Analecta of Structures Formed During the 28 June 1992 Landers-Big Bear, California Earthquake Sequence

Including Maps of Shear Zones, Belts of Shear Zones, Tectonic Ridge, Duplex En Echelon Fault, Fault Elements, and Thrusts in Restraining Steps

by

Arvid M. Johnson, Robert W. Fleming, Kenneth M. Cruikshank, Sumaryanto Y. Martosudarmo, Nils A. Johnson, Kaj M. Johnson, *and* ***Wei Wei***

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Arvid M. Johnson
Department of Earth and Atmospheric Sciences
Purdue University
West Lafayette, Indiana 47907–1397
Tel.: (317) 494–0250 • FAX: (317) 496–1210)

Robert W. Fleming
Geologic Hazards Team
U.S. Geological Survey, Mail Stop 966
Denver, Colorado 80225
Tel.: (303) 273–8603 • FAX: (303) 273–8600

Kenneth M. Cruikshank
Department of Geology
Portland State University
Portland, Oregon 97207–0751
Tel.: (503) 725–3383 • Fax: (503) 725–3025
e–mail:ken@ch1.ch.pdx.edu
http://www.geol.pdx.edu/People/KMC/KMC.htm

Sumaryanto Y. Martosudarmo
Direktorat PTSDM-PKA
BPP Technologi
New Building 18 fl.
M.H. Thamrin 8
Jakarta, 10340
Indonesia

Nils A. Johnson
Kaj M. Johnson
Wei Wei
Dept. of Earth and Atmospheric Sciences
Purdue University
West Lafayette, Indiana 47907
(317) 494-0250 • FAX: (317) 496-1210

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Abstract

Ground rupture that occurred during the 28 June 1992 Landers-Big Bear, California, earthquake sequence has provided an unusual opportunity to map structures that form near the ground surface during strike-slip faulting. The largest structure, which is illustrated in an index-scale map, is the Landers-Big Bear *rotating block*. This block is defined on the east by an arcuate rupture 80-90 km long consisting of *en echelon*, right-stepping right-lateral fault zones that change orientation from north to south. The entire 1992 fault rupture defines an arc of about 60° with a radius of 70-80 km centered near the San Andreas fault zone to the west. In 1992 the Landers-Big Bear block rotated counterclockwise relative to surrounding ground, and deformed internally. Deformation within the rotating block may have caused the left-lateral earthquake sequence near Big Bear Lake.

The arcuate Landers rupture is not a single fault, but rather is a composite of parts of no fewer than four named fault zones, from the Camp Rock in the north to the Johnson Valley in the south. The parts of fault zone in the Landers rupture step right to form large releasing stepovers several kilometers long and wide, connected by right-lateral fault zones and tension cracks. Within the Homestead-Emerson and Kickapoo stepovers are duplex structures, consisting of multiple right-lateral rupture zones. Measurements of shift across elements of the duplex structures by other investigators indicate that there was primarily right-lateral shift, but also growth of pull-apart basins. A zone of tension cracks trending at a high angle to the right-stepping Emerson and Camp Rock faults reflects growth of another pull-apart basin there.

Our mapping is intended to contribute to the understanding of structures within these larger rupture zones. One such structure at Landers is the belt of shear zones, which seems to characterize a large part of the Landers rupture, at least wherever we have examined it. The belts are mentioned here only because we have described them previously. Our more recent research shows, mainly, that belts of shear zones range from about 50 m to 500 m wide, and that they pass through bedrock as well as consolidated and unconsolidated alluvium.

We also mapped the Tortoise Hill tectonic ridge, which grew about 1 m higher during the Landers earthquakes. We have previously explained the surveying methods and results. Here we briefly describe some *spines*, which appear to represent masses within the ridge that grow faster than surrounding masses. We also describe thrust faults and a low dome that grew in the vicinity of a small *restraining step* in the main rupture at the ridge.

The Headquarters duplex structure, along the Homestead Valley fault zone, is on the order of hundreds of meters long and tens of meters wide. It formed at a *releasing stepover* between fault elements, about 1 km long, that defines the northeast side of the Homestead Valley fault zone. The individual faults connecting the bounding faults of the duplex structure are tens of meters long and accommodated mainly right-lateral shift. The individual connecting faults, themselves, are made up of even shorter fault elements, a few meters long, that accommodated right-lateral shift and have *restraining steps*. At the Pipes Wash releasing stepover, along the Homestead Valley fault zone, a different kind of structure formed. Instead of a duplex structure, a left-lateral shear zone formed, bounding a rotating block within the stepover. The left-lateral rupture shows classic examples of *ramps* that formed along oblique, strike-slip/normal faults.

Two areas of the Kickapoo fault zone, which connects the Johnson Valley and Homestead Valley fault zones, contain classic *en echelon ruptures* at several scales. At the Charles Road area, the fault zone itself is composed of restraining, stepping fault elements 800 m long that accommodate both normal shift and right-lateral, strike shift. Some of these ruptures consist of shorter fault elements, about 250 m long, arranged with restraining steps. Parts of these shorter fault ele-

ments consist of even–shorter fault elements, about 25 m long, also arranged with restraining steps. The directions of the *en echelon* elements of progressively–shorter lengths become progressively oriented about 40° farther to the east. The walls of the Kickapoo fault zone are oriented N7°E. The 800-m fault elements that compose the fault zone are oriented about N17°E. The 250-m fault elements are oriented about N24°E. The 25-m fault elements are oriented about N45°E.

In comparing the structures along the Landers rupture with structures described earlier in large landslides, we note that the landslides provide excellent analogs of structures. The same shear zones, tectonic ridges, pull-apart basins, restraining and releasing steps, duplex structures and fault elements are recognized in landsliding and in faulting processes. The structures form sufficiently slowly in landslides, though, that one can observe their evolution, and therefore add to our understanding of the processes that formed the structures.

Introduction

The June 28, 1992, M_s 7.5 earthquake at Landers, California, which occurred about 10 km north of the community of Yucca Valley, California, (fig. 1), produced spectacular ground rupturing more than 80 km in length (Hough and others, 1993). The ground rupturing, which was dominated by right-lateral shearing, extended along 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 Landers earthquakes occurred in the desert of southeastern California, where details of ruptures were well preserved, and patterns of rupturing were generally unaffected by urbanization. The structures were varied and well-displayed and, because the differential displacements were so large, spectacular. The scarcity of vegetation, the aridity of the area, the compactness of the alluvium and bedrock, and the relative isotropy and brittleness of surficial materials collaborated to provide a marvelous visual record of the character of the deformation zones. In following pages we present a series of analecta—that is, verbal clips or snippets—dealing with a variety of structures, including belts of shear zones, segmentation of ruptures, rotating fault block, *en echelon* fault zones, releasing duplex structures, spines, and ramps. All of these structures are documented with detailed maps in text figures or in plates (in pocket). Our purpose is to describe the structures and to present our understanding of the mechanics of their formation. Hence, most descriptions focus on structures where we have information on differential displacements as well as spatial data on the position and orientation of fractures.

Our understanding of these structures is based on mapping, and we have mapped in two, quite different ways. We have mapped fractures at a scale of 1:200 (or rarely, 1:500) using a total-station theodolite to establish a local array of control points. After the points were plotted, we reoccupied the points in the field to make controlled drawings of the surrounding fractures and disrupted ground. We also used photogeologic methods in the laboratory to map ruptures from post-earthquake aerial photographs at a scale of 1:6000. Those areas mapped in detail in the field and those mapped from photographs are clear on the plates and figures because the maps made in the field have appended kinematic information, whereas those made in the laboratory show only traces of fractures of some type.

For some areas we have compared the maps made by the two methods and conclude that the photogeologic maps show traces of fractures that are subsets of the traces visible in the field and shown in our detailed maps. The post-earthquake aerial photography was taken in the morning at a low sun angle. Fractures that contain westerly

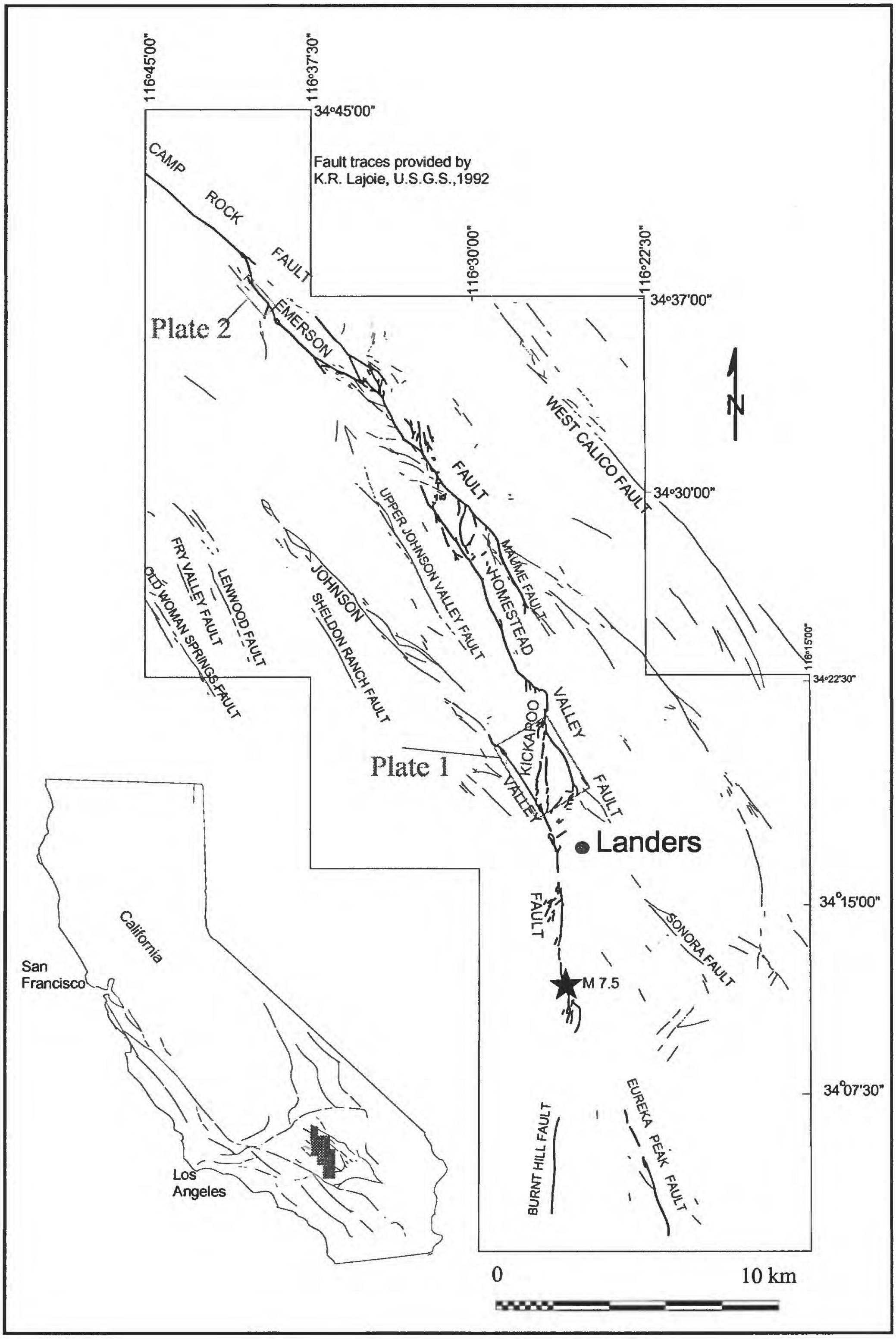

Figure 1. Location map, showing en echelon fault zones that activated during the 1992 Landers, California earthquake. Epicenter of main shock (M_s 7.5) was near Landers at the south end of the ruptures. Inset figure shows some of the major faults in southern California.

facing scarps are particularly distinct (in shadow), but those without a vertical offset or facing easterly are poorly expressed or invisible. Thus, in general, one needs to realize that features that could not be definitely identified as fractures, or fractures that were invisible in the photographs, will be missing in the photogeologic parts of maps. The traces shown in areas mapped photogrammetrically, though, almost always represent fractures.

Ultimately we redrafted, compiled and reduced several map sheets to produce the maps presented here. The maps were scanned and saved as a TIFF computer file, converted to lines with Adobe STREAMLINE[1], and imported into a drafting program Micrografx DESIGNER where they were finished as drawings.

There are several purposes in presenting detailed descriptions of ground ruptures of the Landers earthquake sequence: The main shock of the Landers earthquake was the largest to occur in the United States since the Great Alaskan, Good Friday Earthquake of 1964, and it produced even more clearly surface-rupture patterns than did the 1906 San Francisco earthquake. The maximum credible, differential, lateral displacements at Landers[2]—as much as 400 cm—are comparable to the maximum credible values for the 1906 San Francisco earthquake[3]. They are much larger than those in the 1971 San Fernando and 1989 Loma Prieta earthquakes, [100 to 200 cm]; the 1964 Borrego Peak and Managua Nicaragua earthquakes, [20 to 30 cm]; 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 (ca. 1965) and the inception of the National Earthquake Hazards Reduction Program (ca. 1970). The earthquake produced the most spectacular surface rupture 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, and thus will become a benchmark for revisions of hazards criteria. It is the largest and most disruptive earthquake since development of ideas about "capable" faults and fault 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 concerning earthquake hazards, including the potential hazards of ruptured containment structures for nuclear waste and other extremely toxic waste. For all these reasons, the Landers earthquake, and the associated ground rupture, is scientifically important. But the descriptions are also important as the observational basis for modeling and testing of theories of faulting that must follow if we are to understand processes of faulting. Incomplete and inaccurate descriptions made during previous earthquakes have limited the validity of follow-up investigations, especially those conducted after the surface evidence of ground rupture has been weathered or otherwise modified.

[1]Please note that any use of trade, product or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

[2]There is a strange tendency for earthquakes to be characterized by exaggerated estimates of "maximum displacement." For example, at Landers, maximum displacement has been reported to be 6 to 7 m based on one spot measurement along Galway Lake Road (Engineering and Science, 1992; Sieh and others, 1993) within an area of complex deformation where the structural context for the exaggerated displacement is lacking. This value belies measurements half as large both north and south of Galway Lake Road. See, also, the following note.

[3] Values of up to 6.4 m for the 1906 San Francisco earthquake were reported by G. K. Gilbert, but he warned (to deaf ears) that these values almost certainly are exaggerations resulting from special conditions in soft ground, such as lurching or other superficial adjustments. Yet, 6.4 m is the number typically reported for the San Francisco earthquake and used in all kinds of calculations.

Our approach to any unfamiliar process, including surface rupture, involves application of the following methods:

1. Make detailed and accurate, analytical[4] maps of results of the process.

2. Formulate rheological models and boundary conditions to describe simple elements of the processes that one can recognize from the detailed field observations (e.g., Johnson, 1970; Johnson and Fletcher, 1994).

3. Design and conduct experiments that illustrate the processes and test the models (e.g., Johnson, 1965, 1977, 1996).

Our earthquake research at Landers largely involves the first method.

Acknowledgments

Dick Jahns explained why we should make detailed maps and showed us how to make them.

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We especially thank Michael Machette, U.S. Geological Survey, for an especially thorough critical review of the terminology and logic of the manuscript. We thank James Gardner, Technical Writer at Purdue, who edited the manuscript and corrected many misuses of English. Margo Johnson, U.S. Geological Survey, Denver, did final layout and formatting. We are responsible, though, for remaining errors of language or content.

Bob Fleming and Arvid Johnson have thoroughly enjoyed their Gilbertian vicious circle of Babylonian research together during the past 30 years of collaboration. Too bad it had to end.

[4]The method of making analytical maps, which show features required for mechanical interpretation, is explained elsewhere (Fleming and Johnson, 1989; Johnson and Fleming, 1993; Martosudarmo and others, 1997).

Part I. Basic Considerations

Belts of Shear Zones (Splintering) at Landers

The idea that broad belts of shear zones, rather than narrow shear zones or slip surfaces, form during a faulting-earthquake episode has been revived as a result of observations made of ground ruptures at Landers. Almost 80 years ago, following the 1906 San Francisco earthquake, shear zones and belts of shear zones were recognized along the San Andreas fault (Gilbert, 1907; Lawson, 1908), but the idea has since been largely ignored. It has been ignored because faults have become idealized as slip surfaces, characterized by length of rupture and distribution of slip. Thus, rather than describing the nature of actual surface rupturing, earthquake investigators have idealized surface rupturing. Our approach has been to describe actual surface rupturing.

Early Recognition of Shear Zones

Lawson's Description of Typical Rupture Zone Formed During the 1906 San Francisco Earthquake

During the 1906 San Francisco earthquake, a part of the San Andreas fault zone at least 300 km long (almost four times the length of rupture at Landers) ruptured with large differential right-lateral displacements (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, as wide as 100 m, 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," was 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).

Gilbert's description of zones of rupture

In a report on normal faults near Salt Lake City, G.K. Gilbert (1928, p. 13) described zones along the 1906 rupture of the San Andreas fault zone north of San Francisco (fig. 2 and fig. 3) as follows:

> "Slipping surfaces of another class are not parallel but oblique to the main fault surface. Their obliquity follows a law, and the law is illustrated by analogous phenomena connected with the California earthquake of 1906. The fault movement which caused

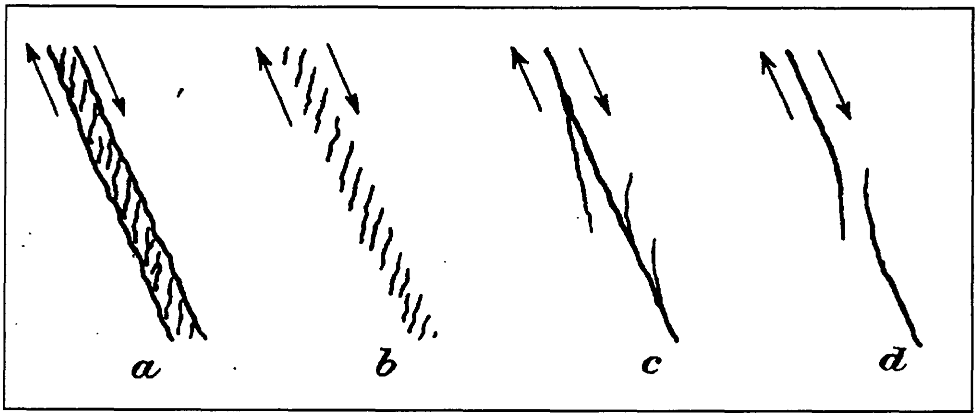


Figure 2. Types of surface ruptures recognized by G.K. Gilbert along 1906 break of San Andreas fault zone north of San Francisco (from Gilbert, 1928, p. 13). Arrows show directions of shift of underlying crustal blocks.

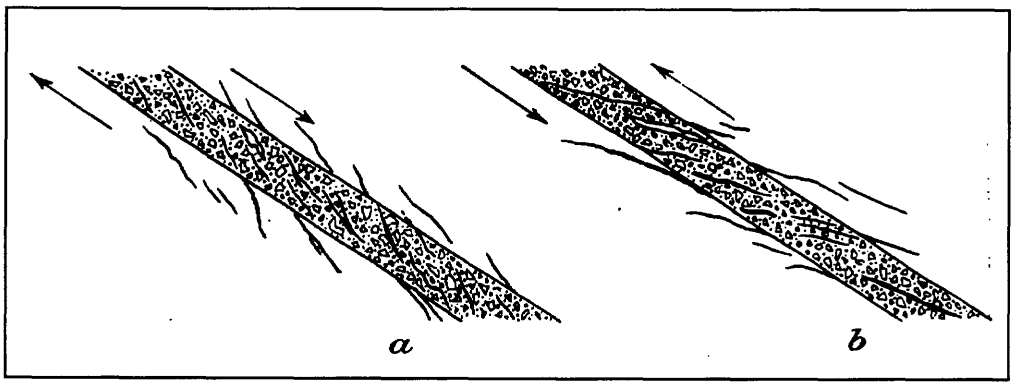


Figure 3. Ideal vertical sections of normal a and reverse b faults and subsidiary slickened partings, illustrating the relations of the attitude of the partings (from Gilbert, 1928, p. 13).

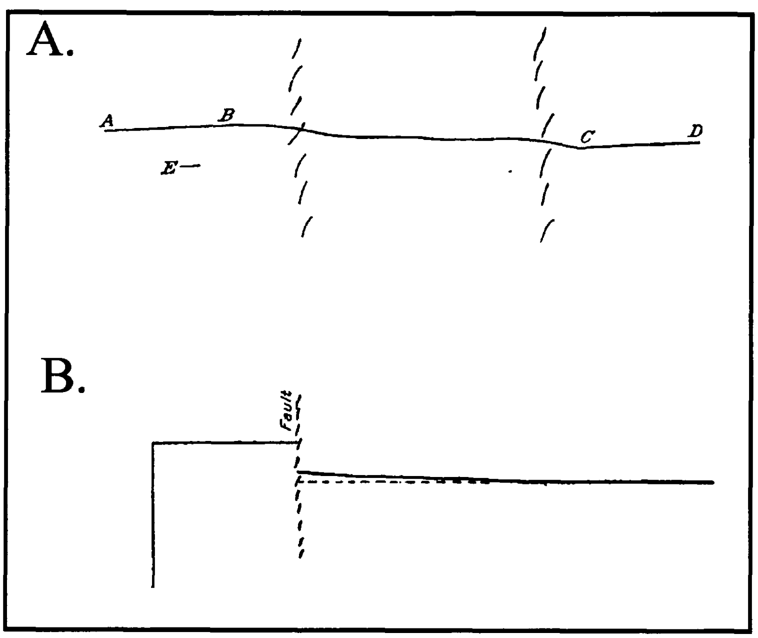


Figure 4. Deformed fences on farm of E.R. Strain, near Woodville, California. 1906 earthquake ruptures (from G.K. Gilbert, in Lawson, 1908, p. 71) . The upper diagram shows two zones of concentrated shearing and an intervening zone of more diffuse shearing. The lower diagram. somewhat north of the one described above, shows the continuation of the shear zone shown near B. The fence is broken and offset 8.5 feet (2.6 m). On one side of the fault the fence is straight. The other the fence is deformed as it approaches the trace.

that earthquake was horizontal, on a plane trending northwest. ...The visible expression of the faulting was mainly in a surface mantle of earth and included a system of oblique cracks, such as are shown diagrammatically in [fig. 2]. In places (a, [fig. 2]) the fault trace included two walls, with relative displacement as indicated by arrows, and between them a belt of broken earth. The principal cracks within the belt were oblique, as indicated. In other places (b, [fig. 2]) the walls were not developed and the fault trace consisted of a system of oblique cracks, as indicated. From the walls of the fault trace ran branching cracks (c, [fig. 2]), the divergence being at various angles but always to the right of one looking along the trace. The trace in places (d, [fig. 2]) swerved to the right and gradually disappeared, to reappear at the left *en échelon.*"

G.K. Gilbert and F.E. Matthes described the feature we have termed a "narrow shear zone" (Johnson and others, 1994) 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).

