

*******US Copyright Notice*******

No further reproduction or distribution of this copy is permitted by electronic transmission or any other means.

The user should review the copyright notice on the following scanned image(s) contained in the original work from which this electronic copy was made.

Section 108: United States Copyright Law

The copyright law of the United States [Title 17, United States Code] governs the making of photocopies or other reproductions of copyrighted materials.

Under certain conditions specified in the law, libraries and archives are authorized to furnish a photocopy or other reproduction. One of these specified conditions is that the reproduction is not to be used for any purpose other than private study, scholarship, or research. If a user makes a request for, or later uses, a photocopy or reproduction for purposes in excess of "fair use," that use may be liable for copyright infringement.

This institution reserves the right to refuse to accept a copying order if, in its judgement, fulfillment of the order would involve violation of copyright law. No further reproduction and distribution of this copy is permitted by transmission or any other means.

Surface Breakage of the 1992 Landers Earthquake and Its Effects on Structures

by Carlos A. Lazarte, Jonathan D. Bray, Arvid M. Johnson, and Robert E. Lemmer

Abstract The Landers, California, earthquake ($M_w = 7.3$) provides an exceptional opportunity to study surface rupture of an earthquake fault. Detailed maps of the lateral distribution of fracturing adjacent to main traces show that rupture patterns are much more complex than documented in past studies of surface ruptures. The rupture occurs in tabular zones, up to hundreds of meters wide. A main trace within each rupture zone accommodates much of the shear deformation, but considerable fracturing occurs throughout the tabular zone. The en-echelon pattern of fracturing in step-over zones between main traces is typically even more complex than those along major fault zones. Inspection of several on-grade concrete slabs indicates that unreinforced concrete foundations generally crack when subjected to distinct ground ruptures beneath them or when they are twisted because of differential ground movements across broad zones. Methods of mitigating the potential hazards associated with earthquake fault rupture are presented.

Introduction

The Landers, California, earthquake ($M_w = 7.3$) of 28 June 1992 produced extensive surface rupturing over a distance of 85 km (Fig. 1). Faulting included significant movement on the Johnson Valley, Homestead Valley, Emerson, and Camp Rock faults, and on the Kickapoo step-over (also referred to as the Kickapoo fault). The focus of the earthquake was notably shallow, not deeper than 10 km (Campillo and Archuleta, 1993). Whereas some structures and lifelines were heavily damaged, the damage was relatively light, because of the low density of facilities in the area. Financial losses were estimated to be at least \$100 million (Mori *et al.*, 1992).

The Landers earthquake had a nearly pure strike-slip focal mechanism and exhibited primarily right-lateral surface displacement. The magnitude of the horizontal offset varied along the fault trace, but was typically 2 to 3 m (Kanamori *et al.*, 1992), with maximum strike-slip offset around 6 m (Sieh *et al.*, 1993). In addition, vertical displacements up to 1.5 m were measured. Many segments of the fault rupture were expressed as a broad zone of shearing (often hundreds of meters wide) rather than as a well-defined linear trace (Johnson *et al.*, 1993, 1994). An example is shown in Figure 2. The broad shear zones were observed in both unconsolidated deposits (compact and loose alluvium) and weathered bedrock, although the shear zones were generally more diffused and broader in unconsolidated deposits.

The Landers earthquake is an important seismic event because of its tremendous ground breakage, combined

NOTICE: THIS MATERIAL MAY BE
PROTECTED BY COPYRIGHT LAW
(TITLE 17, U.S. CODE)

with the high quality of retrieved data. Several research groups have collected field evidence of surface breakage at different scales depending on their specific interests. The earthquake ruptures were mapped at the *regional scale* (features >1 km; fault zones) by a consortium of geologists from the U.S. Geological Survey, the California Division of Mines and Geology, and Caltech. For example, K. Lajoie (1993, Personal Comm.) and Fleming (1993) have mapped parts of the Johnson Valley, Homestead Valley, and Emerson fault zones at scales of 1:4000 to 1:6000, using aerial photographs. Johnson *et al.* (1993, 1994) mapped patterns of cracks and fault segments within rupture zones 50- to 200-m wide at scales of 1:100 to 1:200 along the Johnson Valley, Homestead Valley, Kickapoo, and Emerson fault zones. These maps include representation at the *microscale* (features <1 m; individual fractures). Some of the maps presented here were made at scales of 1:100 to 1:200, but others were at scales of 1:200 to 1:1000. These latter are at the *project scale* (features 1 m to 1 km; movement relevant to specific structures), and the emphasis of the mapping is on effects of ground rupture on engineered systems.

The Landers earthquake offers an exceptional opportunity to observe the phenomenon of earthquake fault rupture. Because fault ruptures occurred in sparsely inhabited areas, there are few buildings, roads, and other structures obstructing the rupture patterns. Moreover, surface fault ruptures were extraordinarily well expressed because of the scarce vegetation and the arid cli-

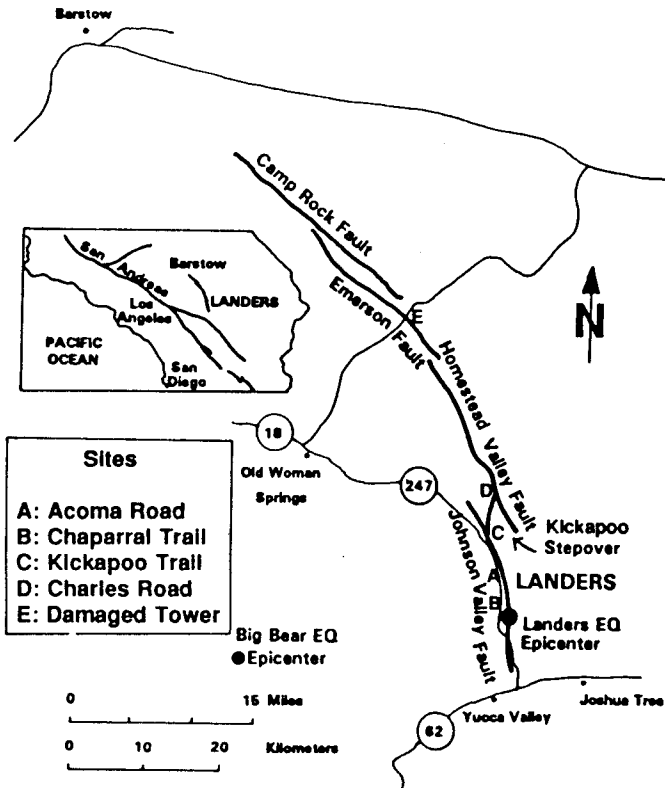


Figure 1. The principal faults activated by the 1992 Landers earthquake.

mate of the area. The principal objectives of this study are as follows:

1. Document the pattern and distribution of cracking associated with the surface faulting at selected sites along the rupture.
2. Assess how far from the main fault trace that ground fracturing can be expected. The data gathered on this topic are relevant to California's Alquist-Priolo Special Studies Zones Act (Hart, 1992), which addresses setback criteria for structures near major faults.
3. Characterize patterns of ground breakage in step-over areas. Step-overs are rupture zones that connect larger fault zones. The deformation within a step-over may be quite complex, and the resulting effects may be as damaging as those along the well-established main fault traces.
4. Investigate structures damaged by the faulting, and develop an understanding of the response of engineered structures to underlying fault movements.

Distribution of Surface Breakage

In this article, we are focusing on the project scale of ground rupturing at Landers. At this scale, the ground ruptures are highly variable, and the zone of faulting ranges from a few meters to hundreds of meters. Within a broad zone, there are thousands of fault segments,

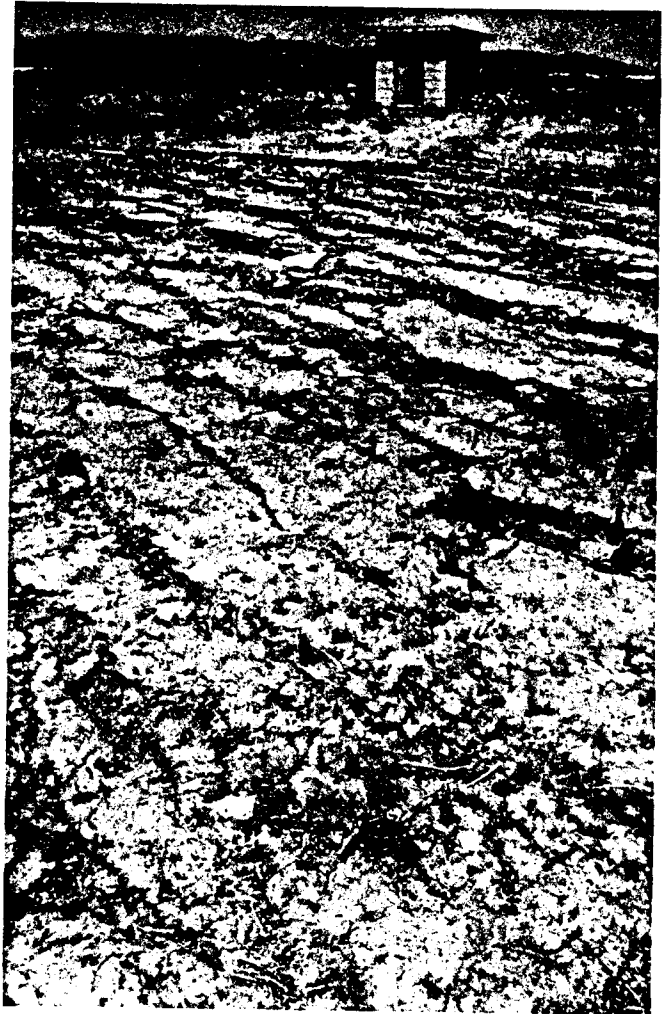


Figure 2. Fault movement distributed across a broad shear zone within the Kickapoo step-over.

