shift and generally 4 cm of dilation and 10 cm of vertical shift, downthrown on east (loc. G, Fig. 5). Within the shear zone, deformation is so highly concentrated that the scarps resemble faults, and may be faults.

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 (Fig. 5). Our measurements of deformations of the fence surrounding the ranch along Bodick Road document the concentrated shearing (lower right of Fig. 5). The northern corner of the fence is on unbroken ground, about 14 m NE of the NE flank of the belt of shear zones, and the bases of the first four fence posts from the corner provide a datum for measuring lateral components of the differential displacement. Between the fifth fence post (counting SW from the north corner), 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 5.9 dm (Fig. 5). Of the two fractures we mapped in this ground, 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 1.3 dm of offset. The seventh and eighth posts are in ground crossed by three fractures, and the offset increases a further 1.3 dm. 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 dm. Thus, measurements of the fence line indicate that, within the NE third—about 70 m—of the broad shear zone, the right-lateral component of the total differential displacement was about 1.2 m. Nearly all of the differential displacement occurred within a zone 44-m wide, with fully 1 m (of the total 1.2 m) occurring within a 12-m-wide shear zone that contains seven or eight fractures. About half the total differential displacement, 0.6 m, was accommodated primarily by one large fracture—a fault—bounding the belt of shear zones and the narrow shear zone along the NE wall.

The narrow zone of intense shearing within about 12 m of the NE wall of the broad shear zone, which accommodated about 1 m of right-lateral shift at the fence line, is a commanding structure, one that can hardly be overlooked in the field. If any of the structures 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. Elsewhere, the scarp is bounded by a wedge-shaped mass of loose soil chips. 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. 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 are gaping fractures that have accommodated right-lateral offsets.

Discussion and Conclusions

Summary of Observations at Landers

The combination of large right-lateral shearing and ideal, highly brittle, surficial materials, in an arid, sparsely vegetated, and nearly unpopulated environment provided an unusual opportunity to document the nature of surface ruptures at a scale where individual cracks could be mapped and their origin interpreted. The documentation reported here and in other publications could well provide important insights into problems such as siting and design of critical facilities in the vicinity of earthquake faults and the nature of rupture during earthquakes in the upper part of the crust. It could possibly even provide further clues to the generation of earthquakes during faulting.

Rather than well-defined faults represented by displacement discontinuities (Fig. 7a), 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 (Fig. 7b). The walls of the belt are well defined by narrow shear zones. In a few locations along other fault zones that ruptured at Landers we did observe fault surfaces. In general, though, in compact alluvium, unconsolidated alluvium, and in bedrock, we observed shear zones, not faults. Thus, we tentatively conclude that the characteristic simple rupture at Landers is not expressed in faulting, but in the formation of shear zones or belts of shear zones. Whether 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 have 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 or anecdotal; 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, 1994a, b, c). 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.

Tchelenko and Ambraseys (1970) described fractures developed in the Dasht-e Baȳaz (Iran) earthquake of 1968. They briefly mention simple shear across a broad zone followed by more intense shearing concentrated in a narrow principal displacement zone (pp. 41, 42). Also, they describe small shear zones about 3-m wide at some distance from the principal displacement zone, so in this sense, they recognized belts of shear zones (p. 53). They mapped the entire rupture zone synoptically at a scale of 1:7500, thus their mapping was not designed to be analytic, as is required to interpret the origin of fractures.

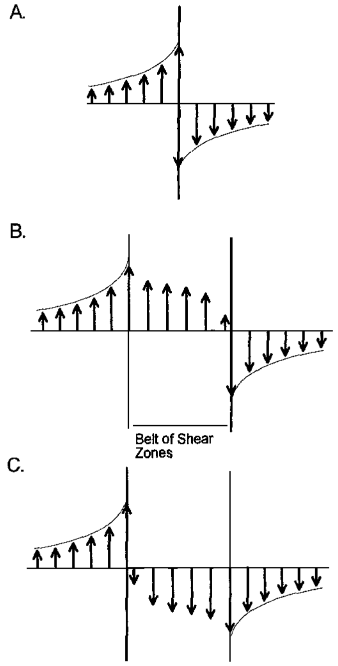

Figure 7. Idealized distributions of relative co-seismic shift at the ground surface in the vicinity of a fault or a belt of shear zones. (a) Distribution of co-seismic shift generally assumed in the vicinity of a ruptured fault, with shift dying out on either side of the fault trace. (b) Distribution of co-seismic shift assumed to occur in the vicinity of a belt of shear zones. Distribution within the belt corresponds 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.

Review of previous literature suggests that shear zones, or parts of shear zones, have been widely recognized, but not singled out for particular emphasis as we have done (Reid, 1910; Philip and Meghraoui, 1983; Armijo *et al.*, 1989). Elsewhere, we have reviewed (Johnson *et al.*, 1993) descriptions of co-seismic 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.

During the 1906 San Francisco earthquake, a segment of the San Andreas fault zone at least 300-km long (about four times the length at Landers) ruptured with differential right-lateral displacements as large as 6.4 m (Gilbert, 1907, p. 5; Lawson *et al.*, 1908, p. 2). 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 a [metre] up to [15 m] or more. Not uncommonly there were auxiliary cracks either branching from the main fault-trace obliquely for [30 to 100 m], 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 [about 100 m]. *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 *et al.*, 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 *et al.*, 1908, p. 55).

Conclusions

On the basis of the descriptions presented here and by Johnson *et al.*, (1993), in addition to those at Loma Prieta (Aydin *et al.*, 1992, 1994; Martosudarmo and Johnson, 1994; Johnson and Fleming, 1994), we draw the following conclusions about simple belts of shear zones. Earthquake faulting is expressed at the ground surface as shear zones and belts of shear zones, if not generally, then very commonly. We are suggesting that the Landers-type of fracturing within belts is a product of co-seismic surface rupture. Such belts 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 belts of shear zones have been overlooked is that we have associated most earthquakes with 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 belt of shear zones we have described at Landers reflects general shearing at depth across a broad zone. One or both walls of the belt of shear zones might be loci of narrow zones of concentrated shearing, and one narrow shear zone along a wall might accommodate most of the shearing. This is a matter of observation. We do not know why this happens, however.

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