G.K. Gilbert (in Lawson, 1908, p. 70) (fig. 4) measured the offsets of two fences on Mr. E.R. Strain's property, west of Woodville, California, 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, to the north, the southwest-bounding branch continues, represented by *en echelon* tension cracks, and the shear zone continues, but the northeast-bounding branch is absent. Here, the southwest-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 northeast 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), 13 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.

Reid's description of broad rupture zones

Reid (1910, p. 33 and 34) also recognized broad shear zones in his part of the report on the 1906 San Francisco earthquake:

> "In the general descriptions of the fault-trace it is shown that when the rupture occurred there was a zone of varying width between the shifting sides which did not partake of their simple movements, but was more or less distorted by the shearing forces to which it was subjected. The existence of this zone in alluvium or disintegrating rock may be explained even tho the fault were a sharply defined crack in the underlying solid rock."

> Reid goes on to explain that if the mantle over the fault in bedrock is consolidated, the zone of distortion in the mantle will be narrow and most of the shift will be by faulting, whereas if the mantle is unconsolidated, all the shift may be by flowage across a broad zone. Then he concludes,

> "...this seems to be the condition which produces the echelon phase of the fault-trace in very wet alluvium, as described by Mr. Gilbert...

> ...The zone was in some places only 2 to 6 feet wide, in others several hundred yards. Where it was broad the shift was divided in some cases among a number of cracks; in others it was distributed more or less evenly over the zone...

> ...When the shift is concentrated in a narrow zone, only a few feet wide, there is more or less demolition, within the zone, or a fence or other object that may cross it, and the broken ends of the fence receive an offset which gives a measure of the shift. The turf in such a narrow zone is torn in a characteristic way; at the beginning of the movement the turf is rent into strips by cracks formed at right angles to the line of greatest stretching; that is, the cracks and the strips of turf between them would trend about north and south, as the fault runs about northwest...They are frequently described by the word *splintering* (Reid, 1910; italics ours)."

Since the time of Gilbert's and Reid's studies, some 80 years ago, details of rupturing across shear zones have been documented in only a few situations (e.g. Brown and others, 1967; Philip and Meghraoui, 1983; and Clark, 1972). Because shear zones are the building blocks of larger belts of shear zones, and belts of shear zones constitute fault zones (fig. 5), we have singled them out for special attention (Johnson and others, 1993, 1994).

The Belt of Shear Zones

Examples of Belts

In many places along the Johnson Valley, Homestead Valley, and Emerson fault zones at Landers, the rupture zones consist of wide belts of shearing, with narrow shear zones, ranging up to a few meters in width, and a few fault surfaces

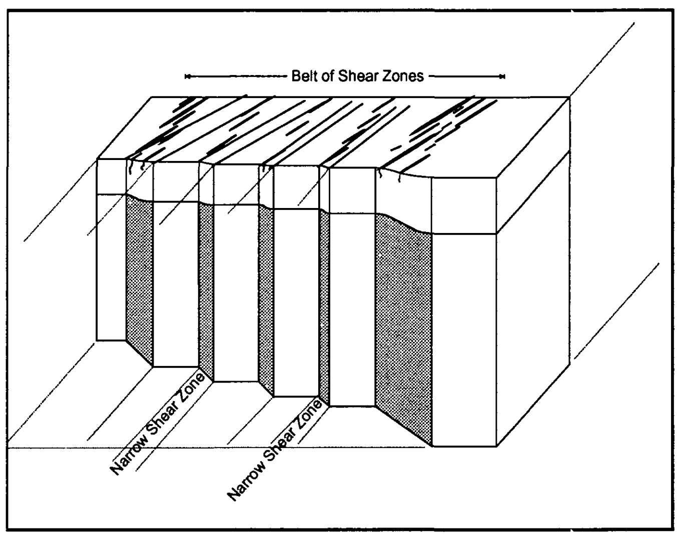
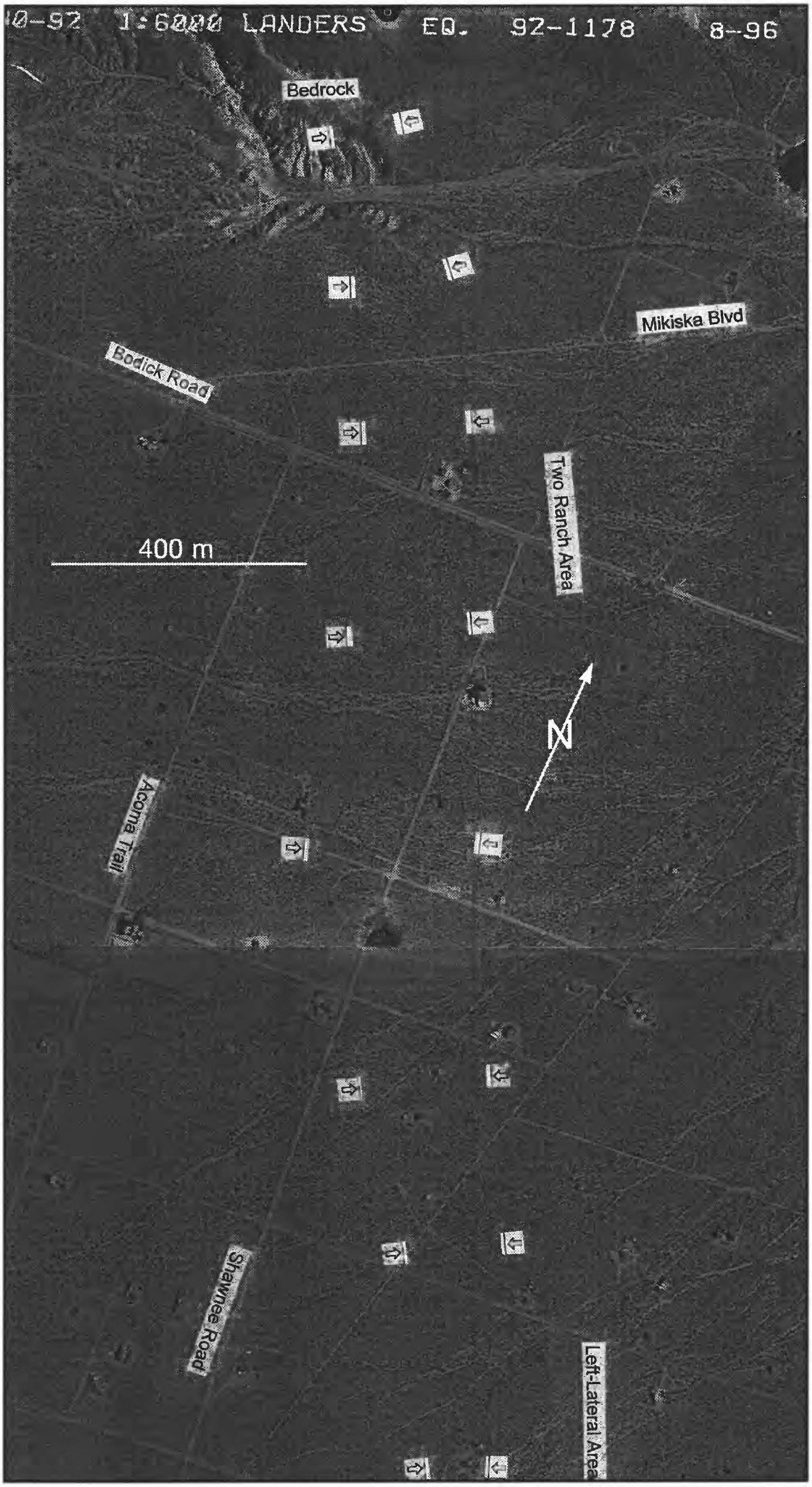


Figure 5. Idealization of a belt of shear zones of the type recognized at Landers. The entire width of the belt consists of a zone of mild shearing, which is responsible for broadly distributed tension cracks oriented north–south. Within the belt, though, are narrower shear zones that accomplish most 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.



← A.

Figure 6. Aerial photographs of part of 1992 Landers rupture along the Homestead Valley fault zone.

← *A. View of rupture zone from near Reche Mountain to south end of Goatsucker Hill ridge in north (see Plate 1). Arrows mark boundaries of belt of shear zones, which ranges in width from about 80 m in south to 200 m in center.*

B. ➔

➔ *B. View of rupture zone from Two Ranches area into exposed bedrock of Goatsucker Hill ridge in north. Arrows mark boundaries of belt of shear zones, which passes from consolidated alluvium in southern half of area into bedrock in northern part of area.*

within the belt. We recognize these belts of shear zones as collections of individual shear zones, and we recognize shear zones themselves as collections of fractures and other structural evidence of deformation that forms a distinctive pattern (Johnson and others, 1994). Belts of shear zones have been mapped at Goatsucker Hill ridge; at the Headquarters step; at Wildey Road, as well as at Reche Mountain along the Homestead Valley fault zone (fig. 6, Plate 1); and at Happy Trail along the Johnson Valley fault zone.

The belts of shear zones at Landers range from perhaps 50 to 500 m wide. Some of them are bounded by faults on both sides, some on only one side, and some have no bounding faults. The belt at Happy Trail is about 100 m wide (Plate 1). At the Racetrack Half-Rift, the Johnson Valley and Kickapoo belts branch, forming two belts about 100 m wide. At the Two Ranches Area, the belt is about 200 m wide (fig. 6A). The walls of all these belts are made visible by the roughly parallel, bounding faults. The Wildey Road belt of the Homestead Valley fault zone, north of where the Kickapoo fault zone merges with the Homestead Valley fault zone, is 400 to 500 m wide (Plate 1). The ruptures within the Kickapoo fault zone also form broad belts, 100 to 200 m wide, but the member shear zones within the belts are arranged *en echelon*, and the walls of the belts are delineated not by bounding faults but by the ends of the *en echelon* shear zones. Some of the belts of shear zones along the Emerson fault zone (Plate 2) are intermediate between these two extremes; commonly one wall of the belt is defined by a fault, and the other by the ends of oblique ruptures within the belt.

Shear Zones

An individual shear zone has a characteristic pattern of fracturing, including long *en echelon* tension cracks, perhaps with some component of left-lateral shift, that are oriented about 20° to 45° clockwise to the walls. Alternatively, there may be a series of opposite–stepping, very narrow shear zones or fault elements oriented about 5° to 20° to the walls of the shear zone (fig. 7) (Johnson and others, 1993, 1994).

We need to explain why we speak of shear zones when, in fact, we observe fractures. Perhaps the most important 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 at depth. Guide fractures*[5] *indirectly reflect* the deformation and, possibly, the structure beneath the ground surface, generally through the stress state, but also through differential displacements generated by the structure at depth. Guide structures form at the ground surface and include fault elements, thrust faults, folds and *en echelon* fractures above strike-slip faults (Fleming and Johnson, 1989). The most familiar fractures are *en echelon* tension cracks, which occur at the ground surface above the termination of a strike-slip fault or narrow shear zone (Pollard and others, 1982) and generally form in a band of relatively uniform width. Traces of individual cracks are generally inclined 30° to 45° to the trend of the underlying strike-slip structure (Fleming and Johnson, 1989; Nicholson and Pollard, 1985; Olson and Pollard, 1991). Because their formation is relatively well understood, *en echelon* tension cracks are diagnostic 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 state of stress at the time of formation.

[5]This term derives from Chapter 12 of Hugh McKinstry's textbook, Mining Geology (1948), called "Fracture Patterns As Guides." McKinstry also used the idea in sections on stratigraphic and lithologic guides, and contacts and folds as guides to the location of ore bodies.

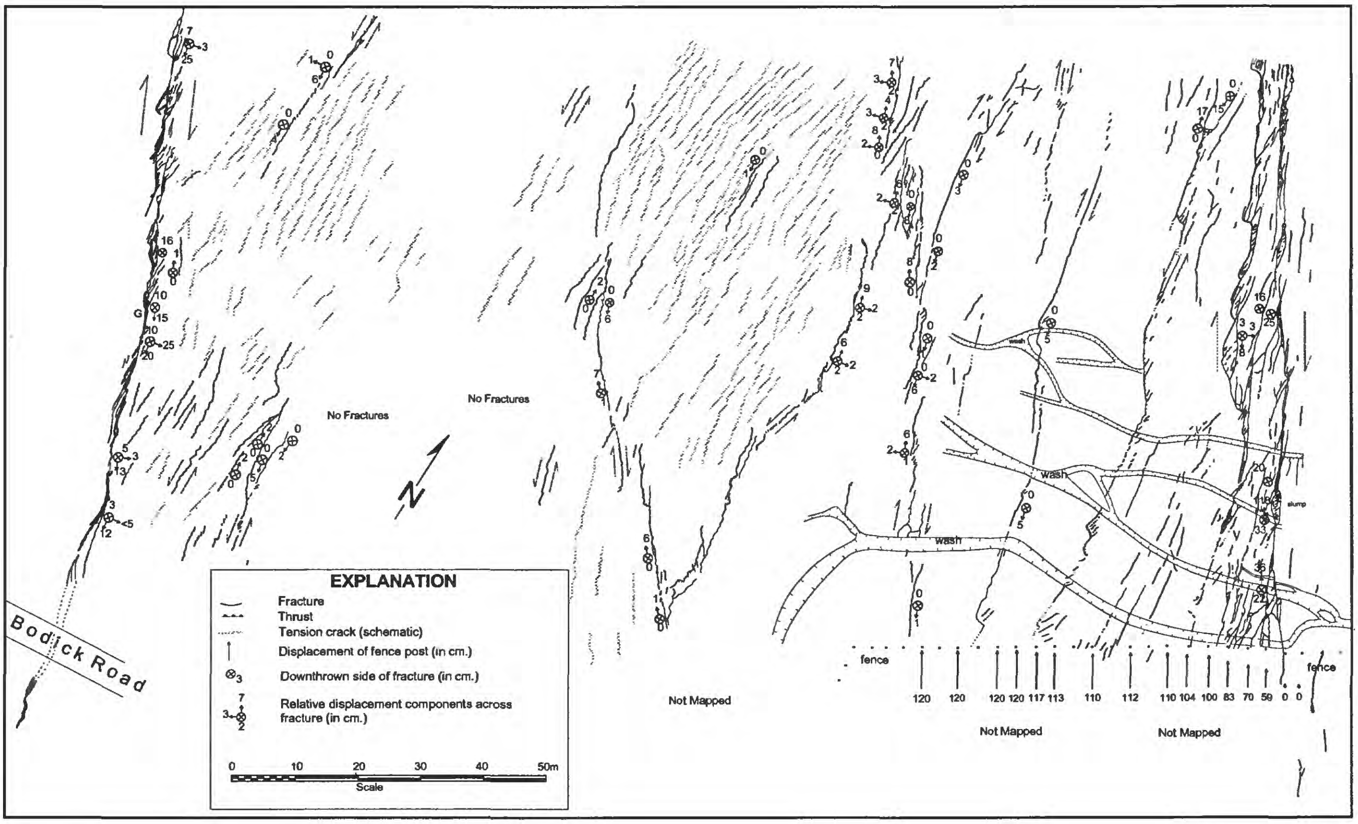


Figure 7. Detailed map of tension cracks, small faults, and right- and left-lateral narrow shear zones along the Homestead Valley fault zone, north of Bodick Road and its intersection with Shawnee Trail. Shapes of individual tension fractures shown schematically with gray lines, but lengths, distributions 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 southwest 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 southwest wall, is about 30 m wide. Much of central third of the belt of shear zones is also characterized by tension cracks oriented roughly north-south. At the northeast 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 northwest to southeast. 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 north-south, and right-lateral fractures generally oriented about N30°W. Components of differential displacement normal to fence line shown along base of diagram. Measurements of offset were from alignment of fence posts.

Modes of Rupture

We first described structures in shear zones in a paper on strike-slip faults that bound masses of landslides that moved several meters over a period of 3 years. (Fleming and Johnson, 1989). We gradually realized that nearly all the fracturing phenomena associated with strike-slip faulting in the landslides are mode *III* phenomena. *The strike-slip structures developed at the ground surface by propagating upward from below, not by propagating horizontally along the fault zone.*

Because the modes of differential displacement across a fault are important in the description of slip and opening of faults, we will define them (e.g., Lawn and Wilshaw, 1975). Consider a vertical, strike-slip fault. If the fault is loaded in mode *I*, the walls of the fault might open (fig. 8A), producing a joint, or a graben might form as the walls try to separate. For the other two loading modes, there is horizontal slip. In mode *II*, the fault propagates horizontally along a vertical fracture front (fig. 8B). In mode *III*, the fault propagates vertically toward the ground surface (fig. 8C). It should be clear that faults can also propagate obliquely, in a mixture of modes *I, II* and *III*.

During earthquakes, faults apparently propagate outward, from a center, so one would expect mixed-mode rupturing along most of the rupture front. Near the ground surface, however, faults commonly propagate primarily in mode *III*, so we would expect mode *III* rupture to control the formation of near-surface rupture zones regardless of what is happening in the subsurface. We emphasize the difficulties in interpreting the formation of fractures along faults and in shear zones along earthquake ruptures without this understanding. Unfortunately, mode of propagation is widely misunderstood[6].

Two Ranches Belt of Shear Zones

The surface rupture along several of the fault zones at Landers is manifest in *belts of shear* zones of the type described above. There is a broad belt about 180 m wide in the Two Ranches area (Plate 1, fig. 7 and Plate 4). The belt extends for about half a kilometer northwest. To the southwest its eastern side becomes the Headquarters step. The long dimension of the map in figure 7 is the width of the belt. The belt consists of a broad shear zone, encompassing the entire width of the

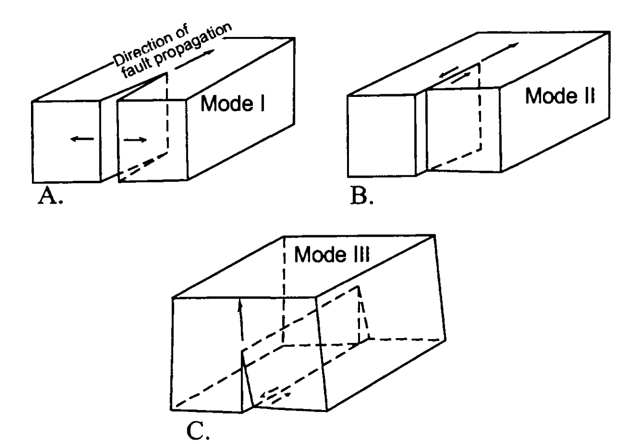


***Figure 8.** Definitions of mode I, mode II and mode III loading relative to a fracture surface and fracture front. In mode I deformation the fracture surfaces separate normally to produce an open crack. The fracture will propagate horizontally, for the geometry illustrated. In mode II loading of a strike-slip fracture, the fracture front is vertical and the fracture surfaces slip at right angles to the fracture front. If the fracture propagates, it will propagate horizontally. In mode III loading of a strike-slip fracture, the fracture front is horizontal and the fracture surfaces slip parallel to the fracture front. The fracture propagates upward, toward the ground surface.*

[6] For example, lack of understanding of the significance of direction of propagation has flawed an interesting study of faulting within a stepover region at Landers by Zachariasen and Sieh (1995). They speculate that they can determine the direction of horizontal propagation around a step. However, the rupture segments are clearly not connected in plan view, so they cannot be a result of horizontal propagation. They use results of fracture kink theory to explain the orientation of some rupture segments relative to others, whereas, again, the rupture segments are not connected, so they cannot represent kinks. The kinds of structures they describe are a three–dimensional phenomenon of fracturing (Cruikshank and others, 1991a; Scholz, 1992).

belt, and several narrower zones of more intense shearing within the belt. Each side is marked by a fault. There are very few fractures outside the belt. The right-lateral shear zones within the belt and the bounding faults are described elsewhere (Johnson and others, 1993, 1994).

The Two Ranches belt of shear zones contains numerous tension cracks (fig. 7). 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 on the maps (e.g., Plate 4). Nevertheless, the locations, spacing, lengths, and trends of tension cracks are shown accurately. Where tension cracks were absent on the ground, they are absent on the map. The tension cracks are most common in two areas: a belt parallel to the southwest edge of the broad shear zone and in a wedge-shaped zone near mid-width in the shear zone. 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-à-vis the ground on either side of the shear zone. Characteristically, the orientation of tension cracks throughout the area is north-south. The walls of the broad shear zone in this area (Plate 1) are oriented N30°W, so the tension cracks are oriented about 30° clockwise from the walls of the shear zone.

Scattered throughout the broad shear zone, and not obviously related to any throughgoing structures within the belt of shear zones, are highly irregular left-lateral fractures. Although the left-lateral fractures in the belt are generally parallel to the tension cracks, the primary fractures are the tension cracks. According to our analysis of the formation of left-lateral fractures of this type in the Summit Ridge shear zone (Johnson and Fleming, 1993), the fractures originate as tension cracks (fig. 9A) 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 overall right-lateral shear, and differential displacement between adjacent "dominos" produces the left-lateral offsets (fig. 9B).

Belt of Shear Zones along the Emerson Fault Zone

The same kinds of structures occur within the Emerson belt of shear zones, in the northern part of the Landers rupture (fig. 1 and Plate 2). The belt of shear zones is about 70 m wide and oriented N45° to 50°W. Tension cracks, oriented at clockwise angles from about 30° to 45° from the walls of the belt, are sparse throughout the width of belt; a few of them have minor left-lateral shift

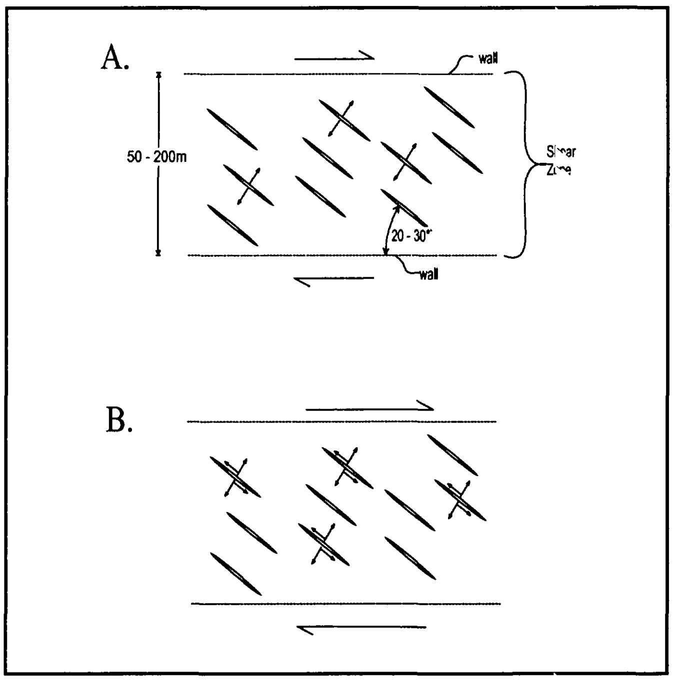


Figure 9. Idealization of rupturing in a broad shear zone. A. Rupture zone is a broad, right-lateral shear zone. Within the shear zone are tension cracks oriented at acute angles of perhaps 20 to 30° to the walls of the shear zone. B. After the tension cracks form, some of the tension cracks become complex fractures, and their modes of deformation change from pure opening to a combination of opening and shearing. The tension cracks become left-lateral, strike-slip fractures oriented at acute angles to the walls of the shear zone.