fractures, and cracks that may affect engineered systems. The largest offsets were along a *main trace*, which is typically considered "the fault." Our observations suggest that the main trace may accommodate 60 to 80% of the total offset across a fault zone, and the remaining offset may be distributed along smaller faults, fractures, and cracks. For example, where the Homestead Valley fault zone crosses Bodick Road, the fault zone is 180-m wide and accommodated 1.8 m of differential offset. The main break, bounding the east side, accommodated about 55% of the total offset; another large break, bounding the west side, accommodated a further 17% of the total (Johnson *et al.*, 1994).

The characteristics of surface breakage resulting from the 1992 Landers earthquake were affected by surficial geology. For example, Irvine and Hill (1993) found, "The [rupture] zone is more discrete within older, more consolidated rocks and becomes diffuse and less distinct within younger, unconsolidated sediments." These observations agree with those by the authors and those developed through previous investigations (e.g., Bray *et*

al., 1994). There appears to be a tendency for surface fracturing to be more spread out in soft alluvium than in compact alluvium and competent bedrock at Landers. A map of the main trace of the Homestead Valley fault, where it crosses a sandy alluvial wash between weathered bedrock outcrops, about 1 km north of Bodick Road, illustrates this tendency (Fig. 3). The ruptures along the main trace in weathered bedrock were restricted to shear zones about 0.5-m wide. In the alluvial material deposited over the bedrock, the rupture zone was about 5-m

wide. The surficial materials at the sites mapped in this study are generally alluvium.

The relation between damage to structures and ground fracturing was studied at five sites. All the sites were relatively level, so the influence of local topographic effects was minor. Two sites were selected along the Johnson Valley fault zone to investigate the distribution of fracturing on each side of the main trace. The rupturing was fairly linear, continuous, and simple. In addition, there were no large engineered structures, only small on-grade concrete slabs and cabins. The first site along the Johnson Valley fault is near Acoma Road (Fig. 1, site A). The second is in Flamingo Heights, approximately 3 km south of the Acoma Road site, referred to as the Chaparral site (Fig. 1, site B). We studied two sites within the Kickapoo step-over where structures were damaged by surface faulting. One site is at Kickapoo Trail (Fig. 1, site C), 400 m north of the intersection of the Johnson Valley and Kickapoo fault zones. The other is the Charles Road site, about 1.5 km south of the intersection of the Kickapoo and Homestead Valley fault zones (Fig. 1, site D). The final site is where a single-tower power line crosses the Emerson fault (Fig. 1, site E).

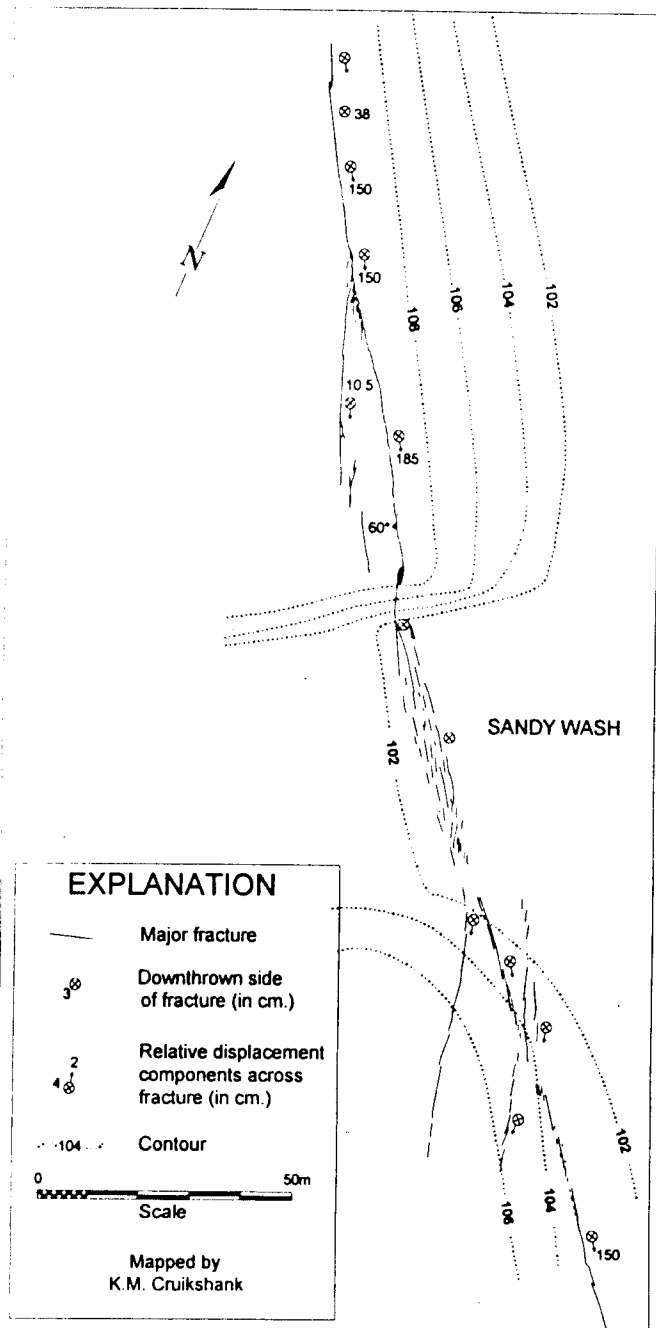


Figure 3. Surface expression of the main trace of the Homestead Valley fault as it crossed an alluvial wash located between weathered bedrock outcrops.

Acoma Site

The Acoma site consists of an area 1600-m long and 30-m wide, with its long sides bearing E-W. The area is bounded by Desideria and New Dixie Mine roads (Fig. 4a). The main trace of the Johnson Valley fault zone in the Acoma area is a linear feature trending about N-S. The main trace is about 90-cm wide and has a scarp up to 30-cm high facing west. Offsets of washes, paths, and bushes indicate that the right-lateral offset on the main trace averages 120 cm. At Desideria Road, to the north, the offset is 180 cm; at New Dixie Mine Road, to the south, the offset is 90 cm. At a fence line 400 m north of the area, the offset is 300 cm. Farther north, offsets increase.

There is less-intense, but still significant, right-lateral displacement within a zone about 100-m wide centered on the main trace. Figure 4b shows fractures within bands of ground 100-m wide on either side of the main trace. Some of the rupture zones contain tensile cracks up to 2.5-cm wide. The amount of accumulated right-lateral displacement across fractures is comparable on either side of the main rupture—15 cm on the east and 11 cm on the west. The total offset across this 200-m-wide zone is estimated to be 146 cm. The features of ground fracturing differ on each side of the main trace. On the east side, lateral displacement is concentrated mostly in a few cracks (Fig. 4b). On the west side, the fracturing is relatively intense and distributed across a zone about 40-m wide. A graben about 25-m wide de-