(Plate 2). There are a few, narrow, right-lateral shear zones within the broad shear zone in the northwest part of the single-tower powerline area. Most of the right-lateral shift across the rupture zone was accommodated by faults bounding either side of the belt.

The fault along the southwest wall of the belt accommodated about 20 cm of right-lateral and 0 to 10 cm of vertical (downthrown on northeast side) relative displacement. Along much of its length it consists of fractures several meters long, oriented north-south, and the blocks of ground between the fractures typically end in low thrusts, directed toward the center of the broad shear zone.

The main fault is along the northeast wall of the belt. It carries about 70 percent of the 2.9 m of total right-lateral deformation across the belt at the Single Tower Transmission Line. The main fault commonly is expressed as a "mole track," with a width ranging from perhaps 0.5 m in the northwest part of its trace to 10 m in the southeast part (Plate 3). It has a beaded, or "pinch-and-swell" structure that is particularly noticeable in the northwest part (Plate 3). The very narrow parts, the pinches, are a few tens of centimeters wide, although along parts of their lengths is a narrower groove, about a 10-cm wide and deep, probably representing a fault surface not far below the ground surface. The broader parts, the swells, are several meters wide and generally have distinctive internal structure. The broader parts contain long fractures oriented at a clockwise angle of about 30° to the trend of the shear zone. Where the fractures bound intact blocks, the blocks resemble the *ramps* that we will describe and illustrate in following pages. Typically, though, one or both ends of the blocks have been thrusted.

Another feature of the main fault is that the ground surface is depressed, perhaps up to 20 cm, along some stretches and raised, perhaps equally as much, along other stretches, so that, along strike of the fault, there will be repeating elongate basins and domes (Plate 3).

Relevance of Shear Zones

Shear zones are not generally recognized by geologists, except in metamorphic rocks, so one might well ask why we emphasize recognition of shear zones along the strike-slip faults at Landers. Part of the answer, of course, has already been iterated. Shear zones were described by investigators of the northern part of the fault ruptures of the 1906 San Francisco earthquakes, they have been recognized at Landers and at Loma Prieta, and they clearly pose hazards to man-made structures. Besides the existence of shear zones and belts of shear zones, there are six questions about these structures at Landers that can be addressed with our map data:

1. Can the ruptures be mapped analytically with photogrammetry? (Yes, at appropriate scales if one understands fracturing.)

2. Do belts of shear zones appear in bedrock as well as in alluvium? (Yes.)

3. Do belts of shear zones extend to depth, or are they near-surface phenomena? (We have no definitive information.)

4. What are the widths of belts of shear zones? (50 to at least 500 m.)

5. Where is offset accommodated? (In more than half, generally along a fault on one side of belt.)

6. Why is it important to recognize belts of shear zones? (Please read on.)

Can analytical maps of ruptures be made photogrammetrically?

In addressing the question about whether belts extend into bedrock, we made a photogeologic map of the Homestead Valley fault zone from its southern end at Reche Mountain, through the Two Ranches area near the intersection of Bodick Road and Shawnee Road, to Wildey Road (Plate 1), where the Kickapoo fault zone joins the Homestead Valley fault zone. As shown in the previous section, we made detailed maps (1:200

scale) of a small part of the rupture zone during the summer of 1992 while the fractures were fresh. A year later, we made detailed maps of surviving fractures from about 100 m south of Mileska Ranch (Shawnee Road) to about 1 km north of Mikiska Boulevard, including the Goatsucker Hill area (Plate 4).

Although we were generally disappointed with the level of detail that remained 1 year after the earthquake, several fascinating and previously unrecognized structures were documented. The tension cracks with the left-lateral shift were gone the second year. Only the right- and left-lateral, narrow shear zones composed of fault elements and tension cracks remained, and these were merely as ghosts of their former expression.

It is worth noting for future reference of geologists who decide to do photogeologic investigations of fault ruptures, that the level of detail we were able to map (even at 1:200 scale) in the field 1 year after the earthquake is comparable to the detail one can map with aerial photos, at a scale of 1:6000, taken immediately after the earthquake (Plates 1 and 2). A significant difference is that more kinematic information may be available in the field than can be obtained with the photos. Displacements can be obtained photogrammetrically, however, by methods described elsewhere (Fleming and others, 1997).

Regardless of scale or method of mapping, though, geologists studying fault ruptures should strive to make *analytical maps*. Analytical mapping of a structure is detailed mapping in which the scale is selected to show the essential features of the elements of the structure. In analytical mapping of fractures, one selects the scale of mapping so that the crucial information required to interpret the fractures is shown on the map. In principal, anyone familiar with fracture mechanics should be able to examine an analytical map and draw the same conclusions about the gross deformation accommodated by the fracturing depicted in the map (Fleming and Johnson, 1989; Johnson and Fleming, 1993; Martosudarmo and others, 1997). The scale of the analytical map is determined by the scale of fracturing, so it is quite different if one is studying the formation of the San Andreas fault zone as a plate boundary than if studying the mechanics of fracturing of ground along a strand of the San Andreas fault that passes through a property being considered for development, or studying microcracks in mineral grains in granite.

Belts in Bedrock?

One of the assertions made by a person in the audience at the 1994 Spring American Geophysical Union meeting, in response to our description of the belts of shear zones at Landers, is that the belts of shear zones are merely manifestations of faulting of soft, unconsolidated sediments and, therefore, are only superficial features.

Our mapping 1 year after the earthquake, however, showed that the belt of shear zones at the Two Ranches area extends northward at least 1 km, mostly through bedrock. Also, Sowers and others (1994) indicated that the belt of shear zones crosses bedrock in a low hill 200 m north of Mikiska Boulevard, as shown in aerial photos taken shortly after the earthquake (fig. 6A and fig. 6B). The boundaries of the belt can be traced from the left-lateral area (Pipes Wash step) shown near the base of figure 6A, through the Two Ranch area along Bodick Road, into the bedrock hills of Goatsucker Hill ridge. All of Goatsucker Hill ridge is shown in figure 6B, which is an unaltered photograph. Dibblee (1967) indicates that Goatsucker Hill is formed in Mesozoic quartz monzonite and diorite. Furthermore, according to our observations and the mapping of Sowers and others (1994), the Two Ranches area is on consolidated alluvium of Pleistocene to early Holocene age. Thus, at least the walls of the belt of shear zones extend into bedrock.

Maps of the Tortoise Hill area of the Emerson fault zone point to the same conclusion, as documented elsewhere (Fleming and others, 1997; Fleming and Johnson, 1997). Tortoise Hill ridge is underlain by granitic bedrock. According to Dibblee's geologic map (1964), Tortoise Hill ridge is part of a large granitic mass that extends for about 8 km along and 2 to 3 km southwest of the Emerson fault zone. The main break is on the northeastern side of the fault zone. Figure 10 shows Tortoise Hill ridge in the south (bottom) and the Single-Tower Transmission Line road in the north. Near the Single-Tower Transmission Line, the fault zone (belt of shear zones) is about 60 to 70 m wide and widens to about 500 m at Tortoise Hill ridge. The main break is on the northeastern side of the ridge and is alternately in alluvium or granitic bedrock. The rest of the fault zone is in bedrock.

Clearly belts of shear zones are not restricted to unconsolidated alluvium.

Do the Belts Extend to Depth?

We have no first-hand information about the depth the belts of shear zones extend into the earth's crust. If one were to assume that the belts extend half as far to depth as they extend along the ground surface, our compiled map of the Homestead Valley fault zone and Kickapoo stepover provides the following information: The Two-Ranches belt, along the Homestead Valley fault zone, extends over a horizontal distance of about 2 km. The belt in the vicinity of the Wildey Road (Plate 1) along the same fault zone is at least 3 km long. The belt of the Kickapoo fault zone is at least 5 km long (Plate 1). On this basis we might suggest that belts are half-circular elements that extend on the order of 1.5 to 2.5 km deep.

Observations by others, though, suggest that the belts extend much deeper. Low-velocity zones have been recognized along some earthquake faults, including those at Landers (Ben-Zion and Aki, 1990; Hough and others, 1994; Li and others, 1994a, 1994b). Hough and others (1994) reported entrapment of seismic waves in fault-zones within the rupture zone at the southern Joshua Tree earthquake area (April 1992). Their analyses indicate that the rupture

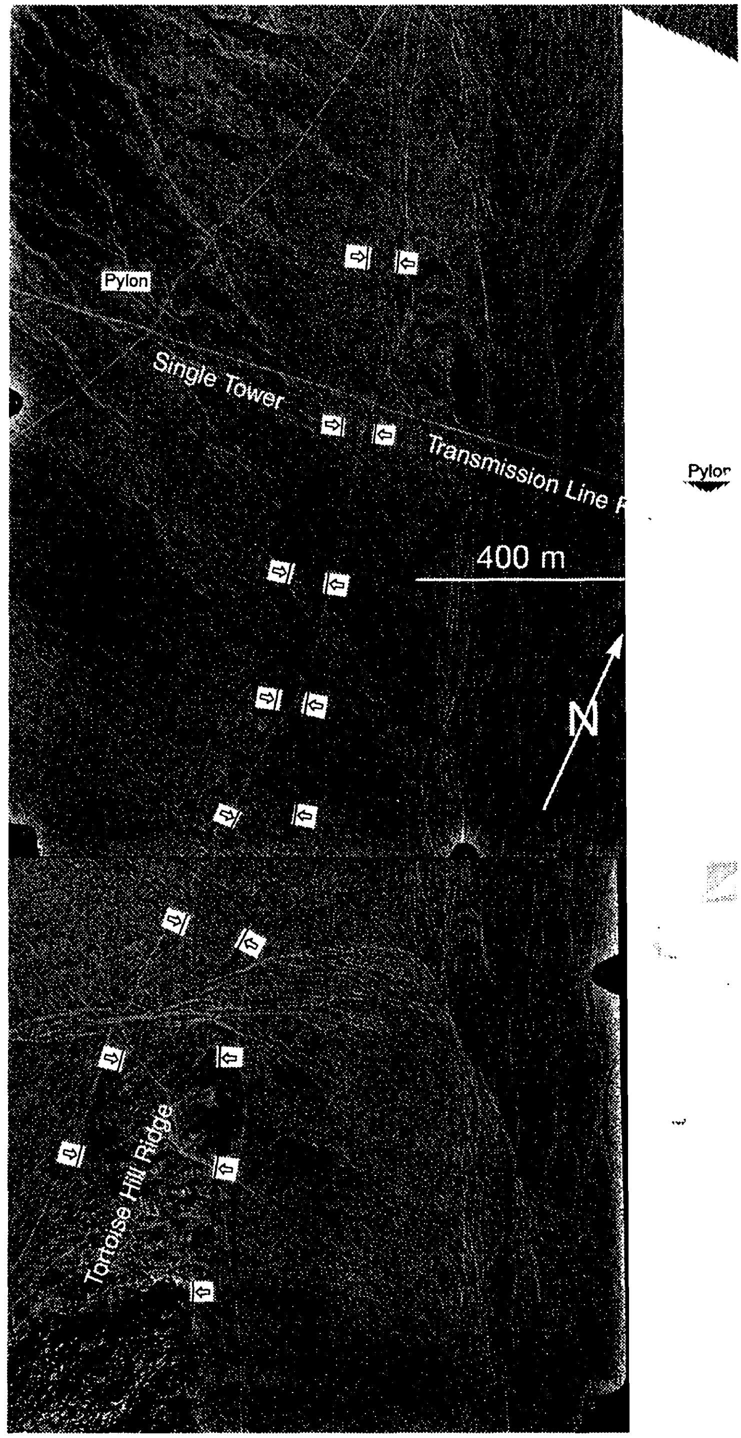


Figure 10. Vertical aerial photograph showing belt of shear zones along Emerson fault zone about 6 km north of Bessemer Mine Road. Road in upper part of area is along Single-Tower Transmission Line. At south end of photo is north end of Tortoise Hill ridge. Edges of belt shown with arrows. East (right) side of belt is defined by the main fault in this area. The belt is about 70 m wide at Transmission Line road and 400 m wide in part of ridge shown.

zones are 50 to 100 m wide. Aki, Li and others presented seismological evidence at the 1994 American Geophysical Union meeting in Baltimore, Maryland, that fault zones can be recognized at depth as low-velocity zones 50 to 200 m wide that extend to at least 10 km depths along the Johnson Valley and Homestead Valley fault zones at Landers (Aki, 1994; Li and others, 1994a). Thus, the belts of shear zones probably are not merely near-surface phenomena that extend for many kilometers along the ground surface, but may extend to depths of at least 10 km.

In spite of the geophysical studies by Aki and others, the subsurface form of belts of shear zones is, of course, unknown. Perhaps the belts of shear zones are surface expressions of "flower structures" at depth. Flower structures have been described in seismic images of strike-slip fault zones (Harding and Lowell, 1979; Harding, 1983; Harding and others, 1983; D'Onfro and Glagola, 1983; Plawman, 1983) and in rifts (Genik, 1993; Roberts, 1983). They have a diagnostic branching appearance, from a supposed single branch at depth (generally many kilometers) to two branches above, and then four, and so forth, as the flower structure approaches the ground surface. The branching structures do not appear in vertical seismic sections of simple thrusting or extensional regimes (e.g., Bally, 1983), so they probably are a results of interaction of strike-slip faulting with a free surface. The same may be true for belts of shear zones.

How Wide are Belts of Shear Zones?

In previous papers we have reported that belts of shear zones range from 50 to 200 m in width (Johnson and others, 1993, 1994). We now have, however, additional information that indicates widths of from 50 to 500 m. The Loma Prieta earthquake in northern California produced a belt of shear zones at Summit Ridge characterized by tension cracks and left-lateral faulting across a zone about 500 m wide. A peculiar feature of that belt is that it contained no throughgoing right-lateral shear zones, and was not bounded by faults, as were most of the broad shear zones at Landers.

The other places we have made observations sufficiently detailed to describe the widths of belts of shear zones are near Landers. The belt of shear zones along the Emerson fault zone at the Single-Tower Transmission Line was about 70 m wide. The belt generally widened southward. If we include Tortoise Hill ridge, the belt of shear zones there was about 500 m wide. The belt of shear zones along the Homestead Valley fault zone ranges up to about 200 m wide. Immediately north of the place where the Kickapoo fault zone and Homestead Valley fault zone join, the belt of shear zones is about 500 m wide.

Where is Offset Accommodated?

It has become common practice in earthquake studies to dig exploratory trenches in order to determine the amount or timing of slip on faults, particularly in developing areas where planners wish to avoid construction of crucial man-made structures on traces of active faults. A fundamental assumption is that the slip of an earthquake rupture is accommodated by a single fracture or a narrow rupture zone that can be exposed in an exploratory trench a few meters long. This assumption turns out to be an unfortunate one. Much of the damage to structures at Landers was a result of position of structures *within* belts of shear zones, not on the bounding faults (Lazarte and others, 1994).

For investigations of siting of structures near fault zones it would be helpful to know how differential displacement is distributed across the fault zone. In general such information is unavailable, for many reasons. In the absence of such information, one might assume that the distribution of strike-slip fault zones will be something like that across the belts of shear zones that we have documented at Loma Prieta and Landers. We have already seen that, at both Loma Prieta and Landers, the offsets are distributed across broad belts of shear zones, ranging in width from perhaps 50 to 500 m. The distribution of offset, though, is drastically different from place to place. In the epicentral area of Loma Prieta, the width of the right-lateral rupture zones ranged from perhaps 2 to 5 m to 500 m. In the former, the zones presumably represented faults and they accommodated 10 to 20 cm of right-lateral offset. In the latter, the zone contained left-lateral displacements on the same order, but the offset was rather uniformly distributed; there were no faults bounding the 500-m wide zone.

At Landers there was a wide variety of distributions of differential displacement but, in general, the shift was accommodated primarily by a fault at the wall of a belt of shear zones. At the Emerson fault zone at the Single-Tower Transmission Line, the belt of shear zones is about 70 m wide; about 2.7 of the 3.0 m of shift across the fault zone was along a fault bounding the northeast side of the zone. A fault on the southwest side of the belt accommodated only about 20 cm of differential displacement. Between Mikiska Boulevard and Bodick Road, along the Homestead Valley fault zone, about 60 cm of the total of 180 to 200 cm of shift was across a fault bounding the belt on the northeast. About 100 cm of shift was across a 12-m wide band, including the fault, on the northeast side of the belt. The shift across the fault bounding the northwest side of the belt was 20 to 30 cm. The shift across each of the shear zones within the belt was generally 5 to 10 cm. About 200 m south, at Mileska Ranch, the shear zone on the northeast side of the belt accommodated only 10 to 20 cm. Across about 20 m of the northeast side, 115 cm were accommodated. The remaining 75 to 85 cm of shift were distributed in some way across a belt 200 m wide there.

Our study of the distribution of shift across the Kickapoo fault zone, in the Two Bikers area at Fifth Avenue and the Charles area north of Bodick Road, indicates that there are no bounding faults (Plate 1). Rather, the faults, or narrow shear zones that make up the belt of shear zones, are arranged *en echelon*, and each member fault accommodates much of the total shift at certain points, but that the shift is transferred from member to member.

Clearly one cannot reasonably assume that slip is accommodated only on a single fault trace during an earthquake.

Why is it Important to Recognize Belts of Shear Zones?

There are several reasons it is important to recognize that surface rupture during earthquakes may be represented by belts of shear zones rather than by faults.

1. One is the simple precept of honest scientific description. If an earthquake rupture occurs across a belt 200 m wide and the rupture is mapped as a line (planar fault), reality has been grossly misrepresented.

2. Another important reason was illustrated at Loma Prieta. Detailed mapping in the epicentral area along Summit Ridge revealed that the area is a broad shear zone or belt of shear zones (Johnson and Fleming, 1993; Martosudarmo and others, 1997). This was not recognized by numerous geologists who examined fractures in the epicentral area (e.g., Ponti and Wells, 1991; Prentice and Swartz, 1991; U.S. Geological Survey Staff, 1989, 1990). Neither did we recognize the shear zone at the time of our mapping there; we were puzzled by the left-lateral fractures, but we did not ignore them (e.g., see Aydin and others, 1992). Only later, after experience at Landers, did we recognize the significance of the left-lateral offsets on fractures in a right-lateral zone (Johnson and Fleming, 1993). The outstanding quality of the ground rupture at Landers provided several examples of small-scale models of the fracturing at Loma Prieta.

3. Many fault studies are based on information derived from exploratory trenches. The studies are to determine amounts and timing of "slip" on faults. Derived slip rates for faults are compared to plate motions and recurrence interval of earthquakes, as well as certain characteristics of causal earthquakes. If large fractions of shift during an earthquake occur across broad zones rather than across discrete fault surfaces

or the rather narrow zones exposed in trenches, much of the shift will be missed in the trenching. Slip rates would generally be under-stated.

4. Perhaps the most important reason is for theoretical modeling. If we are to develop valid theoretical models of essential mechanisms and mechanics of seismic faulting, our models must include the essential features of the ruptures. Belts of shear zones probably do not occur everywhere along earthquake ruptures, so it might be important to understand conditions under which rupture is across belts, or across one, or more, slip surfaces. Perhaps some aspect of belts is incorporated in recent theoretical modeling of earthquake ruptures by Yehuda Ben-Zion and Jim Rice (Rice, 1993; Ben-Zion, 1995; Ben-Zion and Rice, 1993, 1995).

5. There are also practical reasons.

When the senior author was Town Geologist for Portola Valley, California, the town was concerned about the placement of various kinds of structures within the San Andreas fault zone. The problem is that Portola Valley is largely sited in the San Andreas fault zone. Our chore was to find the traces of the recent breaks and provide narrow zones of setback from those traces (e.g., Hart, 1992; Engineering and Science, 1992; Irvine and Hill, 1993; Hart and others, 1993). The procedure we followed in Portola Valley at that time was flawed.

The issue concerns whether the pattern of coseismic ground deformation at a site is highly localized along a fault or is dispersed across a belt of shear zones. At Landers, we noted that the main break occurs on one side or the other of the belt of shear zones. Where this occurs, it is important to provide the setback on the correct (undeformed) side of the main break. At Landers, most of the damage to structures was caused by deformation to houses built within belts of shear zones (Lazarte and others, 1994). By sheer luck, very few structures were built across the main breaks. A possible conclusion is that, with respect to ground rupture, one can more–nearly safely ignore the main breaks than the belts of shear zones!

Of course, there is always the question of spatial recurrence. Will the shear zones rupture along the same belt during the next earthquake event on a fault segment? Data from the Loma Prieta and 1906-San Francisco earthquakes (Sarna-Wojcicki and others, 1975; Johnson and Fleming, 1993; Martosudarmo and others, 1997) indicate that there may be a strong correlation between patterns of surface rupture in succeeding earthquakes. In 1989, though, the main break accommodated only a few tens of centimeters of offset in a few patches, whereas there were generally hundreds of centimeters of offset in 1906. The earlier, San Francisco earthquake was several times larger that the Loma Prieta earthquake. Had the timing of the two earthquakes been reversed, the conclusion of similarity of rupturing might be different.

Control of the Orientations of Tension Cracks Within Shear Zones

Shear zones are expressed in many places by *en echelon* tension cracks, and the primary fractures in broad shear zones are the tension cracks (Johnson and Fleming, 1993; Johnson and others, 1993, 1994; Lazarte and others, 1994). There is significant difference in the angle between the traces of the walls and the traces of the cracks in the shear zones. In this section, we examine the controls on the angle.

Shear-Zone Model

Although the magnitudes of the principal stresses within the belt of shear zones at Landers are unknown, we do know that the deformation responsible for the tension cracks was not pure shear oriented parallel to the walls of the shear zone, as is commonly assumed for simple shear along a fault zone. If the deformation were simple shear, the tension cracks would be oriented 45° (not 30° to 40°) clockwise from the walls of a right-lateral shear zone. The strong preferred orientation of the tension cracks at Landers indicates that the direction of crack propagation parallel to the ground surface was *stabilized* (Cottrell and Rice, 1980; Cruikshank and others, 1991a, p. 875), so the principal stress parallel to the fractures was either zero or compressive. Simple shear parallel to the belt, plus additional pure shear with maximum tension normal to the belt, would provide the orientations of cracks we observe, as well as the necessary compression to stabilize the propagation direction of the tension cracks.

Our interpretation of the stresses near the ground surface, plus the observation that the tension cracks are localized within a distinctive zone a few meters wide, or in a belt a few hundred meters wide, and are absent in ground on either side of the zone or belt, suggest a model in which the ground surface was subjected to localized shearing plus dilation by a broad shear zone at greater depth. This conceptual model is closely related to that which we proposed to explain *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; Pollard and others, 1982).

Our current conceptual model predicts that a combination of shearing and dilation in a shear zone at depth would produce shearing and *tension* in consolidated, 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 walls of the shear zone below, and tension normal to the walls of the shear zone above. The change in normal stress is a result of the tendency for the shear zone to dilate and the consolidated alluvium to resist dilation. Since the material in the shear zone is coupled in terms of shear to the material in the overlying consolidated alluvium, the deformations and stress states of the two materials are compromised via shear stresses generated at the interface between the shear zone and the brittle alluvium. 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 orientations between 0° and 45°. Thus, the conceptual model qualitatively explains the orientation of the tension cracks.

Two 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.

To visualize how the shear zone would produce numerous tension cracks, 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. This is verifiable qualitatively by examining the three-dimensional differential equation of equilibrium for a horizontal direction in terms of stresses (e.g., Johnson, 1970). Because of 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 (also, see Lachenbruch, 1962).

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.

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 the consolidated alluvium above. As shown elsewhere, the ratio of strain increments can, in some circumstances, be related to the *angle of dilatancy, $\mathcal{D}$*, of the material in the shear zone (Johnson, 1995). In dilatant shearing, 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, $\mathcal{D}$.

$$\tan(\mathcal{D}) = \delta\varepsilon_n / 2 \, |\delta\varepsilon_s| \quad (1)$$

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

$$\tan(2\theta) = 2\delta\varepsilon_s / \delta\varepsilon_n \quad (2)$$

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 a maximum, $\delta\gamma_s$, the shear strain is positive if right-lateral, and $\delta\varepsilon_n$ and $\mathcal{D}$ 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:

$$\tan(2\theta) = \cot(\mathcal{D}) \, \mathrm{sgn}(\delta\varepsilon_s)$$

or

$$\theta = [(\pi/4) - \mathcal{D}/2] \, \mathrm{sgn}(\delta\varepsilon_s) \quad (3)$$

in which $\mathcal{D}$ is angle of dilatancy and $\mathrm{sgn}(\delta\varepsilon_s)$ is +1 if the shearing is right-lateral, and -1 if the shearing is left-lateral. This is the general case, for right- and left-lateral shearing.

Curiously, this equation (3) for the orientation of tension cracks within shear zones is identical in appearance to the Coulomb expression for orientations of shear bands in a body of granular material,

$$\alpha = \pm \, [(\pi/4) - \phi/2]$$

in which ϕ is angle of internal friction. Here θ is the clockwise angle between the trace of the wall of the shear zone and the trace of the tension crack (i.e., the maximum compression direction) *within the shear zone*, whereas α is the angle between the direction of maximum compression *within a deforming body* and the trace of the conjugate, Coulomb shear bands within the body.

Example of Dilation

Photogrammetric measurements of displacements and deformations within the Tortoise Hill ridge provide rather detailed information about the horizontal dilation of rock within the ridge and within the belt of shear zones. As described elsewhere (Fleming and others, 1997; Fleming and Johnson, 1997), Tortoise Hill ridge grew about 1 m in altitude as the belt of shear zones about 400 m wide, including the ridge, accommodated about 3 m of right-lateral shift. We used aerial photographs (1:6,000 scale) taken before and after the Landers earthquake to determine the kinematics with the ladder of braced quadrilaterals shown in figure 11 and Plate 5. The horizontal and vertical differential displacements of corners of the quadrilaterals are shown in figure 11. The vertical differential displacements, du(z), and the components of the horizontal displacements parallel du(y′) and normal du(x′) to the eastern wall of the fault zone, are shown in table 1 (original data presented in an appendix of a paper by Fleming and others, 1997). The displacements are relative to one point of Quadrilateral 2 southwest of the Emerson fault zone. Corners of the quadrilaterals are assigned a letter, A, B, C or D, in a clockwise sequence, starting at the northernmost corner of each quadrilateral. The pattern is shown by the letters in table 1. Thus, point D is the fixed point of Quadrilateral 2 at 0.21 m. The vectors obtained by (vector) addition of horizontal components du(x′) and du(y′) are shown in figure 11.

Using this quadrilateral network we found that the walls of the Emerson fault zone (including the ridge) dilated, but the ground within the ridge itself dilated slightly more. The data in table 1 indicate that there was net dilation of 0.18 to 0.21 m between the most distant points of

Quads 2 and 3. That is, the horizontal distance from a point outside the ridge on the southwest to points about 350 m away, outside the ridge in the northeast, increased in length by 0.18 to 0.21 m. The dilation is slightly larger, 0.21 to 0.30 m, for the most distant quadrilateral corners within the ridge, that is, from the lower corners of Quad 0 to points about 170 m away, at the upper corners of Quad 1. Thus the ground within the ridge is, in effect, spilling over the walls of the Emerson fault zone. Although we have suspected such dilation in fault zones (Johnson, 1995), it had not previously been measured.

The dilation within the ridge is expressed in part by a reverse fault dipping about 45° toward the northeast on the southwest side of the ridge, and a very high angle reverse fault dipping about 86° toward the southwest on the northeast side of the ridge (Plate 5). These faults, though, do not account for the net dilation of 0.18 to 0.21 m for points outside the ridge.

With respect to the present discussion, the notion is that a dilating body, analogous to Tortoise Hill ridge, lies below a blanket of com-

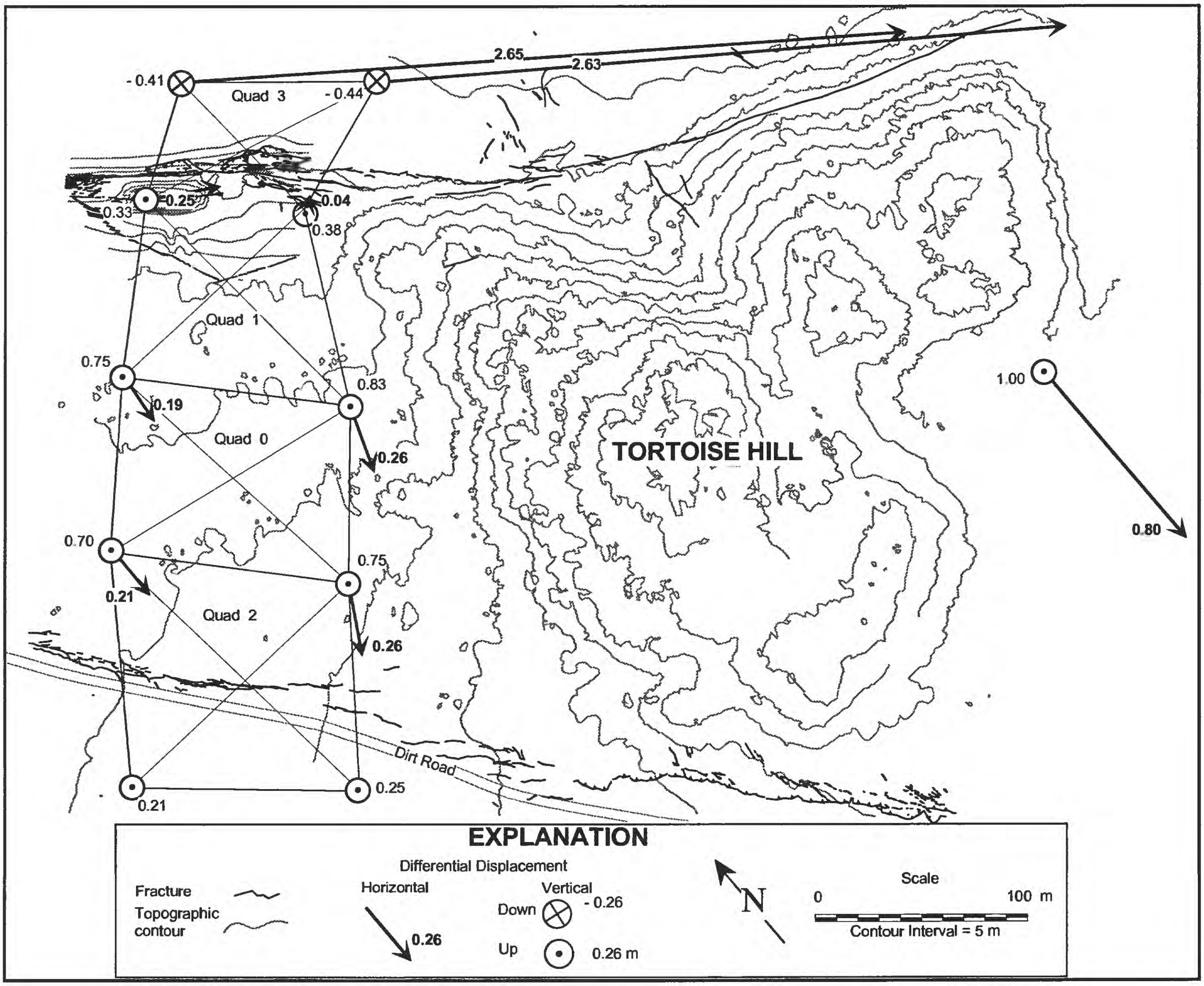


Figure 11. Map showing fractures bounding margins of Tortoise Hill ridge and differential displacements measured photogrammetically. A ladder of quadrilaterals extends across the ridge. At southeast edge, displacements were measured by land survey of regional grid. Maximum horizontal shift across ridge about 2.65 m. Maximum vertical displacement, relative to an assumed fixed point about 6 km south of ridge, is 1.0 m at center of ridge.

Table 1. Relative Displacements of Corners of Quadrilaterals at Tortoise Hill
(D of Quad 2 held fixed)

		du(x′,m)	du(y′,m)	du(z,m)		du(x′,m)	du(y′,m)	du(z,m)
	A	2.64	0.18	-0.41	B	2.62	0.21	-0.44
Quad 3					(3)			
	D				C			
		0.24	0.05	0.33		0.01	0.04	0.38
	A				B			
Quad 1					(1)			
	D				C			
		0.11	-0.16	0.75		-0.09	-0.24	0.83
	A				B			
Quad 0					(0)			
	D				C			
		0.13	-0.16	0.70		0.05	-0.26	0.75
	A				B			
Quad 2					(2)			
	D	0.0	0.0	0.21	C	0.0	0.0	0.25

pact alluvium, and the dilation and shearing are expressed at the ground surface.

Application to Measurements

Unfortunately, we have only three documented examples of orientations of tension cracks within shear zones and belts of shear zones. The examples are in areas we mapped in detail (e.g., 1:200 scale) within a few weeks of the earthquake. The tension cracks soon eroded and filled, and a year later, when we returned to complete the mapping, most of the tension cracks had vanished.

Fortunately, we mapped key areas. Probably the most important is the Two Ranches area (Plate 1) along the Homestead Valley fault zone, which we have described in previous pages and elsewhere (Johnson and others, 1993, 1994). The tension cracks occur throughout the belt, so the entire belt appears to be a broad shear zone. Traces of individual tension cracks within the belt extend irregularly for 1 to 10 m. Although variable, their openings are generally a few millimeters to perhaps a centimeter. They have rough walls—characteristic of tensile failure—and their traces are extremely irregular. The overall trends of the traces of the tension cracks, however, are remarkably consistently north-south throughout the Two Ranches area. The orientation of tension cracks near the center of the belt of shear zones is 34° or 35° clockwise with respect to the northeast wall of the belt and 30° clockwise with respect to the northwest wall of the belt.

Insofar as the assumptions behind the theory in eq. (3) are relevant to the formation of the tension cracks in the Two Ranches area, we can use the orientation of the tension cracks to assess the state of deformation in the shear zone, below. Thus, if we assume that the maximum tension in the near-surface alluvium corresponds to the maximum extension in the underlying broad shear zone, then for the Two Ranches area $\mathrm{sgn}[\delta\varepsilon_s] = +1$, $\theta = +30°$, and therefore, eq. (3) indicates that the angle of dilatancy is $\mathcal{D} = +30°$ for deformation in the broad shear zone. This angle of dilatancy is similar to that computed for deformation bands in Entrada Sandstone in Utah (Johnson, 1995).

The tension cracks within the Happy Trail shear zone (Plate 1), described in previous papers (Johnson and others, 1993, 1994), are oriented about 35° clockwise from the traces of the walls of the shear zone. 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 Happy Trail area, we have $\mathrm{sgn}[\delta\gamma_s] = +1$ and $\theta = +35°$, and therefore, the angle of dilatancy is $\mathcal{D} = +20°$ for deformation in the shear zone.

The surficial materials in the Single Tower Transmission Line area, along the Emerson Fault zone (Plate 3), are much softer than those in the Two Ranches area, indicating that the tension cracks were quite poorly developed, even immediately after the earthquake. As indicated on Plates 2 and 3, though, we were able to map tension cracks in some areas within the belt of shear zones. They are the features shown with short line segments oriented roughly north-south about 80 m southeast, and most of the fractures shown between 40 and 100 m northwest of the Single Tower Transmission Line road. The former are closer to the southwest wall and the latter are closer to the northeast wall of the belt. In both areas, the tension cracks are oriented at clockwise angles of 40° to 45° from the trend of the northeast wall of the belt of shear zones. If we assume that the maximum tension in the near-surface alluvium corresponds to the maximum extension in a broad shear zone below, then we have $\mathrm{sgn}[\delta\gamma_s] = +1$ and $\theta = +40°$ to 45°, and therefore, the angle of dilatancy is $\mathcal{D} = +0°$ to 10° for deformation in the broad shear zone. This angle is much smaller than that for the consolidated alluvium. It is similar to that of some kink bands in the Appalachians and in clay at certain water contents (Johnson, 1995).

Thus, the orientation of tension cracks appears to be a function of the physical characteristics of the material in the shear zone beneath the ground surface.

Kinematics of *En Echelon* Shear-Zones and Fault Elements

The kinematics of individual *en echelon* fault elements (or cracks) are basic to understanding the structural significance of arrays of cracks and fault elements.

Fault Elements

Fault elements within shear zones are nearly as common as tension cracks, but carry a different kinematic signature. In complex structural situations, they are very useful guides to deformational behavior.

En echelon faults were common in the fault zones of landslides in Utah (Fleming and Johnson, 1989), where they appeared to represent blades of an underlying strike-slip fault that reached the ground surface before the main strike-slip fault. The strike of their traces deviates about 10° from the strike of the fault zone (Fleming and Johnson, 1989, fig. 13). In one landslide, a detailed map of 15 fault elements over a horizontal distance of 40 m shows that orientations of the fault elements range from parallel to 20° clockwise (for a right-lateral shear zone) with respect to the trend of the fault zone. Traces of the elements range in length from a few tens of centimeters to about 200 cm. At the ground surface, many of the fault elements are open and have thus become complex fractures as a result of continuing displacement of the landslide. We can recognize the complex history and that the fractures originated as mode *II* or mode *III* structures (faults) because the surfaces of the fault elements are slickensided to within about 5 cm of the ground surface.

There are two obvious differences between the tension cracks and the fault elements in the landslides. First, the traces of tension cracks tend to be oriented 30° to 45° clockwise, whereas those fault elements tend to be oriented 5° to 20° clockwise to the trend of the walls of the right-lateral fault zones. Second, the surfaces of the tension cracks are rough and irregular, whereas those of the fault elements are smooth and slickensided a few centimeters below the ground surface.

In the coseismic shear zones at Landers, the long tension cracks and the fault elements both have traces of several meters to about 10 m. The traces of right-lateral fault elements are oriented at a small clockwise angle, whereas the traces of the tension cracks are oriented at a large clockwise angle to the walls of right-lateral shear zones. The surfaces of all fractures we could observe within a few centimeters of the ground surface were rough and therefore non-diagnostic. We did not excavate.

The foregoing generalizations about differences in orientations of tension cracks and fault elements would be circular if the orientations were used to ascertain the origin of a fracture (as pointed out so clearly by Gilbert, 1928). Probably the best method to distinguish between tension cracks and fault elements in the absence of slickensides is at the terminations of the fractures. A strike-slip-fault segment carries displacement parallel to the trace of the fracture. At the tip of the fracture, the displacement is transferred to an adjacent *en echelon* fracture either through compressive structures (buckle folds, thrust faults, domes, etc.) or tension cracks that develop as opening fractures extending obliquely from the ends of the fault elements (Fleming and Johnson, 1989). The compressive structures are expected between tips of adjacent fault elements because of the sense of stepping. Right-lateral segments step left, and left-lateral segments step right. The tips of *en echelon* tension cracks carry no structures at their tips. Continued shear displacement of a group of *en echelon* tension cracks produces further opening and rotation of the cracks into a sigmoidal form.

Gilbert's Law of Oblique Fault (Restraining) Branches

An important type of *en echelon* faulting was recognized by G.K. Gilbert, both along the 1906 earthquake rupture zone north of San Francisco (Gilbert, 1907; Lawson, 1908) and along normal faults near Salt Lake City. According to the latter, Gilbert (1928, p. 13 reported):

> "Slipping surfaces of another class are not parallel but oblique to the main fault surface. Their obliquity follows a law, and the law is illustrated by analogous phenomena connected with the California earthquake of 1906. The fault movement which caused that earthquake was horizontal, on a plane trending northwest. ...The visible expression of the faulting was mainly in a surface mantle of earth and included a system of oblique cracks, such as are shown diagrammatically in [fig. 2]. In places (a, [fig. 2]) the fault trace included two walls, with relative displacement as indicated by arrows, and between them a belt of broken earth. The principal cracks within the belt were oblique, as indicated. In other places (b, [fig. 2]) the walls were not developed and the fault trace consisted of a system of oblique cracks, as indicated. From the walls of the fault trace ran branching cracks (c, [fig. 2]), the divergence being at various angles but always to the right of one looking along the trace. The trace in places (d, [fig. 2]) swerved to the right and gradually disappeared, to reappear at the left en échelon.
>
> ...The law, both theoretic and empiric, is that the planes of oblique subsidiary slipping surfaces associated with a fault all deviate in the same way from the plane of the fault. In connection with a normal fault their deviation is toward the vertical; in connection with a reverse fault, toward the horizontal (see [fig. 3]). The law applies to oblique slickened partings within the fault rock, as well as to those in wall rock, and is of service in determining the direction of slip on the principal fault plane."

Thus, *Gilbert's law of oblique fault branching* is a statement, in effect, that faults branch to form what has become known as a restraining step. Indeed, in our experience, *en echelon* fault elements commonly are arranged with that pattern.

Releasing and Restraining Steps

Examination of any fault system, though, indicates that fault elements step (or jog) in both restraining and releasing configurations.

Restraining steps form where right-lateral segments step to the left, or where left-lateral segments step to the right (in short, "opposite-stepping"). Releasing steps form where right-lateral segments step to the right or where left-lateral segments step to the left (in short, "same-stepping").

In a study of strike-slip fault elements in Utah sandstones (Cruikshank and others, 1991a), we found where parts of a single fault had restraining steps and releasing steps along its length. In a study of strike-slip faults bounding landslides in Utah (Fleming and Johnson, 1989), our findings were the same, but most newly–formed fault elements had "opposite steps." Thus the newly–formed segments followed Gilbert's law of oblique faulting. There were, however, some releasing steps as well.

Kinematic Analysis of *En echelon* Zones

Geometry

In order to describe the two-dimensional kinematics of *en echelon* faults or cracks, we need to consider several geometric quantities, including the walls, the width, and the spacing, of the *en echelon* zone (fig. 12A). The walls are imaginary lines, or traces of fault elements, that bound the *en echelon* zone. The walls are oriented at a certain angle, θ, measured (for example) counterclockwise from east. The spacing of the walls is the width, *w*. The spacing (average, generally) of the *en echelon* segments is *s*. The (counterclockwise) orientation of the *en echelon* segments relative to the walls is α. These quantities uniquely describe the essential features of a simple pattern of *en echelon* fault or crack elements. We can also relate the geometry of the *en echelon* pattern to the length, ℓ, of an *en echelon* fault element and to the overlap, o, of adjacent fault elements (as defined in fig. 12A). Thus,

$$\ell = w/\sin(\alpha) \quad (3a)$$

$$o = s/\tan(a) \quad (3b)$$

$$(o/\ell) = (s/w)\cos(\alpha) \quad (3c)$$

With these quantities we can completely describe a simple set of *en echelon* fault or crack elements. For example, figure 12A shows a series of *right-stepping, en echelon* segments and figure 12B shows a series of *left-stepping en echelon* segments. Whether they are left-stepping or right-stepping depends on the angle α. If α is between 0° and 90° (or between 180° and 270°) (fig. 12A), the segments are right-stepping. If α is between 90° and 180° (or between 270° and 360°) (fig. 12B), the segments are left-stepping. Table 2 contains summary data for structures that we will be describing in following pages.

The ratio of the spacing of the fractures to the width of the fracture zone largely controls the appearance of *en echelon* fractures. The spacing of *en echelon* fractures in the zone is less than the width of the zone in the examples shown in figure 12A and B, where the zone appears as a compact set of fractures.

The spacing is greater than the width in the example shown in figure 13A, where the zone appears as offset fault elements or blades. This example resembles *en echelon* fault elements in a strike-slip fault in a landslide flank (Fleming and Johnson, 1989) and in some earthquake fault zones (e.g., Johnson and others, 1993, 1994).

Differential Displacement

Another essential piece of kinematic information concerning a set of *en echelon* faults or cracks is the direction (β) and magnitude (D) of the differential displacement across the walls of the *en echelon* zone (fig. 12A). In general we think of the differential displacement being parallel to the walls, and the only remaining question is whether the displacement is right-lateral or left-lateral, but in fact the problem is more complex. The direction of differential displacement may be oblique to the walls, in which case there might be strike slip as well as normal slip or separation along the *en echelon* segments. The normal slip may be compressional, in which case the fault elements accommodate thrusting as well as strike slip, or it may be extensional, in which case the

Table 2. Geometric Elements of Duplex and *En echelon* Structures at Landers
(lengths in meters)

Name*	Width (w) of echelon zone (m)	Spacing (s/w) of echelon segments	Shift (D/w) across echelon zone	Orientation (α) of echelon segments	Overlap (o/w) of bounding segments
STTL	20	0.20	0.140	160°	4
Headquarters	86	0.13	0.014	150°	8.8
Within H.Q.	16	0.18-0.4	—	160°	—
H-E S.O.	560	0.5	0.005	130°	2.1
Kickapoo S.O.	810	0.23	0.004	120-170°	1.6
Within K. fault	230	0.6	0.01	160-170°	
Charles Rd.	100	0.4	—	170°	—
Within C.R.	12	0.2	—	163°	—
Two Bikers	45	0.33	0.027	170°	—
Within T.B.	6	0.5	—	165°	—
Pipes Wash (LL)	5.5	0.6	—	15°	—

* Note:
H-E = Homestead-Emerson.
STTL = Single Tower Transmission Line site along Emerson fault zone.
H.Q. = Headquarters
S.O. = stepover
K. fault = Kickapoo fault zone
C.R. = Charles Road
T.B. = Two Bikers
LL = left-lateral (others are right-lateral)

fault elements accommodate normal faulting as well as strike slip.