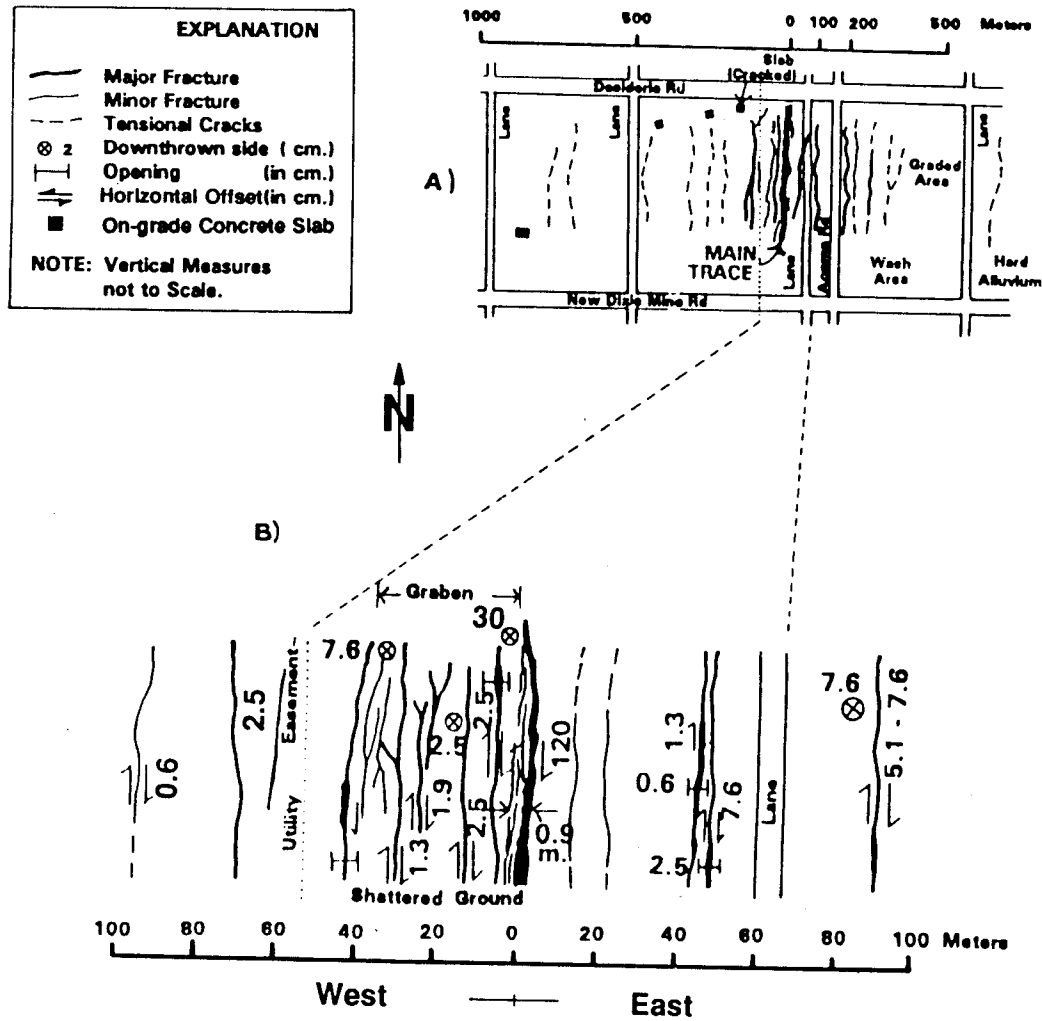


Figure 4. (a) Distribution of ground rupture across a segment of the Johnson Valley fault at the Acoma site; (b) detail of movement around the main trace.

veloped in this area, downdropping the ground 5 to 7 cm. Within the western part of the graben, the ground is shattered, precluding detailed mapping of cracks.

Some minor cracks occur as far as 750 m from the main trace (Fig. 4a). These are tensile cracks with apertures on the order of 1 mm. The separation between cracks ranges from 50 m close to the main trace to 150 m in the outer section. Fresh tensile cracks, observed in an unreinforced concrete foundation slab located 120 m away from the main trace, indicate the broad zone of damage to structures along this fault segment. No damage was observed in the three most distant unreinforced concrete foundation mats within the surveyed area (Fig. 4a).

Chaparral Site

The main trace of the Johnson Valley fault zone at the Chaparral site (Fig. 1, site B) traverses State Road 247 at 5° to 10° clockwise (Fig. 5). The main trace occupies a width of about 2 m and consists of a series of en-echelon fractures generally stepping left. The amount

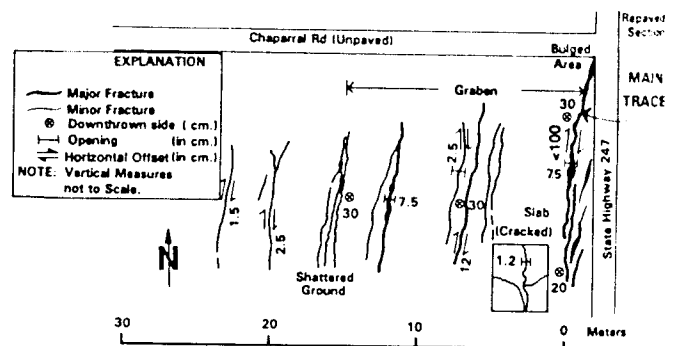


Figure 5. Distribution of ground rupture across a segment of the Johnson Valley fault at the Chaparral site.

of right-lateral displacement could not be measured precisely here, but it is less than 1 m. Adjacent to the repaved section of State Road 247, an area of bulging and shattered ground develops along the main trace. A few meters south of the bulged area, the main trace has a

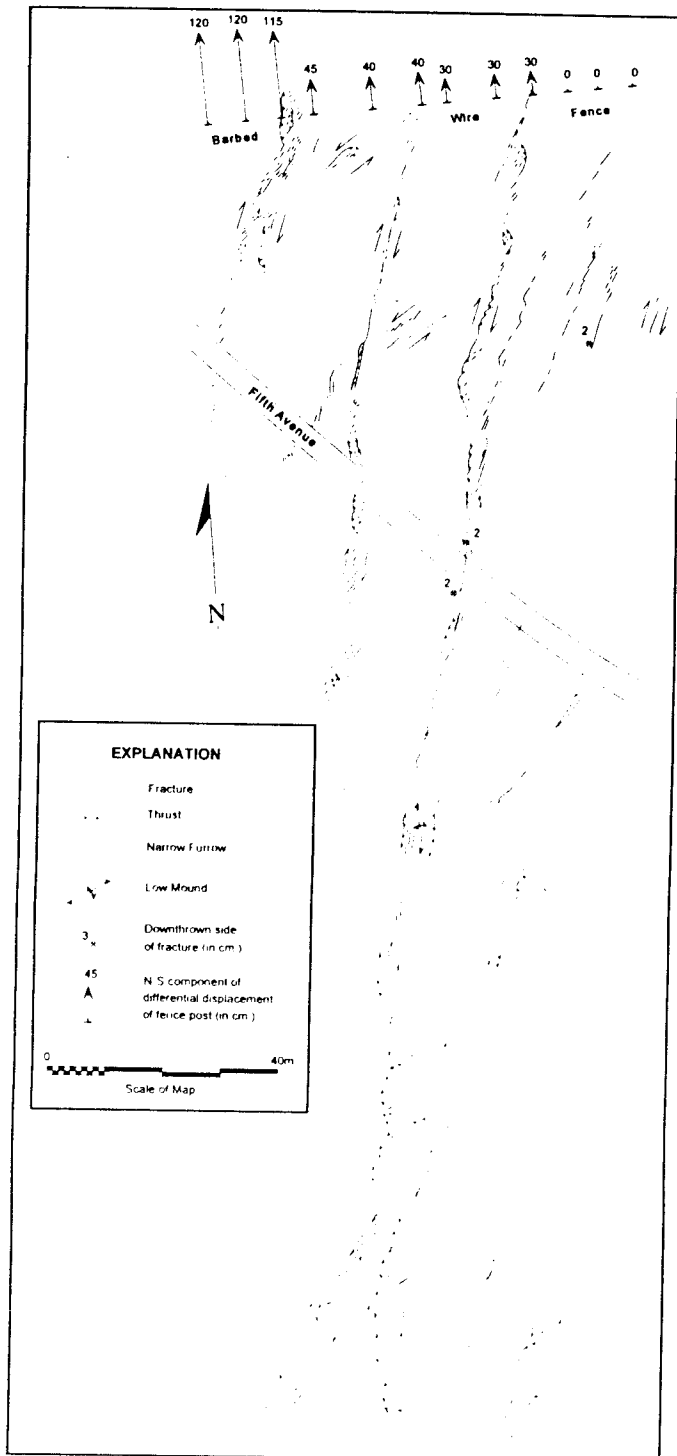


Figure 7. Detailed map of en-echelon shear zones in Kickapoo step-over, immediately east of intersection of Fifth Avenue and Kickapoo Trail. Map shows a nearly complete, long shear zone on right, a complete, short shear zone in middle, and the south end of a long shear zone on left. The latter offsets the fence line about 0.7 m, a large fraction of the 1.2 m of offset for the entire en-echelon belt of shear zones.

sion cracks. There are a few right-lateral ruptures parallel to the narrow shear zones, but distinct fault surfaces are lacking. A striking difference in the narrow shear zones in the Kickapoo step-over and those elsewhere at Landers is that the tensile cracks, rather than being oriented N-S, are oriented N30 to 40E in the Kickapoo step-over.

Kickapoo Trail Site

A detailed map of the ground breakage at the Kickapoo Trail site (Fig. 1, site C) is shown in Figure 8. This detailed map also served to study the damage to the structure situated roughly in the center of the mapped area. The west side of the area displays numerous, closely spaced cracks. The number of cracks of all sizes is astonishing. Offset on individual cracks in the west side ranges from 0.5 to 5.0 cm. The accumulated offset in the three western shear zones is: 15 to 20 cm, roughly 5 cm, and 7.5 to 10 cm, for zones A-A, B-B, and C-C, respectively. In the southwestern part of the area, zones A-A and C-C accommodate more slip than zone B-B. In the northern part of the area, the distribution of right-lateral displacement is more uniform, and the accumulated offset is comparable along the three zones. In the southern end of zone B-B, some of the cracks accommodate little slip (on the order of a few millimeters) and develop as extensional cracks with average openings of 2 to 5 mm. In fact, it is characteristic that minor cracks formed as tensile cracks at early stages of fracture development. The rough, unsheared faces of these cracks indicate that the cracks first opened in tension and then accommodated slip (Johnson and Fleming, 1993). Zones on the west side, especially B-B and C-C, veer progressively from a general trend of N20E to N30 to 45E from south to north. A relatively intact wedge in the center of the surveyed area is bounded by zones C-C and D-D. Only minor, barely visible tensile cracks were noticed in this wedge. The ground is relatively firm in this area.

On the east side, a narrow shear zone D-D accommodates 65 cm of offset which is readily observable along the fence line. The trend of this narrow shear zone is N5 to 10E. The concentrated shear zone degenerates into a graben, which expands laterally to the north. The graben is bounded by shear zones which are branches initiating from zone D-D. Approximately 100 m beyond the structure, zone D-D progressively returns to a general trend of N20 to 30E, and movement across the rupture zone becomes more distributed over that area. Twenty meters north of the house, zones C-C and D-D merge to form a narrow zone 1.5-m wide, containing several subparallel cracks and severe ground breakage. The offset across the zone is 15.2 cm. Beyond this zone, the ground fracturing is more uniform.

Ro
tot
nor
(Fig
the
over
Cha
Kick
Fig
nor
segr
a lo
rock
of pa
hill f
on th

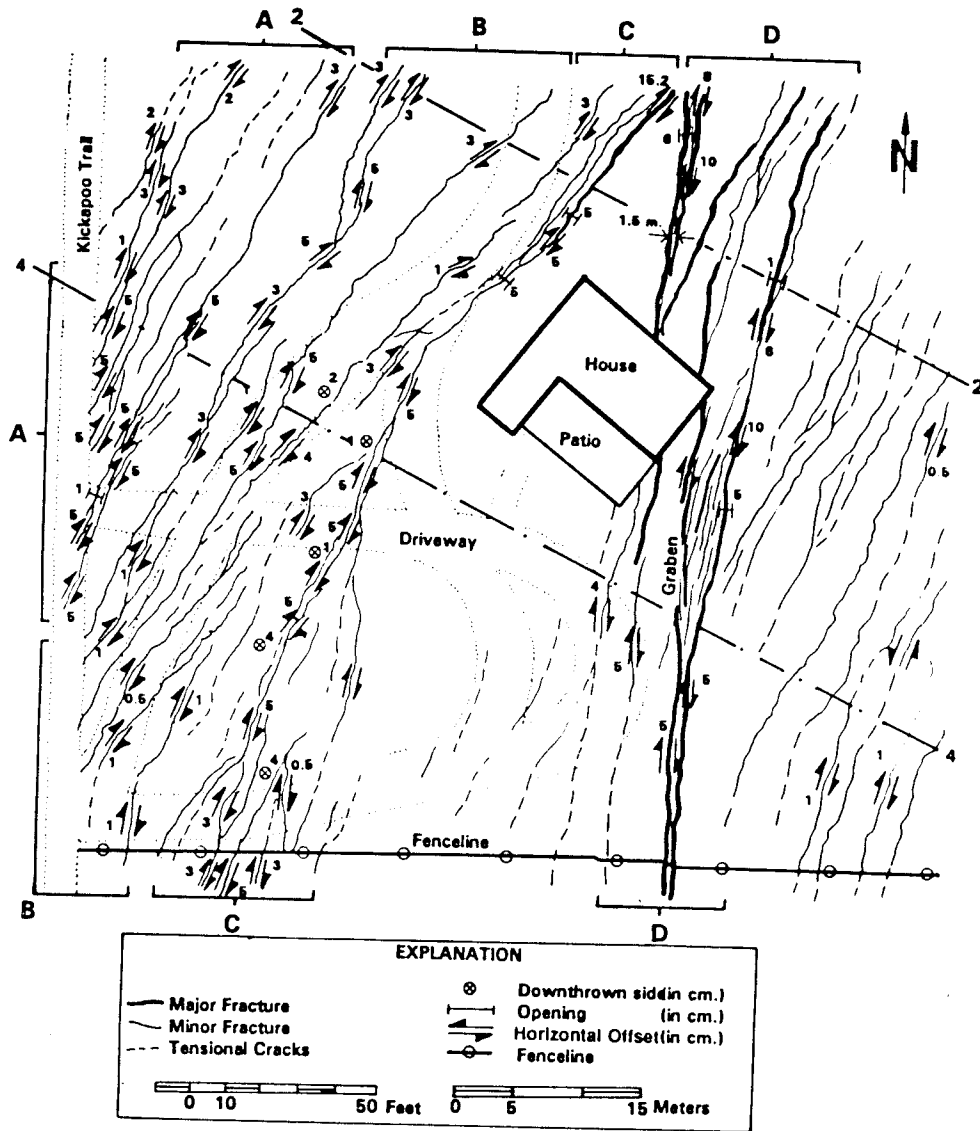


Figure 8. Detailed mapping of ground fracturing at the Kickapoo Trail site.

Charles Road Site

Ground rupturing is more concentrated at the Charles Road site (Fig. 1, site D) than at Kickapoo Trail. The total width of the rupture zone at Charles Road, near the north end of the Kickapoo step-over, is about 120 m (Fig. 9). Most of the fractures trend N5 to 10E; that is, the fractures are oriented about 10° clockwise from the overall trend of the Kickapoo fault. The rupturing at Charles Road represents several long segments of the Kickapoo en-echelon fracture array, much as shown in Figure 7. The southern segment is about 500-m long, the northern segment about 300-m long. The left-stepping segments are separated 40 to 60 m. Within one step is a low rocky hill, composed of highly weathered bedrock about 3-m high. The map (Fig. 9) shows a group of parallel and closely spaced cracks traversing the low hill from north to south, ending in relatively flat ground on the south side of the hill. These cracks occur within

the step between the rupture segments and appear to be a result of interaction of the two segments. The cracks do not exhibit strike-slip offset; rather, they are tensile cracks.

Immediately southeast of the low hill is the central rupture segment, which trends about N10E. It is 5.1-m wide, with much of the slip concentrated in a narrow strip 1.2-m wide. Although it accommodates both right-lateral and vertical differential displacements, its most prominent feature is a scarp up to 120-cm high facing toward the SE. The vertical component of fault displacement is distributed across the entire width of the segment. The relative vertical displacement increases from 30 to 120 cm from south to north along the scarp, with maximum right-lateral offset on the order of 20 to 30 cm on the scarp's central part. The southern rupture segment, south and east of the house, accommodated as much as 120 cm of right-lateral shearing. Much smaller hori-

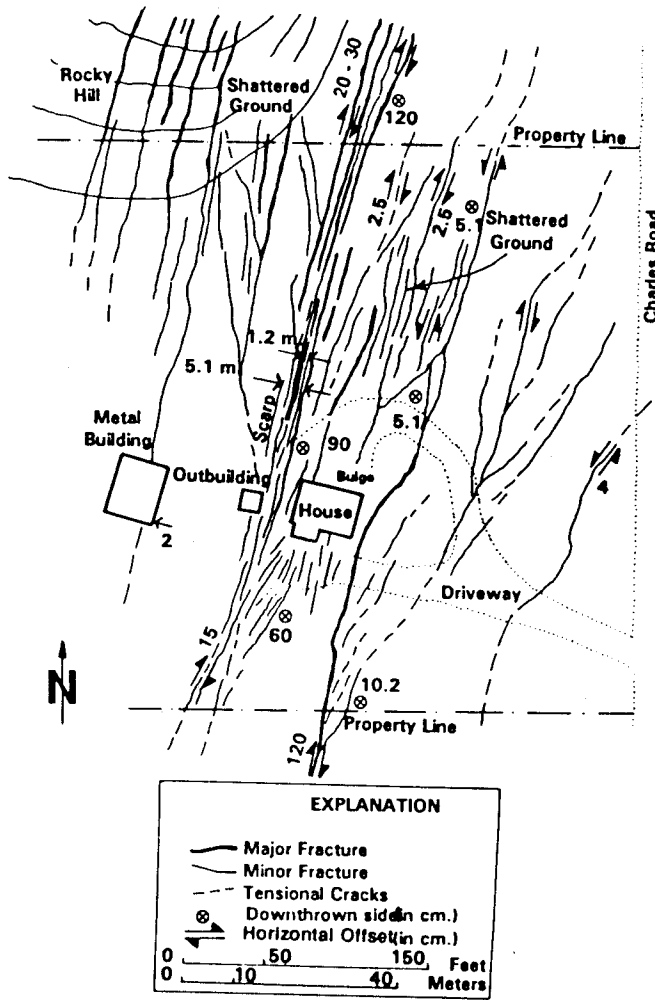


Figure 9. Detailed mapping of ground fracturing at the Charles Road site.

zontal offsets (about 10 cm or less), however, were observed along the northern section of this fracture, so the step between the southern and central segments is at the house. A line of power poles trending approximately perpendicular to Charles Road, and located 15 m south of the property line, is offset on the order of 1 m over a width of about 40 m.