In situations where the *en echelon* fractures separate blocks that are rotating (e.g., Ron and others, 1984), we can describe the slip between blocks in terms of the shift across the rupture zone (e.g., Fleming and Johnson, 1989; Johnson and Fleming, 1993). We have derived the following results (Johnson and Fleming, 1993) for *en echelon* tension cracks: In the derivation, we use the notation in figure 12, except that δU is the component of shift across but parallel to the *en echelon* zone. δU is negative if shearing is right lateral. Assuming no change in width, w, of the shear zone, the increment of angle is related to the increment of slip through the relation (Johnson and Fleming, 1993)

$$\delta U = - w \csc^2(\alpha)\, \delta\alpha \qquad (4)$$

Further, δu is the increment of differential slip between a block bounded by fractures. As the block rotates, an increment of (left-lateral) slip, δu, between the blocks is proportional to the fixed spacing s of the tension cracks and the increase of angle, $\delta\alpha$, due to right-lateral shear

$$\delta u = s\, \delta\alpha \qquad (5)$$

Combining these results,

$$(\delta u / s) = - (\delta U / w) \sin^2(\alpha) \qquad (6)$$

in which the slip along tension cracks, δu, and the shift across the shear zone, δU, are both positive if left lateral, w and s are fixed, and α is the

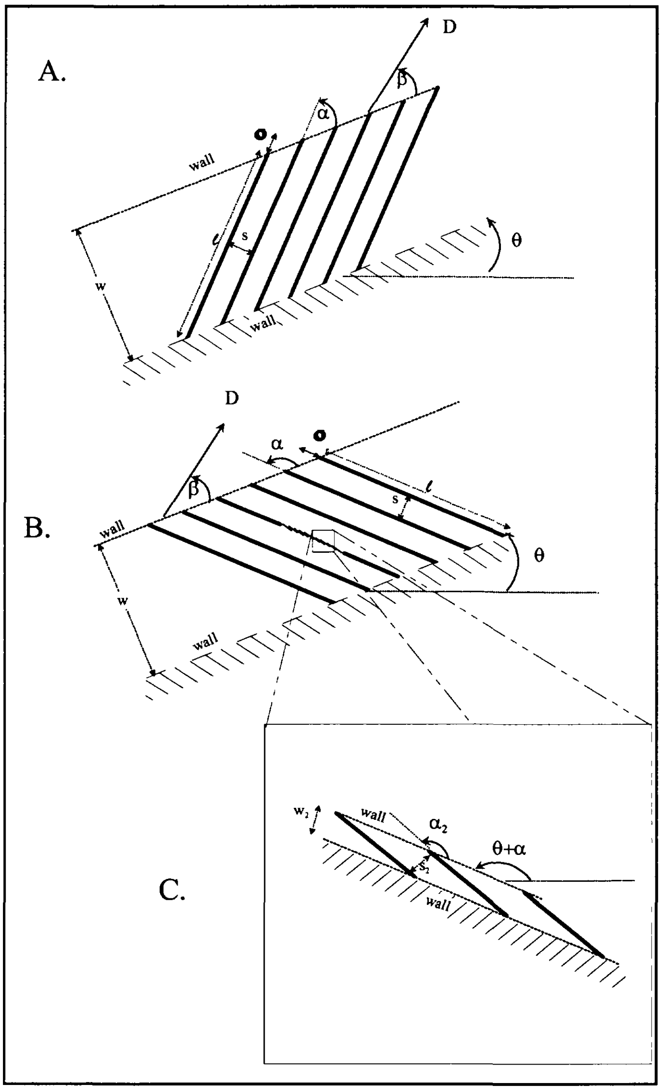


Figure 12. Idealized arrangement of en echelon faults or cracks, showing dimensions and angles measured to describe the geometry of such structures. A. Arbitrarily-oriented belt, showing differential displacement vector, D, of upper wall relative to lower. The dimensions and angles characterize the geometry of the elements. In this case the en echelon fractures are at an acute angle, α, to the walls. B. The en echelon fractures here are at an obtuse angle to the walls. Otherwise, the same as in A. C. Each element of an en echelon fracture may, itself, be composed of shorter en echelon elements, as shown in this detail. Note that the walls for these smaller en echelon elements are parallel the larger elements comprising the larger en echelon structure.

current angle between the walls of the shear zone and the tension cracks. Note that whatever the angle, if the shift, δU, across the zone is right lateral (negative), the increment of slip, δu, across the tension cracks will be left lateral (positive).

With eq. (6) we can relate the slip across *en echelon* fractures separating rotating blocks to the shift across the zone of *en echelon* fractures in terms of the orientation and spacing of *en echelon* fractures and the width of the *en echelon* zone.

Strike-Slip Duplex Structures

Many *en echelon* fractures or faults are part of a duplex geometry (Boyer and Elliott, 1982; Cruikshank and others, 1991b), in which there are shorter faults arranged *en echelon* between longer, stepping, bounding faults. The shorter faults are oriented at an acute angle to the bounding faults, whether the slip on the bounding faults is right lateral or left lateral. If the bounding faults step in a left sense (determined by looking along the trace of bounding faults), the angle is counterclockwise. If they step in a right-lateral sense, the angle is clockwise. In a *right-lateral duplex structure* of the type we observed at Landers, the bounding faults are right lateral, as are the internal faults within the duplex (fig. 14A).

Thus, whether there are bounding faults (and, if so, the geometry of bounding faults) is yet another important factor that determines the kinematic pattern of *en echelon* faults or shear-zones.

At Landers, duplex structures formed at several places along narrow, strike-slip shear zones or faults where faults or shear zones step right, and the shift is right-lateral. We previously described duplex structures along strike-slip faults at Arches National Park in Utah (Cruikshank and others, 1991b). A difference is that the duplex structures at Landers formed at the ground surface where the vertical stress was zero, whereas those that formed in sandstone in Utah formed at a depth of several kilometers and, therefore, under large vertical stresses. In the area of

Arches National Park there are some rather simple conjugate, strike-slip faults that accommodated a few centimeters of offset, and the faults are in segments that form restraining or releasing steps. For either type of step, there, the steps contain ramp faults and thus have the fault pattern of duplex structures. We have shown that the structures not only look like duplex structures, but that their internal kinematics are those of the classic duplex structure described along thrust faults (e.g. Boyer and Elliott, 1982, Johnson and Berger, 1989; Cruikshank and others, 1991b). Although the duplex structures form at restraining as well as releasing steps, left-lateral faults have predominantly right-steps, and right-lateral faults have predominantly left-steps, so the majority of the steps in the area are of the restraining type.

The duplex structures that we observed at Landers are all of the releasing type (fig. 14B).

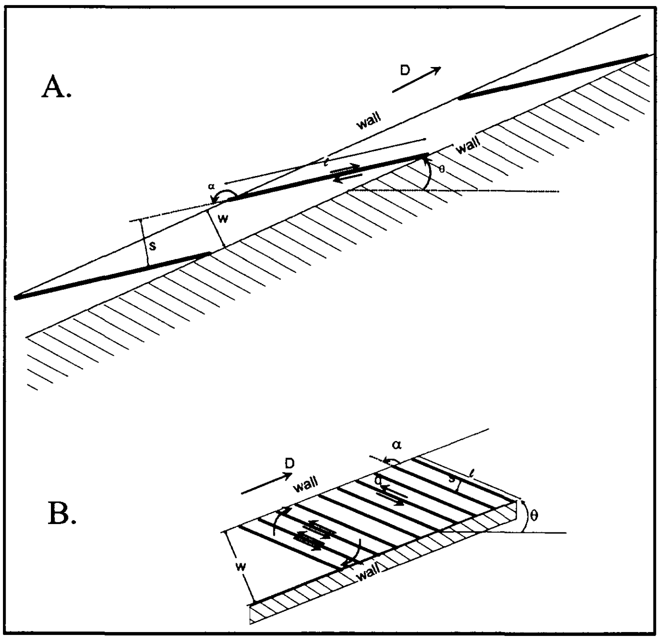


Figure 13. Some of the variation in en echelon zones that depends on the ratio of spacing of segments and the width of the zone. A. Typical geometry of restraining en echelon faults that slip in a right-lateral sense in a right-lateral, en echelon fault zone. B. Typical geometry of en echelon cracks that slip in a left-lateral sense as the blades of ground between the walls rotate during overall right-lateral shearing.

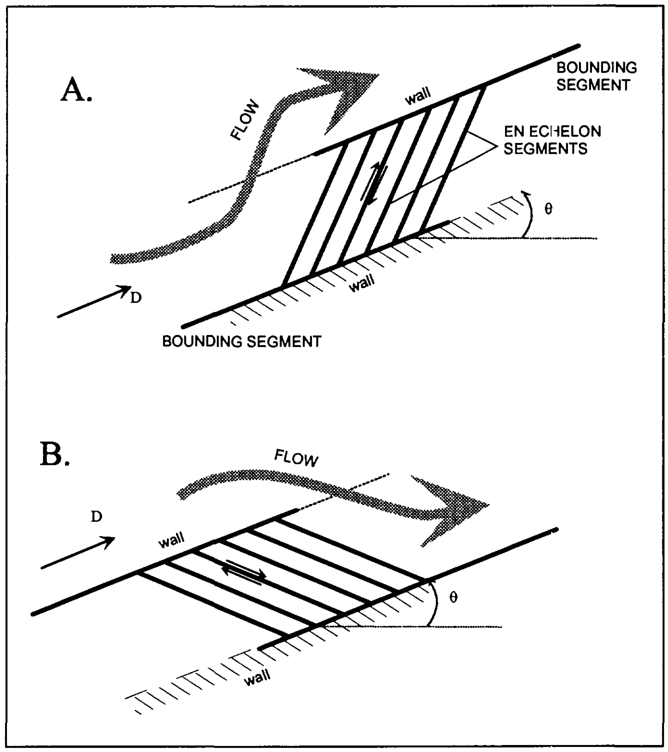


Figure 14. General flow patterns associated with duplex structures, consisting of en echelon, bounding faults and en echelon fault elements. A. Restraining duplex structure. B. Releasing duplex structure.

Part II. Setting of Structures Along Strike-Slip Fault Zones at Landers

The Landers-Big Bear Structure—A Rotating Block

The faults that activated during the Landers earthquake are within the eastern California shear zone. According to Dokka and Travis (1990), the shear zone is about 80 km wide and contains several right-lateral fault zones that accommodate 15 to 20 percent of the motion between the Pacific and North American plates south of the Garlock fault zone. The faults that ruptured to the ground surface during the Landers/Big-Bear earthquake sequence included parts of seven named faults within the eastern California shear zone. From north to south (fig. 15), the Camp Rock, Emerson, Maume (not shown), Homestead Valley, Johnson Valley and Burnt Hill/Eureka Peak faults all exhibited surface rupture along parts of their length. Only the northern third or half of the Emerson fault zone was activated; only the southern half of the Johnson Valley fault zone was activated, but most of the Homestead Valley fault zone was activated during the Landers earthquake.

In the practice of analyzing slip on earthquake faults, the traces of the faults are considered to be straight. As a first approximation, deformation on faults is considered to be translational. As a result, we can describe the kinematics of faulting in terms of differential displacement across the fault.

The Landers rupture is not, then, the typical rupture. As shown in the cover diagram of this report, the parts of the faults that produced surface rupture during the Landers earthquake formed a curved, *en echelon* set of right-lateral fault elements, each about 10 km long and stepping right. The east side of the rupture belt moved clockwise (south to southeast). Overall, the longer fault elements form a curve, with a center of curvature perhaps 80-90 km west of Landers near the San Andreas fault zone (Cover and fig. 15). Thus the first approximation to the deformation that was relaxed by the earthquake was not a right-lateral translation, but a counterclockwise rotation of a block around a center in the San Andreas fault zone.

The actual deformations, of course, could not be purely translational or rotational because fault ruptures end. The rupture at Landers does not produce an entire circle, and the rotating block is joined to neighboring ground. Thus there had to be adjustments between the rotating block and its surroundings. Also, the Landers rupture zone is not a perfect circle, so there had to be adjustments even along the Landers rupture zone. Perhaps the internal adjustments during rotation led to the main shock of the Big Bear earthquake sequence that occurred 3 hours after the main shock of the Landers earthquake. The kinematics of stepping faults have been documented in several tectonic situations, but the possibility of rotations seems to have been ignored except at the global scale of plate motions.

The curved pattern of stepping fault ruptures at Landers is accomplished partially by a series of stepovers with their own distinctive patterns of surface rupture. Because the tectonic situation is one of right-lateral faults stepping right, the stepovers were all in a releasing mode. The stepovers between the 10-km fault elements tend to consist of fault elements an order of magnitude shorter, perhaps 1 to 2 km long, oriented 30° to 45° clockwise relative to the trends of the longer fault elements (fig. 15).

The stepovers are of different types. The Camp Rock-Emerson fault stepover was principally through a series of tension cracks that are oblique to both fault zones. Two others are releasing duplex structures (fig. 14B). The Homestead-Emerson stepover, where the Emerson fault zone steps to the southwest to the Homestead Valley fault zone, and the Kickapoo stepover, where the Homestead Valley fault zone steps to the southwest to the Johnson Valley fault zone, are characterized by several right-lateral fault zones.

Southern Landers Rupture Zones

Kickapoo Stepover (Releasing Duplex)

Sowers and others (1994) described the surface rupture in the Kickapoo stepover area as well as evidence for earlier faulting along the Johnson Valley fault zone[7]. The section of the fault zone centered on Linn Road, and extending northward to the vicinity of Happy Trail (fig. 16), is characterized by a series of west-facing scarps in older alluvium. In some places fault traces are on both sides of uplifted alluvium and represent tectonic ridges[8]. Vertical components of displacement along this stretch generally mimic the vertical components in the geologic record (Sowers and others, 1994). In the northern part of the Johnson Valley fault zone, north of Happy Trail (fig. 16), the scarps are east-facing, and the fault zone separates a bedrock pediment on the west from thick alluvial deposits on the east.

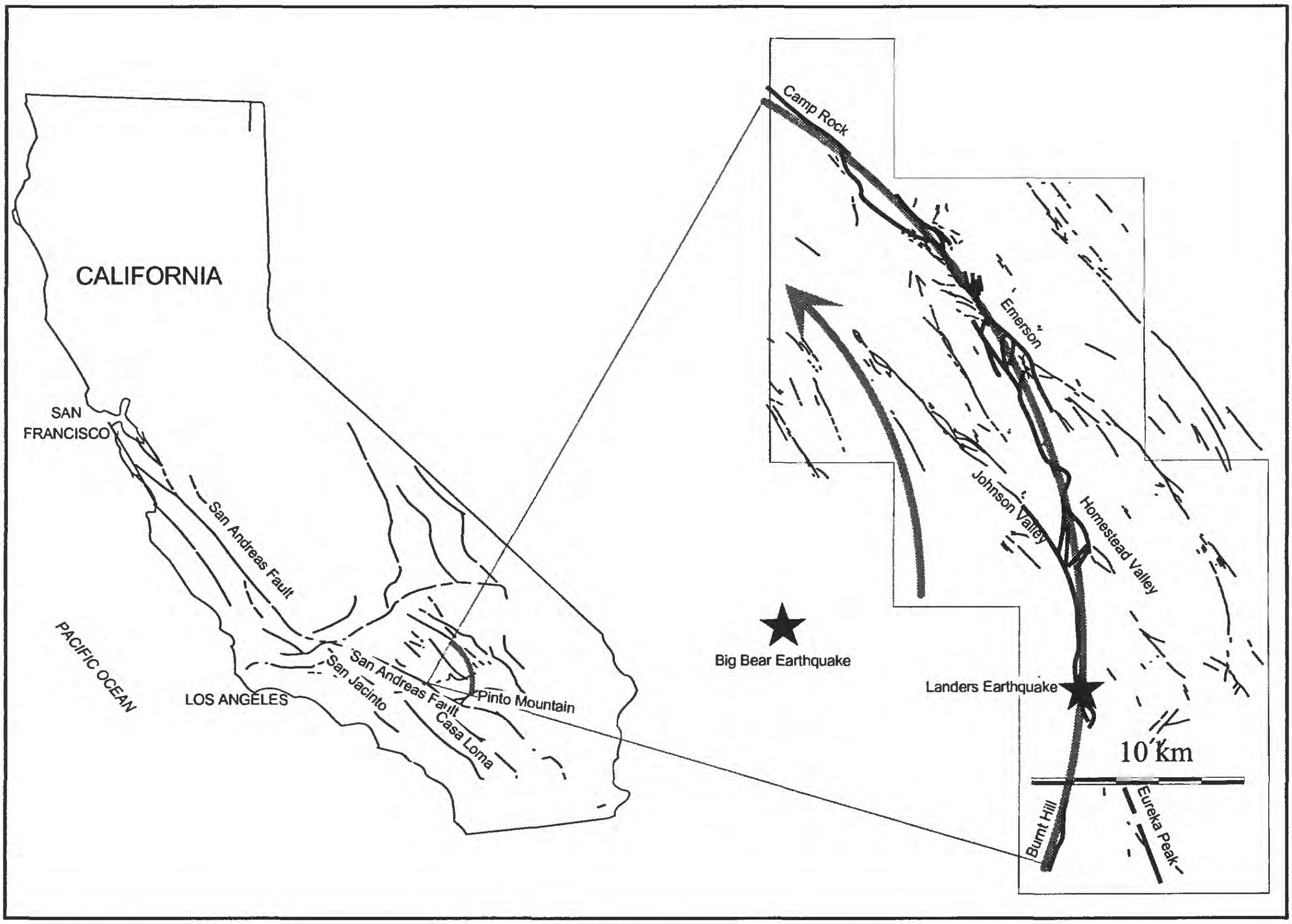


Figure 15. System of fault elements, totaling about 80 km length, that activated during the 1992 Landers earthquake sequence. A circular arc, with a radius of about 80 km, drawn through the fault elements has a center in area of San Bernardino. The segment has an included angle of about 60°, and cuts across the Pinto Mountain, left-lateral fault. (One could draw other arcs, with different centers that would also closely match the fault elements, but they would be within about 10 km of that shown.) Epicenters of main shocks of Big Bear and Landers earthquake sequences shown with stars.

[7]See, also, Unrhu and others, 1994; Spotila and Sieh, 1995.
[8]Sowers and others (1994) use the term, "pressure ridge."

The overall fault zone that makes up the Kickapoo stepover is composed of at least three narrow rupture zones that trend acutely to the bounding, Homestead Valley and Johnson Valley fault zones. The rupture zone that forms the west side of the stepover has been termed the Kickapoo fault by Sowers and others (1994). The Kickapoo fault is characterized by one to three main traces within a zone 50 to 100 m wide of dense, *en echelon* fracturing. There is evidence that the Kickapoo fault follows an older structure. Small knolls of late Pleistocene alluvium and bedrock extending through the young alluvium appear to be related to the restraining, left stepovers between fault elements.

Measurements, by Sowers and others (1994), of shift across fault zones throughout the stepover area, combined with data collected by other investigators, provide a good representation of the distribution of slip throughout the Kickapoo stepover area. Most of the shift, about 200 to 280 cm, is on the Kickapoo fault zone. The other two fault zones in the Kickapoo stepover contain 10 to 30 cm of right shift.

According to Sowers and others (1994) the cumulative slip on the bounding, Johnson Valley and Homestead Valley fault zones and the Kickapoo fault zones increases across the stepover from south to north. Their data on horizontal differential displacements across rupture zones (fig. 16) show that there is a progressive transfer of about 3 m of right shift across the Kickapoo stepover, from south to north through the region (Sowers and others, 1994). The Johnson Valley fault zone, south of its junction with the Kickapoo fault, is the only large fault and accommodates about 95 percent of the right-lateral shift across the entire rupture zone. North of the junction of the Kickapoo fault with the Johnson Valley fault zone, the shift across the Johnson Valley fault zone decreases as the shift across the Kickapoo fault increases. From south to north, the Kickapoo fault accommodates about 25 percent, then 45 percent, and then 48 percent of the total shift in this area. Right-lateral shift is barely measurable on the Johnson Valley fault zone north of Bodick Road. At Bodick Road, the Kickapoo fault zone and the Homestead Valley fault zone each accommodate about 50 percent of the total right-lateral shift. Where the Homestead Valley fault zone and Kickapoo fault join, about 1 km north of Bodick Road, the net right-lateral shift is about 3.3 m (fig. 16).

Rupture Zones in Homestead Valley

We have mapped several areas within the Kickapoo stepover, which we examined in figure 16. We photogrammetrically mapped two areas along the Homestead Valley fault zone, one

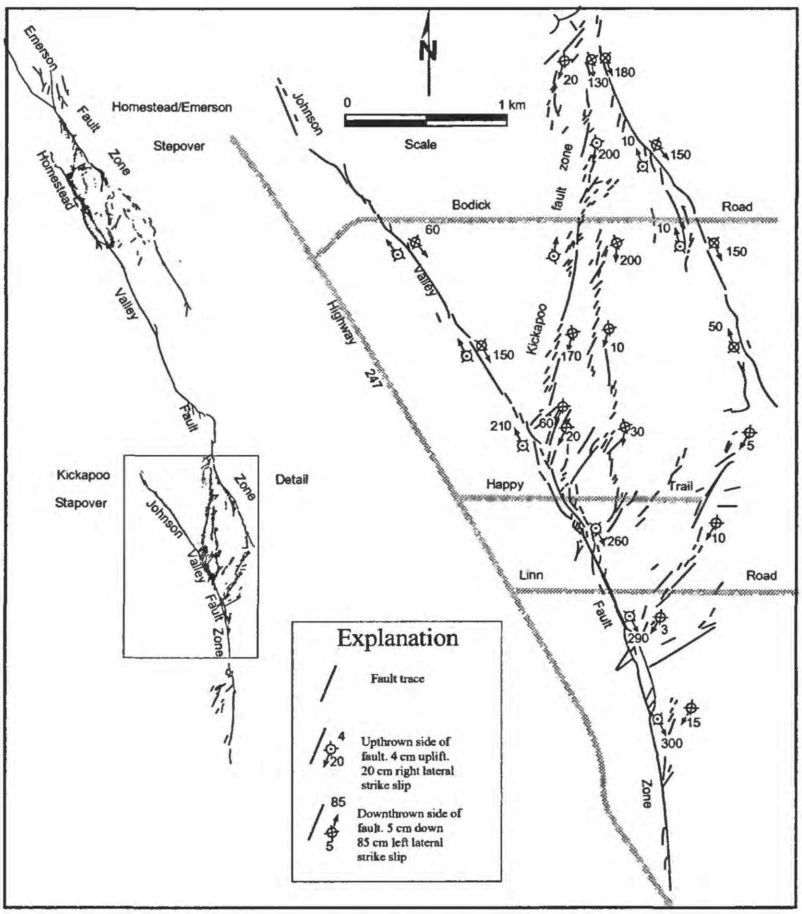


Figure 16. Kinematic features of Kickapoo stepover between Homestead Valley fault zone and Johnson Valley fault zone. Horizontal offsets across individual rupture zones are indicated in centimeters. Data mostly from Sowers and others (1994).

between Reche Mountain at the southern end of the rupture zone and the Mileska Ranch south of the Headquarters step, and the other north of the Goatsucker Hill ridge (Plate 1). Also, we photogrammetrically mapped two areas along the Johnson Valley and Kickapoo fault zones. One area is the area of the intersection of the Johnson Valley and Kickapoo fault zones. The other is the northern third of the Kickapoo fault zone and its intersection with the Homestead Valley fault zone. As indicted in earlier pages, photogrammetric maps show only traces of fractures, not kinematic information, in these areas. Detailed analytical maps, including kinematic information, were made for three areas on the Kickapoo fault zone and two areas on the Homestead Valley fault zone. Detail was obtained at the Crown and Pickle rift, the Charles *en echelon* zone, the Two Bikers *en echelon* zone, the Race Track half-rift, and the Happy Trail shear zone. The Happy Trail shear zone has been described elsewhere (Johnson and others, 1993, 1994). The Crown and Pickle rift and the Race Track half-rift will be described elsewhere.

Differential displacements across ruptures within the three fault zones are shown in a few places in Plate 1. Most of the measurements shown are from Sowers and others (1994), but some are our measurements. Since the faulting was by rupture across broad zones rather than along faults, one must note the distance across which differential displacements are measured. Since the reference marks are typically lines, such as fences or power-pole lines, trails or roads, the measurements of differential displacement are almost all the component at right angles to the linear feature. We have tried to show the distance and direction of measurements everywhere via a special pair of symbols defined in the explanation of Plate 1. Elsewhere, the measurement is made across a very narrow zone or fault, and the direction is parallel to the trace of the fault. In these places we tried to find a bush or similar object that behaved much as a point that was severed by the faulting, so that the differential displacements would define the net slip. Where we can do this, we report three components.

Northern Landers Rupture Zones

Rupture Zones along Emerson Fault

The Emerson fault zone is in the northern part of the 1992 Landers rupture (fig. 1). The fault was mapped by Dibblee (1964) and Jennings (1973) as extending some 55 km in a southeasterly direction from the vicinity of the Single-Tower Transmission Line road, south along the west side of Emerson Lake, to at least as far south as the latitude of Landers. About 20 km of the fault zone activated in 1992, extending from its northwest end southeast to the vicinity of Galway Lake. At its northwest end, it stepped through a series of ruptures northward to the Camp Rock fault zone. At its southeast end, it stepped through the Homestead-Emerson stepover southward across the mountain to the Homestead Valley fault zone (fig. 17). According to the California fault map by Jennings (1973), the Emerson fault zone is a right-lateral, strike-slip fault; it is a Quaternary fault without historic activity, meaning that it was active during the past 2 million years but not the past 200 years. Plate 2 shows traces of fractures within part of the Emerson fault zone, which trends about N30°W between Tortoise Hill in the southeast and the Single-Tower Transmission Line[9] road in the northwest.

The Emerson fault zone accommodated about 290 cm of right-lateral shift at the Single-Tower Transmission Line and 300 to 310 cm at Tortoise Hill ridge. Shift on the Emerson fault zone caused the near collapse of one high-voltage transmission towers whose legs straddled the largest break (Plate 3) in the belt of shear zones. Using

[9]Not to be confused with another place, about 2 km northwest, where the fault zone crosses two more powerlines.

the distances between the legs of the deformed tower and the corresponding distances between the legs of a neighboring, undeformed tower, Fleming and others (1997) calculated that the part of the rupture passing beneath the powerline accommodated 270 cm of right-lateral differential displacement parallel, and 2 to 7 cm of dilation normal to the trace of the shear zone within the base of the tower (about 7.3 to 7.8 m sides). By sighting along the towers of the powerline, we determined that an additional 21 cm of right-lateral relative displacement occurred over a distance of about 200 m to the southwest of the deformed tower, making the total 291 cm.

An additional 69 cm of relative displacement of the powerline to the northeast of the deformed tower is attributed to transfer of right-lateral shift through a belt of tension cracks in the stepover between the Camp Rock and Emerson fault zones (Fleming and others, 1997).

Homestead-Emerson Stepover (Releasing Duplex)

The Homestead-Emerson stepover, between the Emerson and Homestead Valley fault zones (fig. 17), was described by Zachariasen and Sieh (1995) as an *en echelon* stepover, similar to the Kickapoo stepover. The features shown in figure 17 were mapped on a photographic base at about 1:6000 scale and compiled at 1:12,000 scale. Additional map and kinematic data were obtained in the field. The Homestead-Emerson stepover is between fault elements of the Emerson and Homestead Valley fault zones, which overlap about 5 km and are offset here in a right step of about 2 km. Within the stepover are five right-lateral fault zones that project to, and nearly connect with the bounding fault zones. Thus, the structure is what we have termed a releasing duplex (fig. 14B).

The main trace of the Homestead Valley fault zone deviates from a straight line by only about 200 m over the entire length of overlap with the Emerson fault zone. Most cracks and splays associated with the Homestead Valley fault are on the east side of and within the stepover area. Fractures that have accommodated shearing are typically right lateral, but left-lateral fractures are common as well. The one splay on the west side bounds a long ridge, and the ground within the

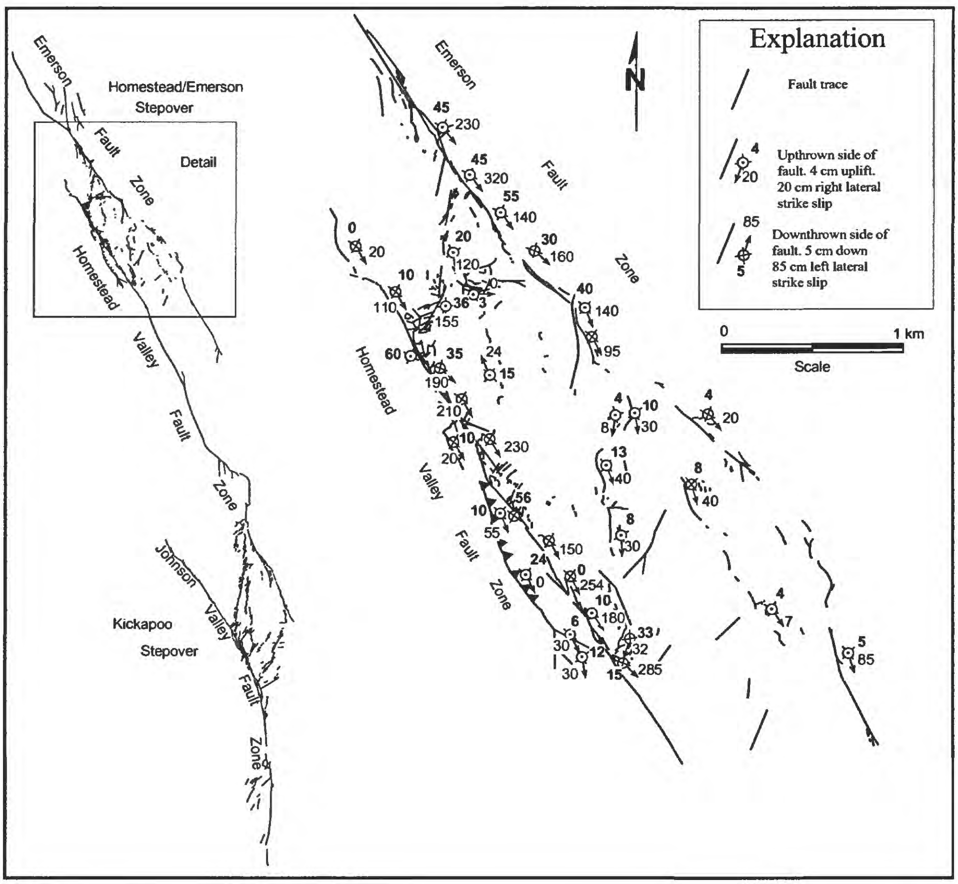


Figure 17. Kinematic features of Homestead-Emerson stepover between Homestead Valley fault zone and Emerson fault zone. Both vertical and horizontal components of shift across rupture zones are indicated in centimeters. Data from Zachariasen and Sieh (1995).

ridge has uplifted along faults on either side. The northwest part of the splay is a thrust that dips 20° to 25° east, under the ridge (fig. 17).

According to Zacharaisen and Sieh, the faults that link the Emerson and Homestead Valley fault zones, forming the releasing duplex, strike north-south and divide the ground into three slabs about 1 km wide. The largest of these linking faults is in the northernmost part of the duplex, and accommodates as much as 155 cm of right-lateral shift. Other, smaller linking faults accommodate 20 to 40 cm of shift.

The right-lateral shift on each of the faults in the Homestead-Emerson stepover changes in complex ways, according to Zacharaisen and Sieh (1995). The slip of the Homestead Valley fault zone near the southern end of the area (fig. 17) is about 3 m, but ranges from about 2 to 3.5 m. The shift on the Homestead Valley fault zone decreases from south to north, at a rate of about 0.2 m/km, to the intersection of the largest linking fault. At the first intersection, the shift decreases by about 1 m, and then decreases at a rate of about 0.5 m/km. Conversely, the right-lateral shift across the Emerson fault zone increases from south to north, to about 3.2 m where the largest linking fault joins its trace (fig. 17). This is close to the shift of 2.9 m measured at the Single-Tower Transmission Line road and 3.1 m measured across Tortoise Hill ridge about 7 and 5 km to the northwest, respectively.

Zacharaisen and Sieh indicated that the vertical shift across faults in the Homestead-Emerson stepover is quite variable from place to place, without special patterns. In general, though, the vertical shift on the Homestead Valley fault zone is down on the northeast and that on the Emerson fault zone is down on the southwest, consistent with downdropping of the block of ground within the releasing duplex. They estimate that the hill containing the duplex subsided an average of 30 cm during the Landers earthquake sequence.

In our view, one of the most interesting results of their study is the evidence for *reversal* of vertical tectonic movement that previously dominated in the area of the Homestead-Emerson stepover. We presume that the topographic ridge in the stepover is a tectonic ridge, resulting from some process that causes ridges along strike-slip faults to increase in height (some discussed by Fleming and others, 1997). The astonishing result is that, during the Landers earthquake sequence, the ground in the ridge did not rise; it subsided. This is as expected in a releasing step in a strike-slip system. The ridge has become the site of a developing pull-apart basin, so the present topography is opposite to the topography that was developing as a result of this earthquake sequence. This interpretation suggests that, at this locality, the organization of the faults and the kinematics of faulting during the Landers earthquake are quite different from those previously active along the Emerson and Homestead fault zones. This interpretation is consistent with the idea that, during the Landers earthquake, parts of fault zones were reorganized into a composite fault zone (fig. 15) that accommodated a kind of regional deformation that is not necessarily typical of previous regional deformations in this area. This is contrary to our observations at Tortoise Hill, which we summarize in the next section.

Part III. Tortoise Hill Ridge

The Ridge

Tectonic ridges, or push ups, are elongated domes of ground in strike-slip regions that range widely from a few meters to a few kilometers in length, such as within the San Andreas system (e.g., Aydin and Nur, 1982; Sylvester, 1988) and within soil in landslides in Utah (e.g., Fleming and Johnson, 1989). The tectonic ridge at Tortoise Hill, along the Emerson fault zone (Plate 2), grew about 1 m in height as the Emerson fault zone shifted dextrally about 3 m during the Landers earthquake (fig. 11). We have described the ridge elsewhere (Fleming and others, 1997; Fleming and Johnson, 1997), so here we present only sufficient background for a description of the setting of previously undescribed structures associated with the ridge.

Tortoise Hill ridge protrudes above the general land surface in an upside-down, keel-shaped outcrop about 400 m wide and 1200 m long (Plate 2; figs. 11 and 18). The northeast side of the ridge is a steep scarp with a relief of 97 m. The southwest side of the ridge is a long, gently-sloping, pediment-like surface. The crest of the ridge is only about 25 m higher than the projection of the sloping surface. An extensive area of quartz monzonite underlies the ridge and pediment-like surface; the valley of Galway Lake to the northeast of Tortoise Hill is underlain mostly by alluvium (Dibblee, 1964).

According to our detailed mapping, Tortoise Hill ridge is within the Emerson fault zone (Plate 5). The Emerson fault zone increases in width from about 70 m at the Single Tower Transmission Line, to 120 m near the north end of Tortoise Hill (Plate 5). At Tortoise Hill ridge the belt splits into two broad shear zones, one extending around either side of the ridge. The belt that passes around the southwest side of the ridge starts as a right-lateral shear zone, then, as it swings around the ridge, accommodates right-lateral/reverse shift along oblique-slip thrusts (Plate 5), with the ridge-side upthrown on the order of a few centimeters to a few tens of cm. This belt ends near the southeast end of the ridge (Plate 5). The belt that passes around the northeast side of Tortoise Hill ridge is predominantly right-lateral, but also accommodates about half a meter of differential vertical uplift, with the ridge-side upthrown (Plate 5). One fault surface exposed along the northeast side of the ridge strikes N65°W and dips 86° south; its slickensides have a rake of 12° and plunge S64°E. The largest differential horizontal shift measured across the belt is 2.65 m, so we estimate that the ridge moved up at least 0.56 m there on the basis of this observation. We show with photogrammetric and survey data, however, that the ridge moved upward at least 1 m (Fleming and others, 1997; Fleming and Johnson, 1997).

Spines

The topography of Tortoise Hill ridge, especially south of the ladder of quadrilaterals (Plate 5), is characterized by highly angular and jagged masses of granodiorite separated by irregular drainages (Plate 2). Although these may be weathering and erosional features, we suspect that many of them represent spines of ground that were thrust upward differentially as the ridge has grown. The topographic features at Tortoise Hill remind us of the very fresh examples of spines in an active ridge found in the Twin Lakes, Utah, landslide (Fleming and Johnson, 1989), but the Tortoise Hill spines are much larger.

Our map of part of the northwest brow of Tortoise Hill (Plate 5) shows two of the spines. North Spine is an elongated, asymmetric dome-shaped feature about 100 m long, 50 m wide, and about 30 m high on the east and 14 m high on the west. The main rupture passes near the crest of the spine, and there is no evidence that the spine moved vertically differentially during the 1992 event. South Spine is smaller, about 40 m long, 25 m wide, and about 10 m tall. This one also

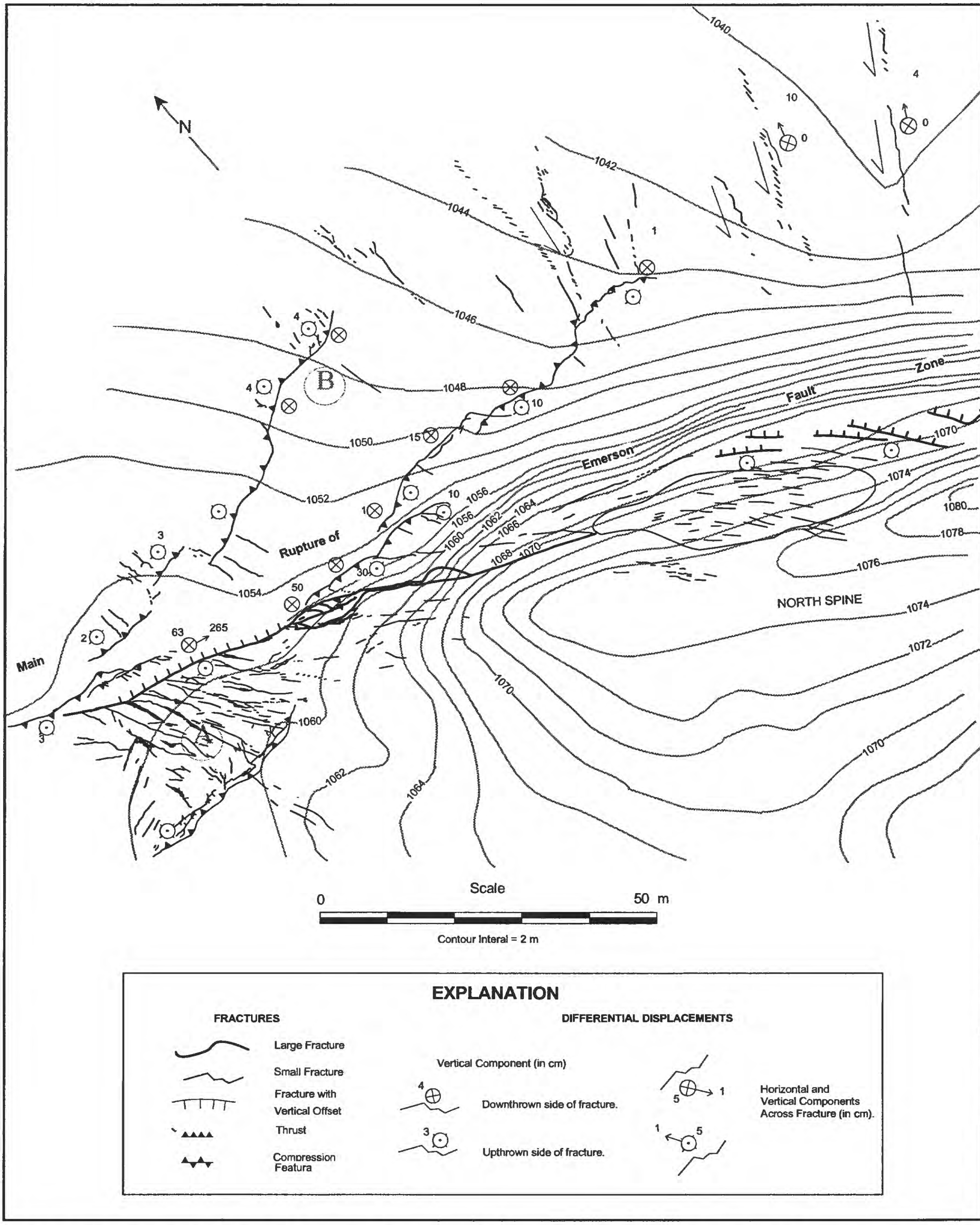


Figure 18. Fractures at left jog in Emerson fault zone at brow of Tortoise Hill, showing compression features on both sides of the jog. The main rupture of the Emerson fault had a scarp about 65 cm high near center of area shown and right-lateral slip was about 265 cm here. The main rupture trends southeast over the east edge of the elongated dome of North Spine. To the north of the rupture are opposite-facing thrusts, dipping north or south, indicating north-south compression and creating low brows that are up to 10 or 15 cm high. To the south there is a welt marked by numerous tension cracks oriented north-south and bounded on the south by a thrust dipping northward.

appeared to be inactive, and a fault trace passes near its crest.

If these spines do sometimes move differentially when the ridge grows, as we suspect, then, rather than bulging upward as a single mass, the ridge may grow vertically with highly–localized differential displacements. Our survey stations were spaced so widely that we could not record differential vertical displacements of the spines, if they occurred during the 1992 event.

The main part of Tortoise Hill ridge to the southeast of the spines does not appear to have been broken up in the same way. Aplite dikes can be traced for many meters across the granodiorite outcrop. Some of these were mapped photogrammetrically and are shown on Plate 2. If the entire ridge were sheared to the degree found in the spines, the dikes would lack the continuity shown on Plate 2.

Thrusts in Small Restraining Step or Bend Within Tortoise Hill Ridge

Tectonic ridges are commonly ascribed to structural crowding that occurs at opposite steps, jogs or bends along faults[10] (e.g., Segall and Pollard, 1983; Aydin and Page, 1984; Sylvester, 1988; Bilham and King, 1989; Scholz, 1990). In contrast, we have observed that structures that form at opposite steps and jogs at various places at Landers, and in large landslides, are near-surface phenomena such as folding or thrusting. In landslides, we generally saw low domes or thrust faults at opposite steps; we did not see ridges at such places (Fleming and Johnson, 1989). The ridges we saw in the landslides were typically along straight stretches of rupture zones. In terms of the prevailing notion that ridges form at restraining steps or bends, perhaps the most important observation at Tortoise Hill is that the ridge itself is within a large releasing step, between the Emerson and Camp Rock fault zones, not at a restraining step (Fleming and Johnson, 1997).

There is a small, restraining left step or double bend in the main, northeast rupture of the Emerson fault zone near the northwest end of Tortoise Hill ridge, shown near the northwest edge of Plate 5. According to various analyses of steps and bends in faults (e.g., Bilham and King, 1989; Cruikshank and others, 1991a), a left step in a right-lateral fault should produce compression in the surrounding rocks. We mapped the area of the left step in detail (fig. 18) in order to determine the kinds of structures that form at this scale. Within the belt of shear zones, on the southwest side of the main shear zone, was a swarm of tension tracks (A, fig. 18), generally oriented north-south in a domical area about 30 m long (parallel to the shear zone) and 20 m wide. The domical area was uplifted 10 to 20 cm and is bounded on the southwest side by a thrust. It is possible that this domical area is a newly–forming spine within the ridge. Outside the belt of shear zones, on the northeast side of the outermost shear zone or fault (B, fig. 18), is a series of thrust faults with average traces trending 30° to 50° counterclockwise from the trace of the outermost shear zone (fig. 18). Uplift by the thrusts ranges from a few centimeters to a few tens of centimeters. The thrusts are represented on the ground not by visible thrust faults, but by low brows (Fleming and others, 1997), although we show thrusts on the map. The thrust faults dip to the north or south, so the upthrown block is different for different thrusts in that area, representing general shortening, not stacking by imbricate thrusting.

An important aspect of the structures that formed at the small left step, or bend, at Tortoise Hill is that compressional structures formed on both sides of it. This is as expected, provided the materials are deformable on each side (Bilham and King, 1989). Neither the compressional struc-

[10]An opposite bend or step would be a left step or jog, or a left bend in a right–lateral, and a right step or jog or a right bend in a left–lateral strike–slip fault.

tures nor the materials, however, are identical on the two. To the northeast where the thrusts formed, the ground is compact alluvium. To the southwest, where the thrust and dome formed, the ground is broken granodiorite.

The structures are clearly local and reflect a small step or bend within the larger structure of Tortoise Hill ridge. Although there is no question that localized compression will be developed within a restraining step or bend, the role of restraining steps in the formation of tectonic ridges may be exaggerated.

Part IV. Structures that Formed in Releasing Steps

Smaller Duplex Structures

In previous pages we described two large duplex structures that form the Homestead-Emerson and Kickapoo stepovers. Here we describe a well-documented structure in the Two Ranch area along the Homestead fault zone and an incompletely documented duplex structure along the Emerson fault zone.