Single-Tower Power Line Site

A high-voltage transmission tower at the single-tower power line site (Fig. 1, site E) nearly collapsed because its legs straddled the main rupture of the Emerson fault zone (Fig. 10) Johnson *et al.* (1993, 1994) calculated 270 cm of offset and 2 to 7 cm of dilation (normal to the trace) for the main rupture at the tower by comparing the geometry of the damaged tower with that of the neighboring, undeformed tower. Additional right-lateral displacement of 21 and 60 cm, measured SW and NE, respectively, from the deformed tower, accounts for the entire 3.5 m of right-lateral differential displacement accommodated by this rupture zone.

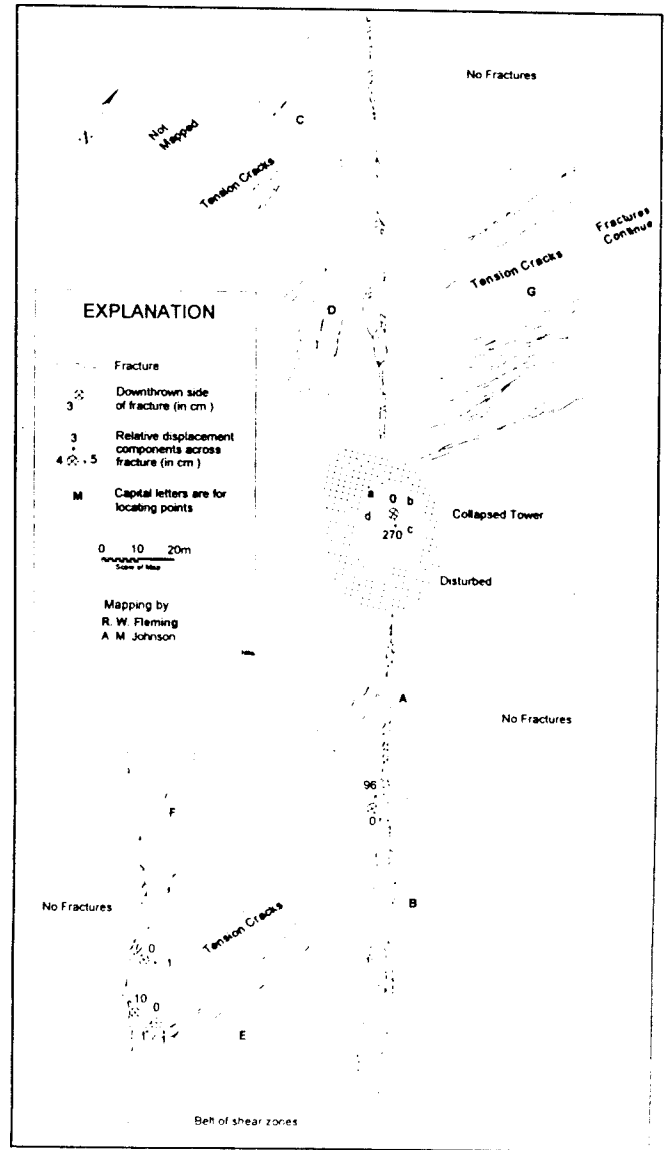


Figure 10. Detailed map of fractures that define the rupture zone along the Emerson fault zone at the single-tower power line. Overall shift across 70-m-wide belt is about 3.5 m. Each side defined by relatively straight, narrow shear zones. Narrow shear zone on right (NE) side is main trace, which accommodated about 2.7 m of right-lateral shifting. Tensile cracks within belt of shear zones generally oriented about N-S to N10E, whereas tensile cracks outside NE side of belt, which apparently are part of a step-over structure with the Camp Rock fault, are oriented about N30E to N40E.

At this locality, the rupture zone is simple and straight for at least 2 km to the NW and 1 km to the SE. Farther southeast, the rupture zone splits and passes around each side of a granite ridge. At the tower, the rupture zone is about 70-m wide, oriented N45 to 50W. Tension cracks oriented N30 to 45W occur sparsely throughout the width

of the broad shear zone; a few of them have some left-lateral shift. There are a few, narrow, right-lateral shear zones within the broad shear zone in the NW part of this area (Fig. 10). Most of the right-lateral shift across the rupture zone is accommodated by narrow shear zones bounding a broad zone of minor shearing (as described by Johnson *et al.*, 1993, along other rupture zones at Landers). The narrow shear zone along the SW wall of the broad shear zone accommodates about 20 cm of right-lateral and up to 10 cm of vertical (downthrown on NE side) relative displacement. Along much of its length, this narrow shear zone consists of NS-oriented fractures several meters long. The blocks of ground between these fractures typically end in low thrusts, directed toward the center of the broad shear zone.

The main trace—which is a narrow shear zone, or “mole track,” along the NE wall—dominates the belt of shear zones. Its width ranges from 0.5 m in places in the NW part of its trace, to 10 m in the SE. It has a beaded (or a pinch-and-swell) structure that is particularly noticeable in the NW part. The narrow segments (the pinches) are a few tens of cm wide, and along parts of their lengths is a narrower groove, about 10-cm wide and deep, probably representing the fault surface not far below the ground surface. The broader segments (the swells) are several meters wide and generally have distinctive internal structure. These broader segments contain long fractures oriented at a clockwise angle of about 30° to the trend of the shear zone. The ground has been thrust at one or both ends of the blocks separated by fractures. Another feature of the narrow shear zone here is that the ground surface is depressed (up to 30 cm) along some stretches and raised (perhaps equally) along other stretches. Therefore, along the trend of the narrow shear zone, there is an elongated basin, then an elongated dome, then an elongated basin, and so forth.

At this site, there is another step-over zone—in this case, between the Emerson and Camp Rock fault zones. This step-over, rather than consisting of en-echelon shear zone segments, consists of a swarm of tension cracks east of the Emerson fault zone. These cracks occur in a belt, about 50- or 60-m wide, trending N20 to 30E, and extending at least 1000 m toward the Camp Rock fault zone, 1.5 km to the NE (Johnson *et al.*, 1993). The tension cracks within this step-over are oriented differently than those within the broad shear zone along the Emerson fault zone. Interestingly, the tension cracks in the step-over have the same orientation observed in the Kickapoo fault to the south, rather than those within the broad shear zone along the Emerson fault zone. The tension cracks in the shear zone along the Emerson fault are oriented N–S, at a clockwise angle of 30° (but as great as 45°) to the walls of the shear zone. The tension cracks within the step-over are typically oriented at a clockwise angle of 60° to 70° to the walls of the Emerson fault zone.

Summary of Surface Breakage

The rupture zone produced by the 1992 Landers earthquake is not a simple, linear fault zone as usually described in textbooks; instead, it is a relatively wide tabular zone, which accommodated shear deformation (Johnson *et al.*, 1993, 1994). The shear zone is often hundreds of meters wide. There are numerous fractures within this zone, and here we can observe the main trace. The number of fractures and cracks observed in the shear zone, especially within the Kickapoo step-over, is truly astonishing. A substantial number of subsidiary fractures were noticed in areas adjacent to main traces (e.g., Figs. 2 and 4). Despite the fact that most of the ground fracturing occurred in an area some tens of meters wide, we noticed extensional cracks several hundreds of meters from the main trace.

For the Landers event, we can define three levels of intensity of ground fracturing: high, intermediate, and low. High-intensity ground fracturing occurred along the main trace and in its immediate vicinity. The offset in this area, about 10-m wide, ranged between 1 and 3 m. Intermediate-intensity ground fracturing is located mainly in an area about 100-m wide. The offsets along these fractures were on the order of a few decimeters. In spite of the relatively small differential displacements and apertures associated with this intermediate category, the fractures may pose a hazard to structures and lifelines. Finally, low-intensity ground fracturing is observed in areas up to hundreds of meters from the main trace. The nature of the fractures in this zone is primarily extensional. Offsets along fractures were on the order of a few millimeters. The cumulative concentrated right-lateral horizontal offset across some of the mapped areas is shown in Figure 11. Figures 11a and 11b show a more concentrated offset along the main trace of the Johnson Valley fault, whereas Figures 11c and 11d depict a more distributed horizontal offset within the Kickapoo step-over. These figures do not include the relative displacement between individual fractures resulting from ground distortion, which may be important.

We should expect an exceptionally large number of surficial cracks in transfer areas. The transfer mechanism, which accomplishes geometric compatibility between subparallel fracture segments, is observed at two scales. At the scale of the Kickapoo step-over, the step-over transfers right-lateral displacement between major fault segments. At a scale of a few tens of meters, individual en-echelon fault segments along the fault trace also transfer relative displacement. The transfer takes place at the ends of the segments, where they step laterally. The magnitude of ground breakage associated with the transfer mechanism, however, is significant both in the larger and the smaller scales. The most spectacular example of ground rupturing associated with transfer areas at the larger scale is that in the area near the intersection

of the Kickapoo and Johnson Valley faults (Fig. 6). At the smaller scale, intense ground fracturing in transfer areas was also damaging (Fig. 7). Two heavily damaged structures (which will be described later) were located where significant lateral transfer took place.

Faulting-Induced Damage to Structures

The Landers earthquake offers some important lessons, particularly regarding the distribution of ground breakage on a project scale and its consequences to engineered systems. About 30 houses were damaged, with an additional 50 houses that may have been affected by fault rupture in the Landers area (Hart *et al.*, 1993). Damage to water and sewer lines was estimated at \$27 million. Lifelines in the towns of Landers and Flamingo Heights were heavily damaged. As a result of hundreds of water-line breaks, customers were without water for as long as two weeks. Most of the pipeline damage resulted from rupturing within fault zones (Topozada, 1993). State Highway 247 was disrupted in 10 locations by movement on the Johnson Valley fault, and the roadway was not fully restored for eight days (Topozada, 1993). The faulting-induced damage to structures during the 1992 Landers earthquake did not kill anyone. This sparsely populated area, however, was not a true test of the life-safety risks associated with fault rupture. None-

theless, given the low density of structures in this area, a significant number were heavily damaged. Two houses in the Kickapoo step-over and a damaged high-voltage transmission tower are described to relate the structural damage to ground breakage in the vicinity of the structures.

Kickapoo Trail Site

The house at the Kickapoo Trail site is a conventional one-story, wood-frame house (130 m²) built on an on-grade, unreinforced concrete slab. The wood-faced exterior walls are insulated with fiberglass batting, and the inner faces of the walls are standard gypsum wall-board. The wood truss roof structure is covered by plywood sheathing and shingles. With respect to building damage resulting from ground deformation, it is important to note that the concrete slab did not even contain wire mesh. The ground in the vicinity of the house is composed of well-graded sand with less than 20% non-plastic fines. The *in situ* density ranged between 18.1 and 20.4 kN/m³, characteristic of dense, cohesionless soils. The density and apparent cohesion of the soil favored the preservation of ground cracking features. It is likely that dilation occurred within the top layer of the dense sand deposit.

The location of the house relative to the ground breakage is shown in Figure 8. Perhaps the most important ground rupture zone, with respect to damage to the house, is D-D, which trends about N5 to 10E. This shear zone is about 10-m wide and accommodates 65 cm of right-lateral offset. At the fence line along the southern edge of the map area, most of the offset is concentrated along a very narrow zone. The map suggests that this zone steps across 10 m and continues with the same trend toward the north. Near the house, the zone becomes a graben, about 5-m wide and a few cm deep. Movement within the graben produced major damage to the building and supporting slab. West of the graben, subparallel fractures, which accommodated 4 to 5 cm of offset, also damaged the house. The NE corner of the house is situated in a minor step-over feature. In this left step, the foundation of the house is subjected to N-S compression (Segall and Pollard, 1980). Measurements of offsets across the ground fractures indicate that 30 to 50 cm of differential horizontal displacement occurs in the ground beneath the foundation of the house.

A complex pattern of cracks developed in the foundation slab of the house (Fig. 12). In general, cracks formed in the slab where fractures occurred in the underlying ground. Damage is concentrated in the eastern part of the slab, where the adjacent ground movement is largest. Cracks B, C-E-G, and D-F appear to have formed where fractures impinge on the foundation. Crack A appears to be unassociated with a specific ground fracture, and likely formed to accommodate the torsional displacement induced in the structure.

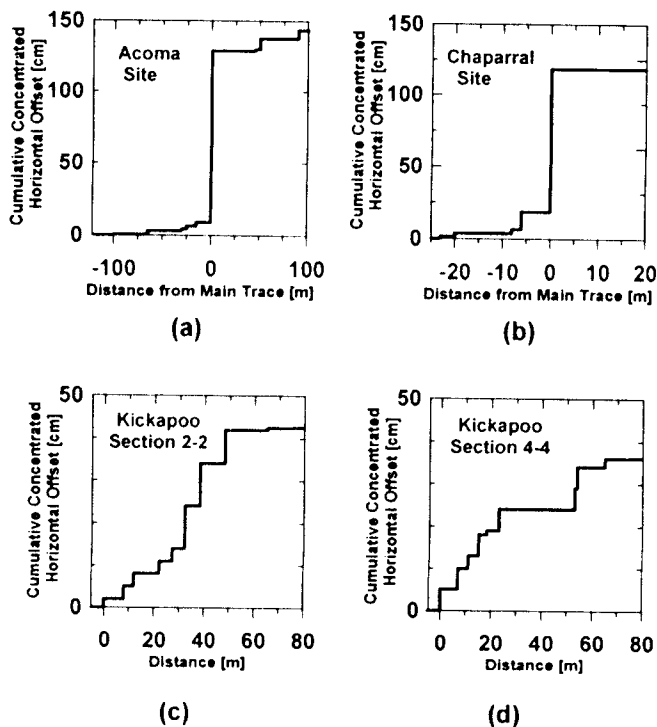


Figure 11. Cumulative concentrated right-lateral horizontal offset across selected fault zones: (a) Acoma site, (b) Chaparral site, (c) section 2-2 at the Kickapoo Trail site, and (d) section 4-4 at the Kickapoo Trail site.

(Fig. B is 13). so th the h The s and n Crack NW-C and

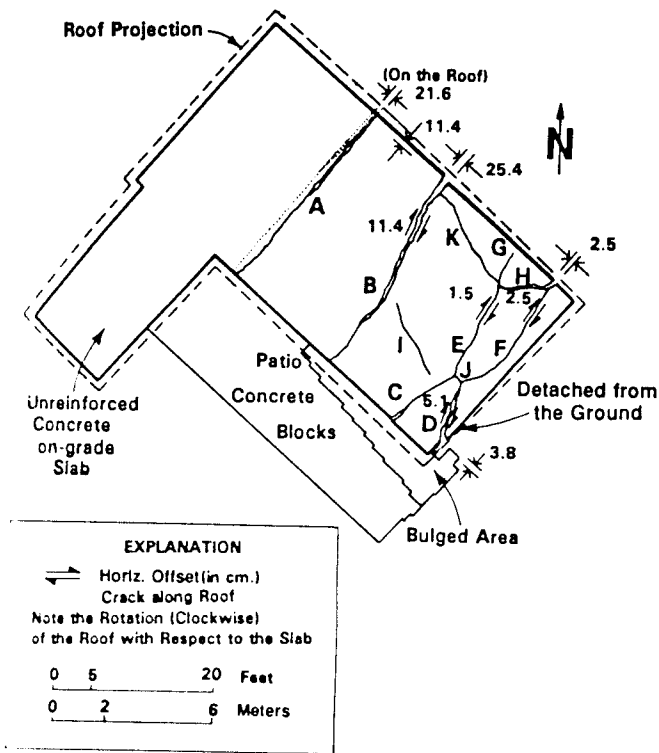


Figure 12. Distribution of cracking in the unreinforced concrete slab at the Kickapoo Trail site.



Figure 13. View of ground-rupturing-induced crack in concrete slab at the Kickapoo Trail site.

The largest crack in the foundation slab is crack B (Fig. 12). At the slab's NE edge, the aperture of crack B is 25.4 cm, with 11.4 cm of right-lateral offset (Fig. 13). The relative vertical displacement is less than 4 cm, so the net displacement is 28 cm, and the direction of the horizontal differential displacement is about N20W. The side of the house east of crack B rotated clockwise and moved right-laterally with respect to the intact side. Cracks that formed oriented approximately NE-SW and NW-SE produced blocks, bounded by fractures B-K-E-C and B-G-K. These blocks constitute a mechanism that



Figure 14. View of the NE side of the house damaged at the Kickapoo Trail site. At the lower left corner, the largest crack (B) is noticeable. Note the influence of the ground rupture extending from the ground, up the wall, and to the roof in the center of the picture.

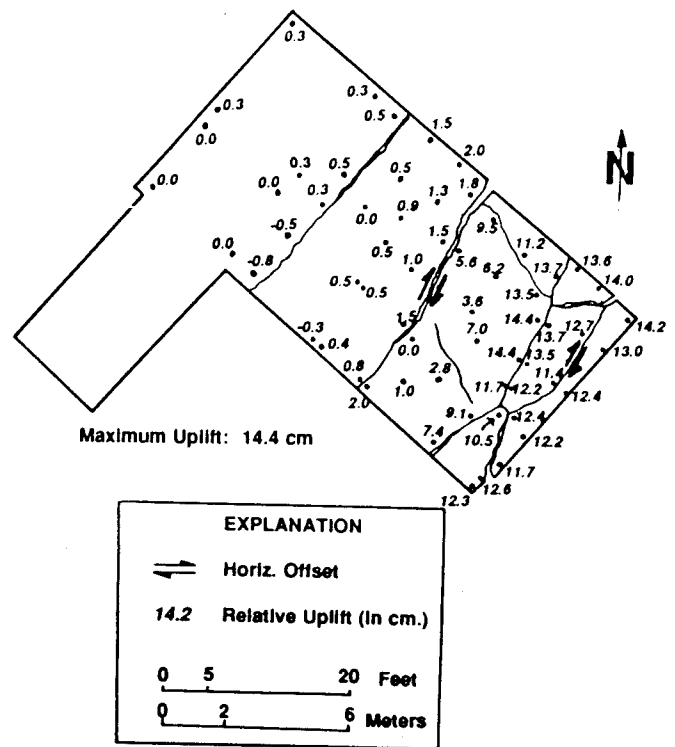


Figure 15. Relative vertical uplift of blocks formed in the cracked unreinforced concrete slab at the Kickapoo Trail site.

allows clockwise rotation to accommodate ground deformation. Apparently, the imposed deformation is not sufficient to develop other blocks, such as B-I-C. The shearing deformation at the ground caused the slab to rotate, which, in turn, rotated the roof framed structure clockwise. This torsional movement caused a portion of the wall panel on the NE side to be torn apart at its seams



Figure 16. Ground bulging and foundation detachment produced by rotation of the structure's concrete slab.