Headquarters Duplex in Homestead Valley Fault Zone

The Headquarters duplex is along the northeast side of the rupture zone of the Homestead Valley fault zone (Plate 1). Between Goatsucker ridge in the northwest and Reche Mountain in the southeast, the fault on the northeast side of the rupture zone consists of three *en echelon* elements about 1 km long. The segments step right in releasing steps. Different structures form in the two intervening steps between the segments. At the Headquarters step, there is a duplex structure; at the Pipes Wash step, farther south, there is a left-lateral rupture zone bounding a rotating block.

The duplex begins near Mikiska Boulevard, north of Bodick Road, and extends about 400 m south to Mileska Ranch, on Shawnee Road (Plate 1). The duplex structure is about 400 m long and 90 m wide. It consists of diagonal, shear-zone segments that form the internal elements of the duplex structure plus the bounding faults (Plate 4). The bounding fault on the east extends southward, to near the building marked "Headquarters", about half the length of the duplex. The bounding fault on the west extends northward to near Bodick Road, about two-thirds the length of the duplex.

The shear zones within the duplex are right lateral, as are the bounding faults. Individual shear zones are spaced about 10 m apart, are 100 to 150 m long, and are oriented at a clockwise angle of 20° to 30° to the bounding faults. The shear zones within the duplex are, themselves, short, right-lateral, *en echelon* fault elements 5 to 10 m long. Between many of the fault elements are short thrusts (Plate 4) that shift displacement across from one fault element to another.

The Headquarters step consists of a hierarchy of stepping elements (Plate 4). The Headquarters duplex itself forms a releasing step (fig. 14B) because the bounding faults are right lateral and they step right. Within the duplex, though, the fault elements have restraining steps, at two different scales. The shear-zone elements within the duplex have restraining steps because they are right lateral and step left (fig. 12B and fig. 14A). Furthermore, many of the shear zone segments are composed of short fault elements also arranged as restraining steps (fig. 12C).

The lateral shift in the internal shear zones in the northwest part of the duplex, between Bodick Road and Mikiska Boulevard, was evident in the deformation of the fence on the north side of the Northern Ranch (Plate 4). The lateral shift there was generally 5 to 10 cm. In the southeast part of the duplex there were few markers, but we would estimate an average of 30 cm accommodated by each short shear-zone segment, about 5 to 10 m long. We could measure vertical shift, generally a few cm, with downthrowing on either side (Plate 4). The openings of cracks along the internal shear zones were similarly on the order of a few centimeters (Plate 4), indicating some dilation in the releasing duplex.

Offsets of fences with different orientations at the North Ranch indicates that the bounding fault on the east side of the duplex accommodated 1 to 1.2 m of right lateral shift (Johnson and others, 1993). Offset of fences with different orientations at Mileska Ranch indicates a net shift of 1.6 m across the bounding fault segment on the west side of the duplex. This later number was determined as follows: The bounding fault accommodated about 1.4 m of right-lateral shift in the south fence and 70 cm of right lateral shift in the west fence of the Mileska Ranch. Thus the net shift was about 1.6 m. Besides the lateral shift, the ground to the west of the west fence of the Mileska Ranch was relatively downdropped about 10 cm.

Table 2 compares the geometric elements to those for other duplex structures at Landers. Nothing about this duplex is remarkable, geometrically.

Duplex at Single-Tower Transmission Line Site

We have already described the belt of shear zones at the Single Tower Transmission Line area along the Emerson fault zone. Starting about 40 m southeast of the deformed tower (Plate 3), the shear zone bounding the northeast side of the belt broadens from about 3 m width to 15-20 m width over a horizontal distance of about 200 m. Then it abruptly narrows to 1-2 m width. We made only a photogeologic map of the fractures in this area, but the widening appears to define a narrow duplex structure of right-lateral fault elements. The duplex accommodates a shift of perhaps 2.7 m. Table 2 compares the geometric elements of this duplex structure (STTL) with those of others in the Landers area.

Pipes Wash Rotating Block in Releasing Bend

The right step between fault elements along the Homestead Valley fault zone at Pipes Wash (Plate 1) has an internal structure that is quite different from that at the Headquarters duplex step. Rather than a group of right-lateral ruptures connecting the stepping right-lateral bounding faults, there is a left-lateral rupture, plus some associated normal or oblique faults (fig. 20, Plate 7). In many respects, the left-lateral rupture plays the same role as the left-lateral fractures between rotating blocks in the Summit Ridge shear zone at Loma Prieta (Johnson and Fleming, 1994), and the left-lateral fractures within the Happy Trail shear zone along the Johnson Valley fault zone at Landers (Johnson and others, 1993, 1994). The rotated block at Pipes Wash is, in some ways, also reminiscent of the Landers/Big Bear rotated block mentioned in earlier paragraphs.

Along the Homestead Valley fault zone, south of Virginia Avenue (Plate 1), the belt of shear zones is about 300 m wide. The rupture bounding the northeast side of the belt of shear zones forms a double bend, by turning clockwise and proceeding laterally about 100 m over a horizontal distance of about 200 m, and then turning counterclockwise back to its original orientation. Thus, the structure forms not in a step, but in a double bend. Within the belt of shear zones, fractures are oriented north-south in the area north of the bend where the wall is oriented about N25°W. The fault elements are a few meters long and bound blocks that have been thrusted, suggesting that the blocks were rotating (accommodating left-lateral slip between blocks). The amount of shift across this part of the northeast side of the Homestead Valley fault zone was 1.65 m, according to measurements of offset of fences on two sides of the property shown in figure 20. Farther south, the northeast side of the Homestead Valley fault zone turns clockwise about 25°, to roughly a north-south orientation. It continues to be composed of *en echelon* fault elements (and tension cracks) bounding blocks that have rotated and thrusted. The fault elements are oriented about N20°E, a clockwise change of orientation of about 20°, roughly the same as the change of orientation of the walls. We have some kinematic information for individual faults and tension cracks within this zone. The differential vertical displacements across the faults within the right-lateral *en echelon* zones are small, generally 3 cm, to as large as 5 cm. The downthrown side is typically on the inside of the belt of shear zones, although there is a small, shallow graben near the channel of soft alluvium, shown at the south end of figure 20.

On the western side of the short, misoriented segments of the bounding shear zone is a left-lateral rupture zone. It is in the position of duplex structures in many of the other releasing steps at Landers. The detailed maps of the Pipes Wash area (fig. 20 and Plate 7) illustrate fractures formed at the first bend in the wall of the Homestead Valley fault zone and in the left-lateral fault zone that formed at the northwest end of the structure. Although much of the detail of deformational structures was gone, because we mapped the area about a year after the earthquake, we could still see that the bend in the wall of the Homestead Valley fault zone consists mainly of *en echelon* fault elements.

At the northeastern end of the left-lateral shear zone its walls are oriented about N30°E, and fault elements within it are oriented about N20°E. Thus, the angle between the walls of the right-lateral *en echelon* zone north of the bend and the walls of the left-lateral *en echelon* zone is about 80°. The trend of the left-lateral zone curves and then, at its southwest end, turns north-south and is replaced by tension cracks. The downthrow across the left-lateral rupture is much larger than on the right-lateral ruptures, on the order of 10-20 cm, and as large as 25 cm along the left-lateral *en echelon* rupture. We have no information about the magnitude of the left-lateral shift across the left-lateral zone.

The geometric features of the *en echelon* zone are unremarkable. In table 2 we have listed the geometric information that we use to compare and describe *en echelon* fault structures. The walls of the *en echelon* zone are separated by about 5.5 m, and the spacing of the faults is about 3.5 m. So, the ratio of spacing to width is about 0.6, and the length of the fault elements is about 18 m, at least in the northern part of the map area (Plate 7). The angle, α, between the walls is about 15°. A geometrically–similar symmetric right-lateral rupture zone would have an alpha value of 175°. Table 2 indicates that, although this left-lateral zone contains some of the shorter fault elements, the relative spacing of fault elements and the equivalent orientation (of 175°) of the fault elements relative to the walls are quite similar to those of several right-lateral *en echelon* zones.

We view the left-lateral rupture as a boundary of a block rotating clockwise within the right bend of the main break of the Homestead Valley fault zone in this area.

Tension Cracks and Growth of a Pull-Apart Basin

Another type of accommodation within a stepover formed at the Single Tower Transmission Line site along the Emerson fault zone (fig. 1). A swarm of tension cracks, shown near the damaged tower in Plate 3, extends across the valley of Galway Lake from the east wall of the Emerson fault zone toward the Camp Rock fault zone on the east side of the valley. The Single Tower Transmission Line site is one of several places along the valley of Galway Lake where rupture connections have formed between the Emerson fault zone and the Camp Rock fault zone. The 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 (Plate 2 and Plate 3). 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 northeast. 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. By sighting between the supports for the formerly–aligned transmission towers we found that 69 cm of offset was contained within the transfer between the Emerson and Camp Rock fault zones.

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.

A 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 N60°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 interaction across the valley. Studies by Pollard and his students (e.g., Segall and Pollard, 1983; Martel, Pollard and Segall, 1988; Martel and Pollard, 1989; Martel, 1990) 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 stepping, faulted joints. The angle for bounding right-lateral fault zones at the Single Tower Transmission Line site is equivalent—60° to 70° clockwise.

The tension cracks presumably formed in response to pull apart, and we have evidence that a pull-apart basin subsided at least 0.3 m during the Landers earthquake described elsewhere and illustrated in figure 19. An obvious feature of the map of altitude change contours in figure 19 is a broad trough of differential vertical displacement underlying the valley northeast of Tortoise Hill, between Tortoise Hill and Rodman Mountains to the northeast. The trough of vertical displacements in the valley of Galway Lake is probably a reflection of a pull-apart basin forming where the shift across the Emerson fault zone is decreasing and the shift across the Camp Rock fault zone is increasing. More detailed data indicate that, near the northeast side of Tortoise Hill ridge, the ground has dropped at least 0.3 m, and a control point between Sections 19 and 24 dropped 0.2 m. Thus, this pull-apart basin subsided at least as much as that in the Homestead-Emerson stepover, described by Zachariasen and Sieh (1995).

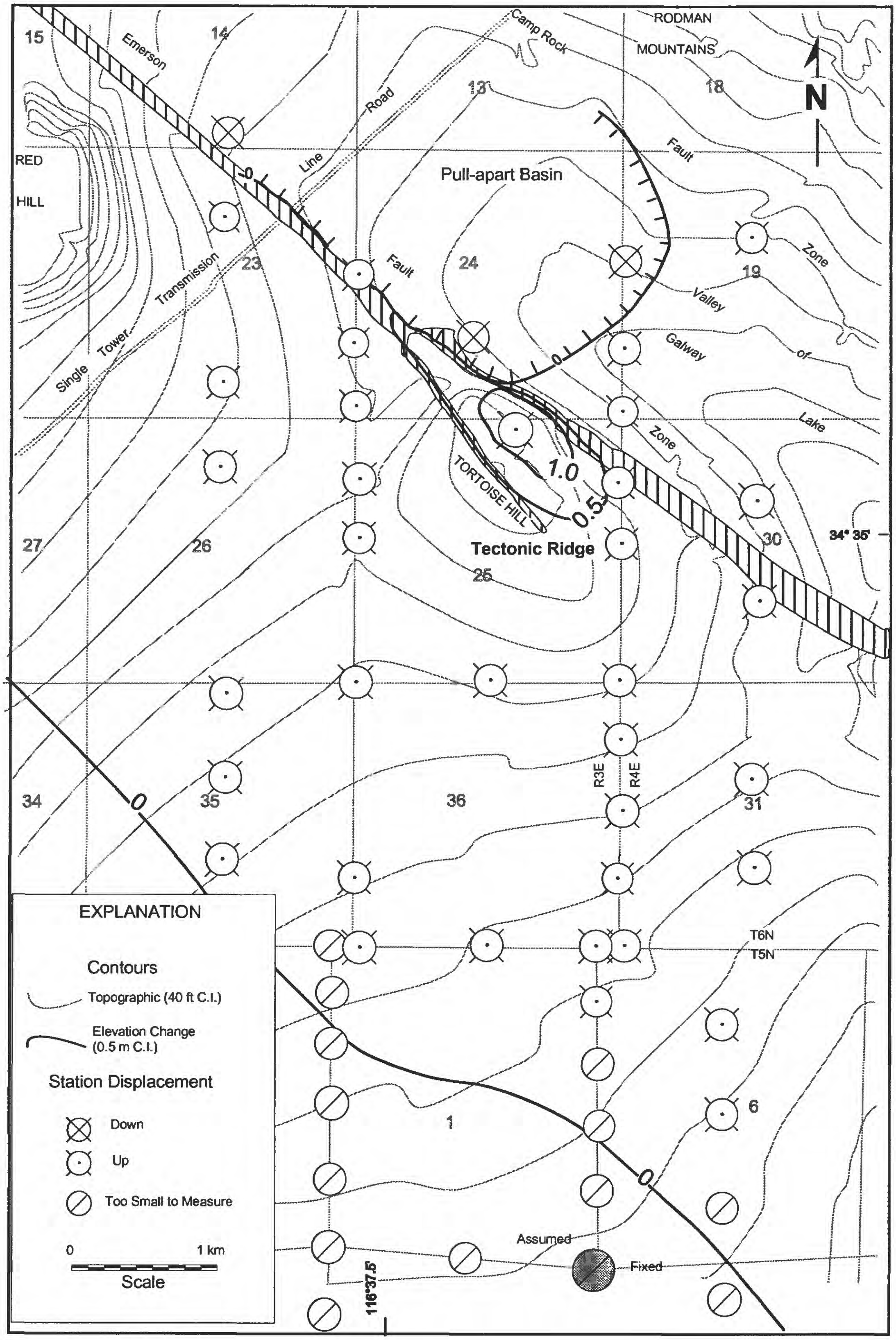


Figure 19. Contours of vertical displacement, relative to a point (large shaded circle) near Bessemer Mine Road, showing concentrated uplift at Tortoise Hill ridge, within Emerson fault zone. Land survey control points, surveyed in 1973 and 1994, shown with circles. Circles with cross (arrow moving away from observer) indicate downward movement. Circles with dot (and tips of feathers) indicate upward movement (arrow moving toward observer).

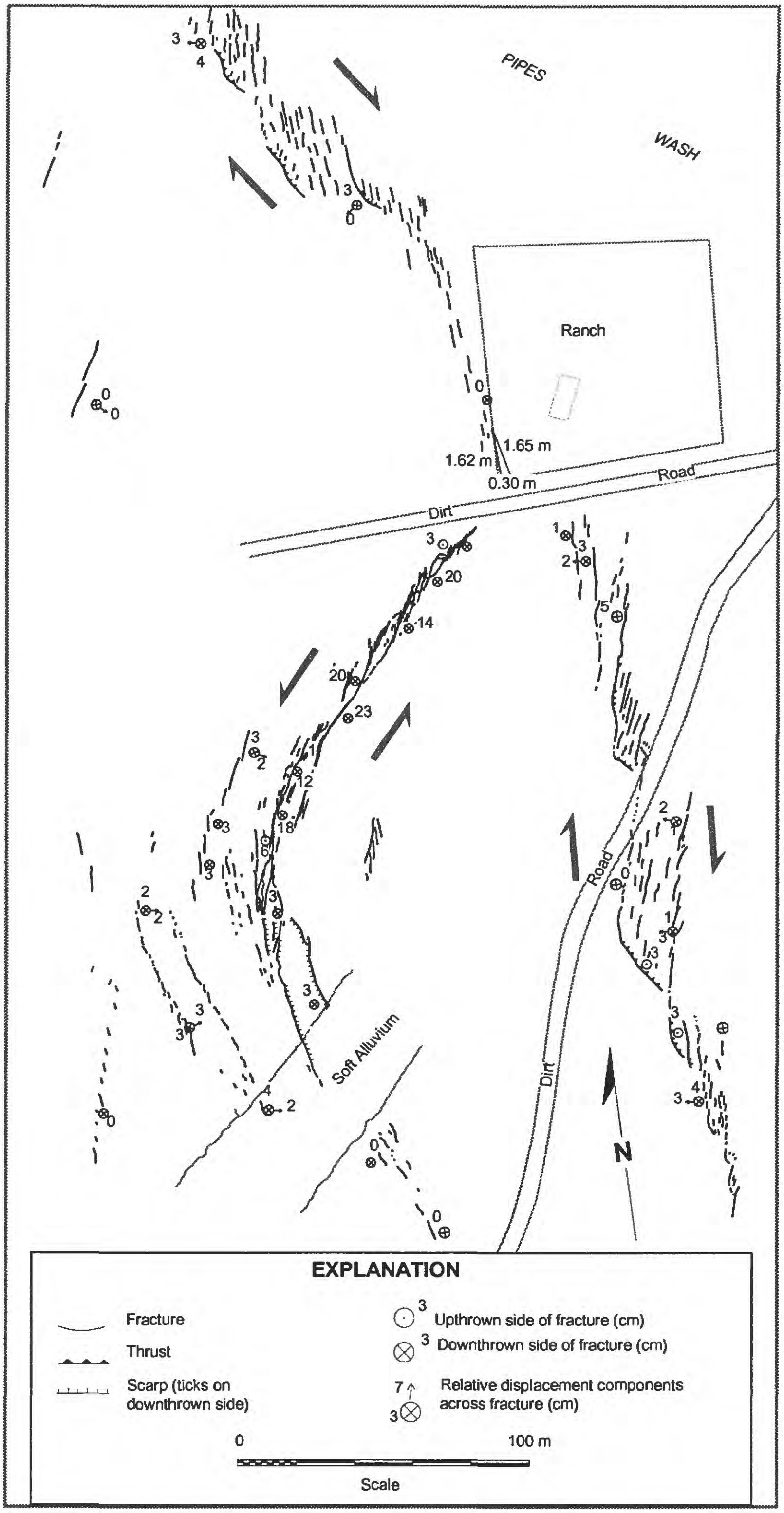


Figure 20. Fractures in Pipes Wash stepover in Homestead Valley fault zone as mapped 1 year after Landers earthquake. The main rupture of the Homestead Valley fault zone is defined by en echelon swarms of tension cracks oriented north-south and thrusts at the southwest ends of individual swarms. As indicted in Plate 1, the main trace turns clockwise near the ranch, so most of rupture shown here is within the stepover. The stepping segment to the south is out of view. Within the stepover is the left-lateral/normal rupture zone shown near the center of the figure. It extends from near the ranch southwestward about 150 m to right-lateral/normal faults. Details of the left-lateral rupture are shown in Plate 7.

Part V. *En Echelon* Fault Elements

En Echelon Fault Elements in Landslides

Fleming and Johnson (1989) described *en echelon* fault elements at landslides in Utah, where elements were well expressed and where movement was sufficiently slow that we could observe their formation. The principal difference between fractures produced by earthquakes and landslides is that the earthquake fractures are the result of sudden movement. There is no opportunity to observe the formation of a fracture produced by an earthquake, and fractures must be interpreted as a snapshot in time. Strike-slip-fault elements bounding landslide masses typically dip 80°-90°, differential displacements are subparallel to the surface traces, the surfaces are generally slickensided, and the slickenlines generally plunge at the average slope angle of the ground surface, indicating slope-parallel movement. The faults are segmented into elements, and adjacent elements have different orientations or step laterally. The strike-slip faults we studied in the Aspen Grove landslide propagate toward the ground surface in mode *III* (fig. 8); they do not propagate parallel to the ground surface after they reach the surface. The fault elements appear to represent fingers of an underlying strike-slip fault that has reached the ground surface (Fleming and Johnson, 1989, fig. 13).

The fault elements typically are *en echelon*, and continued displacement of the landslide produces folds, thrusts, and tension cracks between the elements. Along one part of the Aspen Grove landslide, the fault elements are parallel to the walls or are oriented 10° to 20° clockwise with respect to the walls of the right-lateral *en echelon* zone. The traces range in length from a few tens of centimeters to about 2 m. Many are open but have slickensided surfaces. The obliquity of the fault elements relative to the walls of the *en echelon* zone causes the elements to open and form compound cracks with continuing displacement across the walls.

The *en echelon* fault zone in the flank of the Aspen Grove landslide in Utah appears to have developed above a propagating strike-slip fault that initiated at depth, along the base of the landslide, and turned upward and propagated toward the ground surface in fingers or blades. As it approached the ground surface, it separated into a series of fault elements whose new surfaces twisted as they propagated toward the ground surface. Near the ground surface the fault traces are typically oriented about 10°-20° clockwise with respect to the trend of the fault surface at depth (Fleming and Johnson, 1989).

Fault elements of *en echelon* zones in the landslides are analogous, at least superficially, to the fault elements in *en echelon* zones that formed during the Landers earthquake. In a landslide, the slip rate on the continuous fault at depth is presumed to be constant. There is, however, typically a gradual change in slip amount and rate along the trend of a landslide flank, from a value of zero above the head, to zero below the toe. In between, the rate, and hence the amount of slip increases to some maximum value and decreases to zero. This change in slip rate or amount occurs on the flanks of large landslides over distances of hundreds or thousands of meters. For example, displacement rate on a flank of the 3.7-km-long Slumgullion landslide in southern Colorado increases gradually from zero at the head, to about 6 m/yr about 2 km from the head, and decreases gradually to less than 2 m/yr at the toe. Along any given stretch of a few hundred meters, the change in displacement rate may be 0.1-0.2 m/yr.

At the scale of fault elements produced by earthquakes or in landslide flanks, the displacement underlying an element can also be assumed to be a constant. The displacement on each fault element that is viewed at the ground surface, however, must change from zero at the element tip to a finite value along the element, and to zero again at the other tip. Displacement is transferred from one element to another by thrusting or buckling the material between the tips of the elements or in the zones where the elements overlap.

En Echelon Rupture Elements of Kickapoo Fault Zone

The Kickapoo fault zone is a right-lateral fault zone that connects the right-lateral Homestead Valley and Johnson Valley fault zones. It is highly segmented into elements at several levels. The elements are stepped *en echelon*, and the individual elements themselves are divided into smaller *en echelon* elements. Furthermore, the largest elements accommodate vertical shift as well as right-lateral shift, and the overall morphology of the stepping structures reflects the complex shift.

Two areas of the Kickapoo fault zone were mapped in detail; each contains interesting structural details. The elements in the Kickapoo fault step left so there are restraining steps at their terminations that are similar to fault elements in landslides. In the case of the elements in the Kickapoo, there is a broad bulging or uplift of the areas between the overlapping elements.

Two-Bikers Area

The Two Bikers area is at Fifth Avenue, about 500 m north of the intersection of the Kickapoo fault zone with the Johnson Valley fault zone (Plate 1) and east of Kickapoo Trail. We selected the area for analytical mapping, at a scale 1:200, because there is a wire fence at the north end to measure the lateral-shift distribution, and there are several fault elements in the area. The geometric elements of the *en echelon* zone in the Two Bikers area are given in table 2. The orientation of the Kickapoo fault zone, within the Kickapoo stepover, is about $\alpha = 140°$ (table 2). The walls of the Kickapoo stepover are oriented about N35°W, so the Kickapoo fault zone is oriented about N5°E. The walls of the *en echelon* ruptures in the Two Bikers zone are oriented about N5-10°E, and the angle of the elements within the Two Bikers zone is $\alpha = 170°$. The walls of the small *en echelon* zone within the long element in the Two Bikers area are oriented about N20-25°E, and the orientation of the elements is $\alpha = 165°$. Thus, at each level, the elements are oriented farther toward the east. According to table 2, for the three levels of *en echelon* ruptures, the ratio of spacing to width ranges from 0.2 to 0.5.

In the Two Bikers zone, a right-lateral shear zone appears to merge with another shear zone (Plate 1). A zone with a trend of N30°E is shown to join the Kickapoo fault zone at the southern end of the detailed map (fig. 21). This shear zone extends across open ground for several hundred meters to the southwest, nearly reaching the Johnson Valley fault zone. The rupture zone that enters from the west crosses the long element and then turns to become subparallel with, but about 17 m east of the longer element, where it ends. There is no other evidence of interaction of the two right-lateral rupture zones.

Although the two shear zones superficially appear to be conjugate (one right-lateral and the other left-lateral), the kinematic signatures show that both zones are right lateral. It is difficult to understand how intersecting faults could have the same sense of shift if they occurred simultaneously or how the stress state could change enough during the earthquake sequence to sequentially produce two right-lateral shear zones. As mentioned above, however, the map view does not show the direction of propagation of the surface rupture. The situation at depth may be a product of misalignment of the fault zone, similar to the Kickapoo fault zone relative to the Johnson Valley fault zone (Plate 1), and to the Sargent and San Andreas fault zones in the Loma Prieta earthquake (see Johnson and Fleming, fig. 4, 1993).

The Two Bikers area includes parts of three *en echelon* rupture zones, trending about N10°E, that is, 10° to 20° clockwise from the overall north-south orientation of the walls of the Kickapoo fault zone. The longest element extends for about 250 m and ends in the vicinity of the fence. The right-lateral shift across this long, narrow zone was about 30 cm at the fence, as compared to a shift of 120 cm for the entire *en echelon* zone (fig. 21). To the west of the long shear-zone element shown in figure 21 is another shear-zone element about 80 m long that accommodated about 10 cm of right-lateral shearing at the fence line. Still farther west, starting at Fifth Avenue and extending for at least 200 m to the north (well off the map area) is a third shear-zone element. This shear zone accommodated the most shift, of the three, at the position of the fence line, offsetting the fence an additional 70 cm (fig. 21).

Each of the narrow shear zones consists of the same fracture elements described elsewhere at Landers (Johnson and others, 1993, 1994). The fracture elements are dominated by diagonal tension cracks oriented about 30° clockwise with respect to the overall trend of the zone. Some of these have accommodated subsequent, left-lateral offset of a few centimeters. There are small thrust faults, generally marked by low lobes, at one or both ends of the blocks of ground bounded by the tension cracks. There are a few right-lateral ruptures parallel to the narrow shear zones, but distinct fault surfaces are lacking. A striking difference between the orientation of tension cracks in the narrow shear zones in the Two Bikers area of the Kickapoo fault zone and the narrow shear zones elsewhere at Landers is that the tension cracks, rather than being oriented north-south, are oriented N30-40°E in the Two Bikers area.

Whereas the Johnson Valley and Homestead Valley fault zones step in a releasing mode (right step of right lateral elements), the individual elements within the Two Bikers area and the individual short elements within the longer element both step in restraining modes (left step of right-lateral elements).

Charles Road *En echelon* Zone

The Charles Road *en echelon* zone, part of the Kickapoo fault zone, extends north from Bodick Road about 800 m to a small ranch (Plate 1). The right-lateral shift across the fault zone is about 2.8 m as determined by sighting along a line of power poles.

Even at the scale of the location map (Plate 1), we can see that the Charles *en echelon* zone has a well-defined west wall and an ill-defined east side. The west wall is not a continuous fault, but

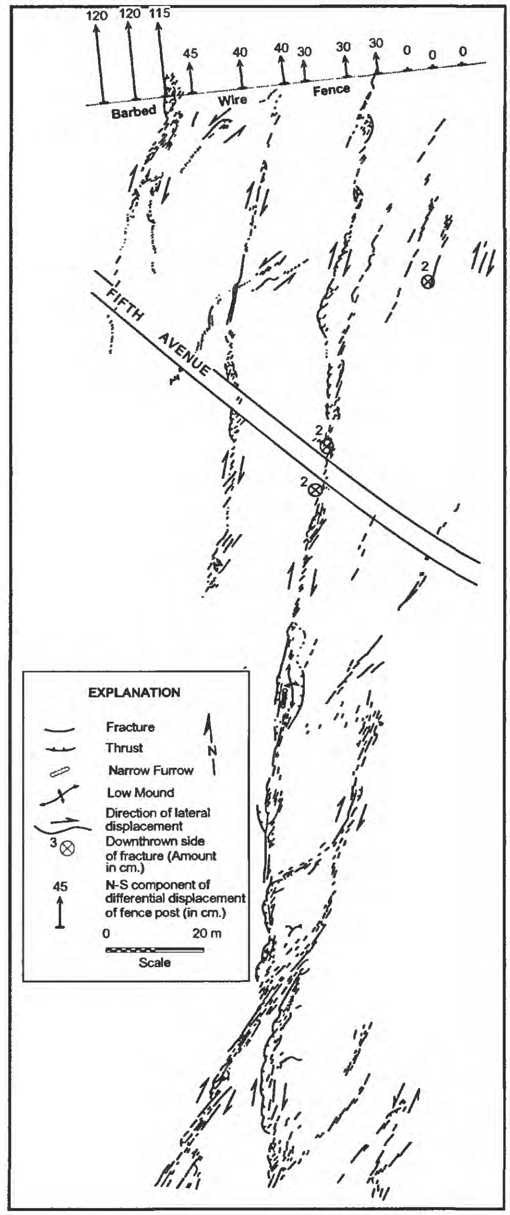


Figure 21. En echelon shear zones in the two-bikers area along the western side of the Kickapoo fault zone near intersection of Kickapoo Trail and Fifth Avenue. Each longer element of the zone consists of several smaller elements in a restraining orientation with respect to the longer element. Thrusts reflect the restraining steps or bends. Shift on the longest element nearly dies out before the element reaches the fence line at the northern end of the area. The element offsets the fence about 30 cm. Total shift recorded by the fence line for the en echelon shear zones is 120 cm. Another right-lateral rupture zone enters the south end of the map area with an orientation of N30°E, crosses the longest element of the north-south rupture, and then turns roughly north-south on the east side of the longest element. The two rupture zones seem to share tension cracks.

rather is defined by the southwest ends of numerous *en echelon* fault elements. The Kickapoo fault zone is 200-300 m wide in this area and its walls are oriented about N7°E. The Charles *en echelon* zone is about 800 m long and is oriented N17°E. As indicated in table 2, the width of the *en echelon* zone is about 230 m and the angle α (fig. 13) is about 170°.

The left step of the Charles *en echelon* zone is abrupt (Plate 1). It extends from Bodick Road to Charles Road, where it ends, between houses east of Charles and a small ranch west of Charles. We could see no damage to the houses or deformation of the fences east of the road. Neither could we could see any distortion of the southern fence bounding the small ranch west of the road. The next element to the left (north) is roughly in line with the ranch house. There are a few cracks in the vicinity of the house, and we were told that there was minor damage to the house. Thus, the elements of the main rupture of the Kickapoo fault zone stepped through this area of relatively dense housing, almost miraculously, without seriously damaging any of them! Houses in other places along Charles were not so luckily sited; they were directly underlain by fault elements (Lazarte and others, 1994).

A compilation of three detailed maps (1:200 scale) of the Charles *en echelon* zone is shown in Plate 6, and part of the center of the three maps is shown in even greater detail. The northern part of the map of the Charles Road area was constructed photogrammetrically, and no kinematic information is available. The other maps show kinematic information where such information could be determined in the field. The maps also show scarps and, in places, rubble on the downthrown side of scarps. The surficial debris in this area was quite sandy and friable, and we mapped the area a year after the earthquake, so the fractures were neither well formed nor well preserved, and kinematic information was difficult to obtain.

The most distinctive feature within the Charles *en echelon* structure is the zone of lower-order, *en echelon* shear-zone elements. The roughly 250 m–long elements are oriented N24°E and bound the Kickapoo fault zone on the west. The elements define a restraining, *en echelon* zone with a width of about 100 m, and the ratio of spacing of individual elements to width is about 0.4 (table 2). The shear-zone elements are uniformly downthrown on the southeast side, generally 30 to 60 cm to as much as 1 m. We could measure strike-shift offsets of some of the smaller fractures, but not along the main rupture zone, where it must be on the order of 2 to 3 m. The vertical shifts are normal, not reverse, so the net shift is right-lateral strike-shift and normal-shift, with the southeast side downthrown.

The detailed map on Plate 6 shows that the second-order elements (about 250 m long), arranged in a restraining configuration, are themselves composed of third-order, *en echelon* elements about 25 m long, which also arranged in a restraining configuration. Whereas the 250 m elements are oriented about N24°E, the 25 m elements are oriented about N45°E.

It is interesting that, at each scale, the fault elements trend further in the clockwise direction. The Kickapoo fault zone trends, overall, N7°E. Within it, the first-order shear-zone elements are oriented about N17°E. The second-order shear zone elements along those are oriented about N24°E, and the third-order shear zones are, in turn, oriented about N45°E.

Although the configuration of the shear-zone elements appears to be fractal-like, we believe it is not. Only in some places are the 800-m elements broken into 250-m elements. Neither are all of the 250-m elements broken into 25-m elements; the 25-m elements occur only locally. We suggest that the various elements simply reflect the vertical dimension of the element. The 25-m elements are exposed only where they are near the ground surface, and extend only a few tens meters into the subsurface. These, though, are like fringes locally on the larger, 250-m elements. Likewise, the 250-m elements are exposed only where they are near the ground surface, and extend only a few hundred meters into the subsurface. They are like fringes locally on the larger, 800-m elements.

We suggest that they are analogous to—but not of the same mechanical origin—the "twists" described along joints in Arches National Park (Cruikshank and others, 1991a; Scholz, 1992).

Ramps in *En Echelon* Fault Zones

Willard's Ramps

The development of structures called ramps[11] are diagnostic of the sense of shift on a rupture, as has been known for a long time. As far as we know, such ramps were first described by Willard Johnson (1907; published by Hobbs, 1910, and then by Bateman, 1961). The ramps occurred along scarps formed during the 1872, Owens Valley earthquake, about 1 km west of Lone Pine, California. According to Bateman (1961, p. 492-493),

> "These show that in detail the faults consist of a series of *en echelon* elements. Each fault element can be seen to be offset to the east from the next element to the north, and the overlapping ends are separated by northward-sloping ramps. This geometry requires a minor component of right-lateral movement as well as the major dip-slip component."

Thus, Willard's ramps occur along strike-slip *en echelon* zones where there is a combination of lateral shift and normal, vertical shift. In this situation, between many of the *en echelon* fault elements is a vertical slab of ground, the top surface of which is tilted, providing an unbroken tilted surface up which one can walk from the downthrown side to the upthrown side of the scarp. Hence the term, "ramp." The vertical slip on the fault elements bounding the ramp changes along the fault trace, from zero on the downthrown block, to a maximum at midlength up the ramp, back to zero on the upthrown block.

Ramps at Pipes Wash

We mapped one left-lateral *en echelon* fault zone at Landers. It is at the Pipes Wash releasing step, along the Homestead Valley fault zone, south of Virginia Avenue (Plate 1). The left-lateral zone is shown in more detail in Plate 7, an analytical map of the structure that shows not only the traces of fractures, but also the small thrusts, scarps and wedge openings along irregular fractures that show the sense of strike slip. The walls of the *en echelon* ruptures are oriented about N35°E, and the individual fault elements are oriented about 10° counterclockwise from the walls. The vertical displacements across the fault elements are substantial—they are typically 10-20 cm and locally as large as 25 cm.

The photographs in figure 22A, B, and C, show views of the ramps that formed in the *en echelon* zone. In figure 22A the view is toward the south along the narrow ramps in the northern part of the map area. There are at least six ramps visible in the view. In the middle distance is a well-defined, narrow ramp, between dry, low bushes on the upthrown block, which extends to the south toward a tall, dark bush on the downthrown block. A person is standing beyond the bush, providing a scale (ca. 2 m). The ramps in the southern part of the structure are wider, as shown in figure 22B, a view down three of the ramps which, here, are about 2-3 m wide. The bounding scarps are clearly shown as shadows. The photo was taken on the upthrown block; the downthrown block is beyond the scarps. Figure 22C was taken farther south, on the *en echelon* structure, where the ramps are about 5 m wide. Again, the view is roughly south, and the scarps are made clear by shadows. These photos were taken and the maps made about a year after the earthquake sequence.

Some other nice examples of ramps, in right-lateral *en echelon* zones, are shown in the maps of the Charles Road *en echelon* zone (Plate 6).

[11]These should not be confused with ramp faults that connect thrust faults at different horizons.

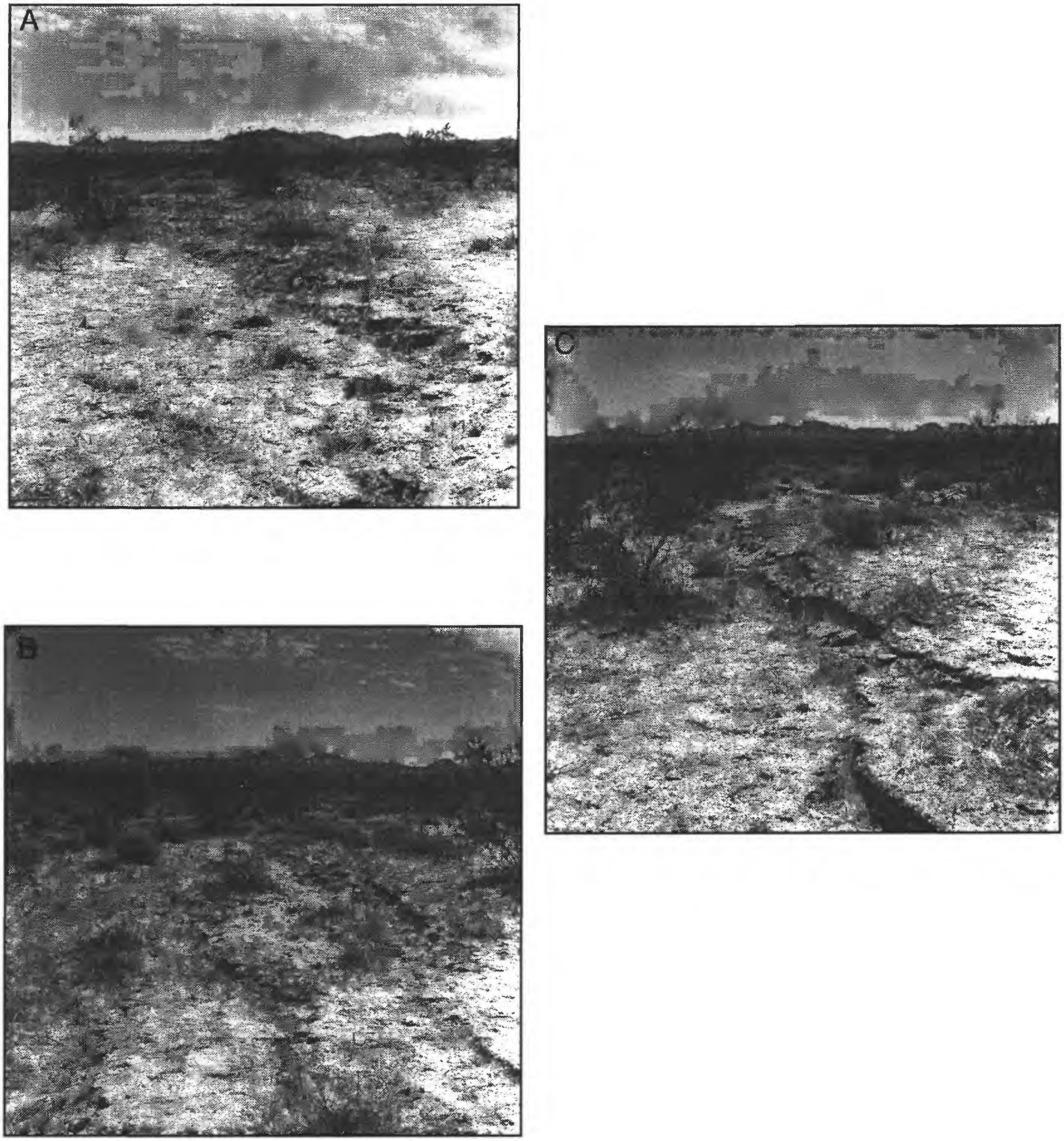


Figure 22. Views along left-lateral ruptures at Pipes Wash releasing bend. All views to the southwest. A. Belt of closely-spaced ruptures trends away from observer whereas individual ruptures trend obliquely across view. Downthrown side of most ruptures is toward camera. Ramps are the tilted blocks that connect the downthrown side of the left-lateral rupture zone on the left with the upthrown side on the right. B. More widely spaced ruptures and wider ramps farther southwest than in A. C. Most widely spaced ruptures, and widest ramps, near southwest end of left-lateral rupture. Because of their breadth, only two members of the en echelon belt are visible.

Some Summary Remarks

The object of this report has been to describe and explain several of the structures along the rupture zones at Landers. We have been fortunate to have been involved in detailed mapping of ground ruptures that formed in three large earthquakes in California—1989 Loma Prieta, 1992 Landers, and 1994 Northridge. From these studies and other descriptions of earthquake ruptures and descriptions of landslide structures, we have become infused with the similarities in surface rupture and deformation styles caused by earthquake and large-landslide ruptures. Single fractures of the types described in Utah by Fleming and Johnson (1989) and at Landers by Johnson and others (1993, 1994) are the basic building blocks of these structures.

We have learned that, if we are to understand the structure underlying a fractured area, we must first learn to interpret the fractures. In such interpretations there are two basic principles. First, groups of fractures in surficial materials are *guide fractures,* and as such provide insight into the growth of the structures (Johnson and Fleming, 1993; Martosudarmo and others, 1997). They reflect what is happening at depth, where we cannot directly observe the conditions or processes. Second, the work accomplished by the formation and further displacement across a fracture is defined in terms of its orientation and kinematics as a function of position. One can describe a piece of a fracture as a point quantity—the orientation of a fracture plane and a vector of differential displacement—as was done by most investigators at Loma Prieta (e.g., U.S. Geological Survey Staff, 1989, 1990; Spittler and Harp, 1990; Prentice and Schwartz, 1991). As Ponti and Wells (1991) and Martosudarmo and others (1997) have demonstrated, however, such descriptions are incomplete and confusing. Descriptions of fractures without the spatial distribution of orientation and differential displacement are inadequate for deducing the kinematics of a deformation.

In one place at Loma Prieta, we showed that two blocks of ground are separated by a rupture that is right lateral in one place, left lateral in another, and pure opening in a third, plus transitions in between. Without recognizing and mapping the orientation of the rupture and the distribution of differential displacement, we would not have been able to determine that the blocks of ground were simply moving apart, more or less like tectonic plates. The faulting appeared to be very complicated because the trace of the rupture was complicated. The block kinematics, however, were simple.

We have come to these realizations gradually as we have tried to make sense of the information on various maps. In many cases we made detailed maps, not because we knew where the mapping would lead us, but believing that, if we mapped carefully and faithfully, we would later be able to understand what had happened. When asked at the time why we were mapping in detail, we answered that we really did not know, yet. In our landslide mapping, we eventually interpreted most of the structures represented by the guide fractures shown on the maps. It turns out that, in this way we inadvertently found ridges, broad shear zones, structures at fault bends, and pull aparts at right-stepping right-lateral faults. We also mapped ruptures in detail at Loma Prieta. Again, we were initially puzzled by the map patterns, especially the left-lateral fractures (Aydin and others, 1993). As it turned out, our subsequent mapping and analysis of fractures at Landers showed that we had mapped part of a broad right-lateral shear zone at Loma Prieta (Johnson and Fleming, 1993) that had gone unrecognized by ourselves and others.

And now at the conclusion of these studies of surface rupture at Landers, we once more realize that our map information, alone, is largely insufficient to carry these observations to an understanding of structures much larger than the areas we mapped. In general, our detailed mapping and structural measurements will probably be investments in the future. As we examine other structures, and return to the observations at

Landers preserved in the maps of this report, we will be able to recognize the significance of map patterns that have thus far been obscure. The recognition of the left-lateral fractures at Loma Prieta as a common feature of broad right-lateral shear zones is an example; the understanding of the left-lateral rupture in the Pipes Wash step as a reflection of rotation of blocks is another. At the time we did the mapping, we saw these structures in sufficient detail to map them, but did not understand their meaning. The recognition of the Landers-Big Bear rotating block is yet another example. We understood the significance of the crude arc of fault traces at Landers only after working out a theory of faulting in flowing materials, and considering the general kinematics of slip on curved and straight faults (e.g., Johnson and others, 1996).

One can hardly avoid drawing broad conclusions about these structures. A striking feature of rupture zones, whether produced by landslides or faulting during an earthquake, is the structures' independence of form and scale. For example, the *en echelon* fault elements that follow Gilbert's law of obliquity are beautifully developed, at scales of 1 to 10 m, in the Aspen Grove landslide and, because of their slickensided surfaces, are clearly faults. Many of the freshly-formed fault elements at Landers, at scales ranging from 1 m to 500 m, also follow Gilbert's law. There are many other examples: The *en echelon* tension cracks, a few centimeters to a meter long, above an upward-propagating strike-slip fault in the Aspen Grove landslide, appear to be analogous to *en echelon* tension cracks, 1 m to perhaps 10 m long, within shear zones and belts of shear zones at Landers. The long thrust faults at restraining steps are clearly analogous to short thrust faults at restraining steps in Utah landslides.

We simply end, however, by admonishing ourselves from becoming overly excited about the conclusions and the correlations between the theoretical ideas and the field observations, with a quote from G.K. Gilbert's final paper: The context is a discussion of Gilbert's law of oblique faulting which, he states, applies also to slickened surfaces (Gilbert, 1928, op. cit., p. 13):

> "The law applies to oblique slickened partings within the fault rock, as well as to those in wall rock, and is of service in determining the direction of slip on the principal fault plane...The discussion of slickensides depends largely on my own observations. This statement is not a claim but an admission. *The inferences* that flexuous slickensides indicate small slip and the rule that the attitudes of oblique subsidiary slip surfaces are symmetrically related to the direction of fault movement *were derived largely from the very phenomena to whose interpretation they are to be applied,* and I would warn the critical reader of the possible danger of the logician's 'vicious circle.' "[italics ours.]

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