(Fig. 14). The torsional movement also induced a permanent twist in the roof structure, and a crack 21.6-cm wide along its NE edge. The relative vertical uplift of the blocks formed in the concrete slab is shown in Figure 15.

The relative right-lateral displacement and rotation of the severed part of the slab caused the ground to bulge in the patio at the front of the house, and the foundation to become detached from the surrounding ground at the back of the house (Fig. 16). This situation indicated that passive and active zones developed on the SW and NE edges, respectively, of the concrete foundation slab. This situation can be referred to as the development of conjugate zones of principal stress, i.e., active and passive zones, in the soil. These observations are in accord with the findings by Duncan and Lefebvre (1973), who studied the field of stress induced around a rigid buried body subjected to an underlying strike-slip fault movement.

Charles Road Site

There are three buildings at the Charles Road site (Fig. 9). The house is a one-story wood-frame structure (85 m²) on an on-grade, unreinforced concrete slab. The house is constructed similarly to that at the Kickapoo Trail site. The larger auxiliary structure is a metal, prefabricated storage shed, and the smaller is a wood shed. The metal shed is astride a tension crack, oriented N5E, extending southward from the rocky hill. The SE corner of the metal building moved 1.5 cm, but there is no apparent damage to this structure.

The west side of the house is about 3 m east of the eastern edge of the central rupture zone (Fig. 9). There are many subparallel fractures in a zone about 8-m wide trending about N20E and extending from the main trace to the south side of the house. Across most of these fractures, the ground is drowndropped a few cm on the east side. There are only a few fractures extending NE from

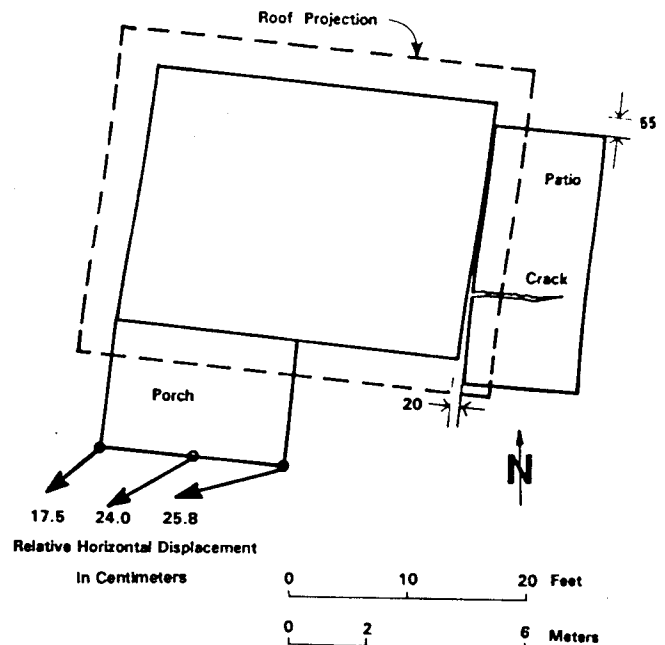


Figure 17. Schematic representation of the visible damage to the house at the Charles Road site. The relative horizontal displacement between the roof (height = 2 m) and the ground is also shown.

the northern side of the house; the offset appears to be more concentrated here.

The distribution of fractures in the vicinity of the house indicates that, like the house at the Kickapoo Trail site, the house at Charles Road is situated within a left step between two right-lateral rupture segments. The relatively large (120 cm) right-lateral offset measured at the southern end of the property (Fig. 9) appears to have been transferred through the subparallel fractures in the ground south of the house to the more-northerly segment that passes between the house and the small building. Measurements of net displacement of posts supporting the porch roof at the south side of the house indicate that ground beneath the western half of the house moved 18 to 26 cm in a right-lateral sense relative to the ground beneath the eastern half of the house (Fig. 17). The patio slab on the eastern side of the house also moved relative to the house. There is a right-lateral offset of 55 cm between the house and the slab. The house rotated in a clockwise sense with respect to the slab so that its SE corner became separated 20 cm from the slab. It is likely that the transfer of the right-lateral displacement between the two segments of the main trace occurred immediately beneath the house. The unreinforced concrete foundation slab was twisted and broken into discrete sections by numerous fractures.

Single-Tower Power Line Site

The damage to the high-voltage, steel-frame transmission tower shown in Figure 18 illustrates the vulner-

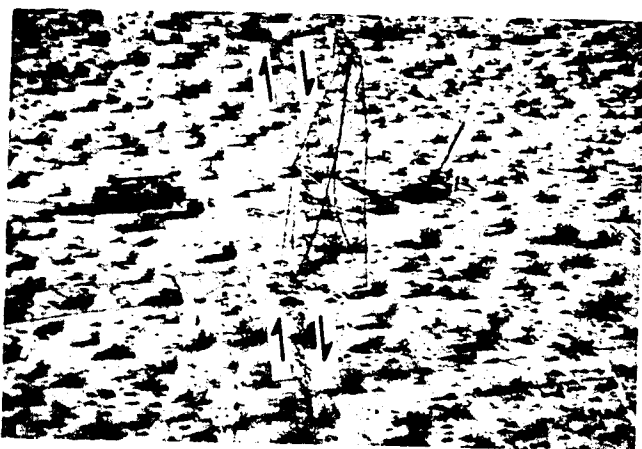


Figure 18. Damaged high-voltage transmission tower which nearly collapsed because its legs straddled a narrow shear zone.

ability of lifelines that cross active faults. Linear systems such as power lines and pipelines can be distorted and laterally pulled apart where they cross broad shear zones. Narrow shear zones are especially damaging since ground deformation and induced strains are concentrated along shorter segments of the system. As shown in Figure 10, the legs of the transmission tower straddled a narrow shear zone that formed the right side of a 70-m-wide shear zone. According to analysis of the tower's deformed legs, this narrow shear zone accommodated approximately 2.7 m of right-lateral offset. The legs were pulled apart 2 to 7 cm. The ground deformation twisted the steel-framed tower structure to the point of nearly collapsing the structure. The high-voltage power lines did not break, and may actually have helped support the damaged tower. This flexible system was heavily damaged and required replacement immediately following the earthquake, but did not fail catastrophically. Buried pipelines and other lifelines, however, do not possess this level of flexibility, and the 2.7 m of concentrated shear across this narrow zone would probably have induced catastrophic failure in these types of engineered systems.

Summary of Damage to Structures

A significant number of structures and lifelines were damaged by surface ruptures produced during the 1992 Landers event. Concentrated slip along narrow ground fractures typically produced similar fractures in overlying foundation slabs. Distortion of the foundation slab, resulting from underlying left-stepping fault segments, produced cracks in the concrete slab and the development of passive and active earth pressure zones in the surrounding ground. The damage to the houses and transmission tower described in this article is indicative of the damage observed within the fault zones.

We inspected numerous, similar structures, includ-

ing reinforced and unreinforced concrete on-grade slabs which support light wood-framed houses. For similar levels of adjacent ground fracturing, the damage was substantially greater to unreinforced slabs than to reinforced slabs. The fact that reinforced slabs performed well, however, does not imply that they had been specifically designed to resist this type of boundary deformation. In fact, resistance to ground breakage is largely undeveloped in structural design, and some basic notions are clearly needed. For instance, these observations lead to the idea that concrete structures must be adequately reinforced to resist the boundary strains imposed by the localized differential displacements in the adjacent ground. Alternatively, structures that can be partially isolated from underlying ground deformation could perform satisfactorily.

Mitigation of Fault Rupture Hazards

The principal surficial hazards of earthquake fault rupture are as follows (Fig. 19):

- (A) propagation of the distinct shear rupture plane to the ground surface,
- (B) differential settlement or angular distortion of the ground surface,
- (C) compressive and tensile horizontal strains at the ground surface, and
- (D) development of surficial tensile cracks.

There are three principal means of mitigating the potential hazards associated with earthquake fault rupture: avoidance, geotechnical engineering, and structural engineering. The success of each of these methods depends, first and foremost, on proper interpretation of the geology on regional and project level scales. Although the profession requires continual enhancement of its understanding of the complex fault rupture phenomenon, sound judgment, coupled with reasonable interpretations of surficial geology and crack propagation theory, can be applied to develop earthquake-resistant designs without resorting to arbitrary, specified setback criteria. More realistic criteria can be established on a project/site-specific basis (e.g., Bray *et al.*, 1993). Once detailed studies of the geology and local site conditions (soil and topography) are completed, a combination of the methods described below may be employed to reduce damage resulting from surface rupturing.

The first method is avoidance. All structures and lifelines may be deliberately positioned to avoid crossing identified shear rupture zones. Obviously, this method's success depends on identifying all likely rupture zones, and on the characteristics of the next earthquake complying with our expectations. The 1992 Landers earthquake provides numerous examples of our imperfect understanding, and shows that some movement should be

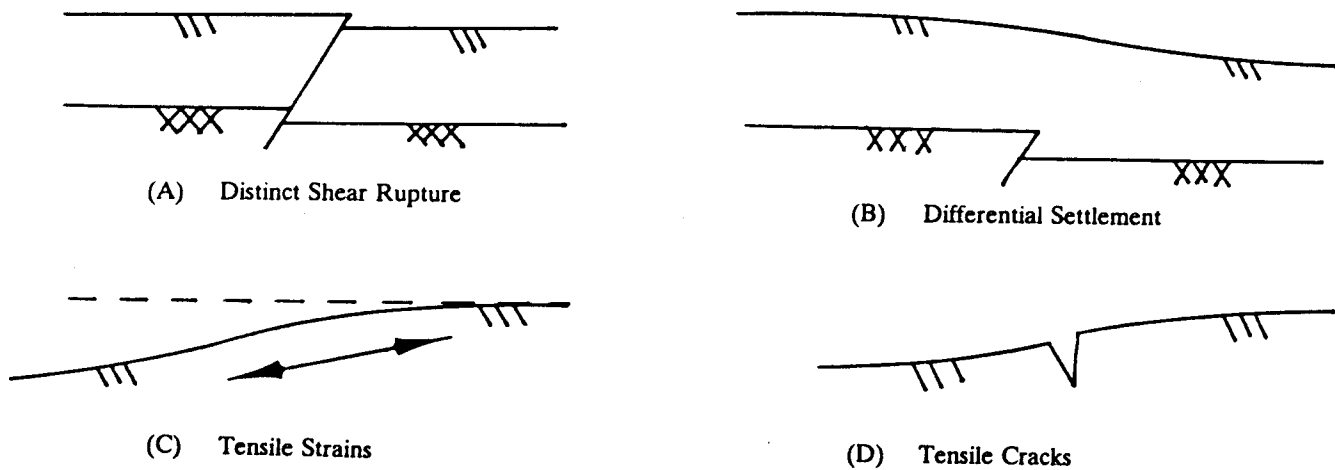


Figure 19. Principal surficial hazards of earthquake fault rupture (2D dip-slip fault movement shown for clarity).

anticipated throughout fault zones. For example, Hart *et al.* (1993) noted that 45% of all 1992 Landers earthquake surface ruptures fell outside established A-P Special Studies Zones that delineate "approximately wide . . . zones to encompass all potentially and recently active [fault] traces." In another study of over 1200 active faults strands exposed in fault trenches, Bonilla and Lienkaemper (1991) found that about 45% of these strands either appeared to die out, or actually did die out, even though surface faulting was known to have occurred recently. They concluded that a fault strand overlain by an apparently undisturbed deposit is not necessarily older than the deposit.

The next approach is to use the inherent capability of unconsolidated geomaterials to "locally absorb" and distribute distinct bedrock fault movements. Previous field, physical model, and numerical studies (e.g., Bray *et al.*, 1990) have found that differential movement across distinct bedrock faults dissipates as the shear rupture plane rises through overlying fills, especially if the fills are reinforced (Bray *et al.*, 1993). The relative displacement across a distinct bedrock fault is spread across a wider zone in the overlying fill. This spreading of the localized bedrock fault displacement over a wider zone at the ground surface reduces differential settlement and tensile strains at this level. Hence, ductile compacted fill or reinforced fill may be used at a site to mitigate the surficial hazards associated with fault rupture.

Finally, the constructed facility can be engineered to undergo some limited amount of ground deformation without collapse or significant structural damage. Design of structures subjected to ground deformation resulting from mining subsidence are applicable (e.g., Kratzsch, 1983). Similar to observations of foundation performance at Landers, mining subsidence studies indicate that foundation elements should be reinforced to improve ductility. The maximum allowable tilt is approximately 1/400. Fiber reinforcement and/or welded wire mesh

reinforcement will reduce tensile cracking in floor slabs. The maximum allowable horizontal tensile ground strain below buildings is on the order of 0.3%. Post-tensioning the floor slab will improve its ability to bridge over irregular ground deformation of limited extent. Spread footings and floor slabs should be constructed atop a double layer of smoothly laid-out polyethylene sheets sandwiched between layers of clean coarse sand to fine gravel. This measure will reduce the extent of tensile cracks just below the building's foundation and minimize the transfer of horizontal strains in the ground below the foundation to the structural foundation elements. Trenches excavated to construct grade beams and underground utilities should be backfilled with loose soil or styrofoam to reduce lateral earth pressures developed against these elements.

The experience at Landers has provided contrasting signals. On the one hand, avoidance of faults in the siting of structures has become more difficult because these observations show that the rupture zone can be much wider than normally assumed, and rupturing can occur in previously unidentified zones. Conversely, the fact that simple structures located across major fault movements were able to survive ground fracturing, in terms of life safety (but not damage), suggests that we should consider engineering structures to withstand ground rupture.

Conclusions

The surface breakage of the 1992 Landers, California, earthquake provided numerous examples of the complexity of earthquake fault rupture. Maps prepared at the project scale presented in this article indicate that broad shear zones, often hundreds of meters wide, can damage structures located at significant distance from the main fault trace. Rotation of the sheared ground can induce torsion and tensile cracking in foundation elements. Moreover, narrow shear zones located within these broad

shear zones concentrate differential movement in the ground beneath structures and are especially damaging. Step-over zones are also particularly dangerous since they are difficult to identify, and are typically broader and more complex. Given the scarcity of facilities in this region, the damage produced by the 1992 Landers earthquake surface breakage was significant. However, although often heavily damaged, no structures collapsed as a result of fault rupture. Evaluation of the regional and local geology combined with measures to mitigate the potential hazards associated with fault rupture can assist in designing structures to safeguard human life and reduce damage.

Acknowledgments

Johanna Fenton assisted in collecting information on the 1992 Landers earthquake and in reviewing the manuscript. Scott Merry of U.C. Berkeley, Robert Fleming of U.S.G.S., Denver, and Kenneth Cruikshank of Stanford University helped map the sites. Eldon Gath of Leighton and Associates assisted in performing the initial survey of the area and in planning the study. Ken Lajoie of the U.S. Geological Survey eagerly shared useful observations. Jim Gardner of Purdue University edited the manuscript. Financial support was partially provided by Leighton and Associates, the National Science Foundation under Grant No. BCS-9157083, a Department of Energy Grant, and a David and Lucille Packard Foundation Fellowship, and this support is gratefully acknowledged.

References

- Bonilla, M. G. and J. J. Lienkaemper (1991). Factors affecting the recognition of faults exposed in exploratory trenches, *U.S. Geol. Surv. Bull.* 1947, U.S. Geological Survey, Washington, D.C.
- Bray, J. D., R. B. Seed, and H. B. Seed (1990). The effects of tectonic movements on stresses and deformations in earth embankments. Earthquake Engineering Research Center, University of California at Berkeley, UCB/EERC-90/13.
- Bray, J. D., A. Ashmawy, G. Mukhopadhyay, and E. Gath (1993). Use of geosynthetics to mitigate earthquake fault rupture propagation through compacted fill, in *Geosynthetics '93*, Vancouver, Canada, 379-392.
- Bray, J. D., R. B. Seed, L. S. Cluff, and H. B. Seed (1994). Earthquake fault rupture propagation through soil, *ASCE J. Geotech. Eng.* 120, no. 3, 543-561.
- Campillo, M. and R. J. Archuleta (1993). A rupture model for the 28 June 1992 Landers, California, Earthquake, *Geophys. Res. Lett.* 20, 647-650.
- Dibblee, T. W., Jr. (1967). Geologic map of the Emerson Lake Quadrangle, San Bernardino County, California, *U.S. Geol. Surv. Map* 1-490, 1:62, 500.
- Duncan, J. M. and G. A. M. Lefebvre (1973). Earth pressures on structures due to fault movement, Presented at the ASCE National Structural Engineering Meeting, San Francisco, California.
- Hart, E. W. (1992). Fault-rupture hazard zones in California, in *Calif. Dept. Conservation, Div. Mines Geol. Spec. Rept.* 42, 1-26.
- Hart, E. W., W. A. Bryant, and J. A. Treiman (1993). Surface faulting associated with the June 1992 Landers earthquake, California, *Calif. Geol.* 46, no. 1, 10-16.
- Irvine, P. J. and R. L. Hill (1993). Surface rupture along a portion of the Emerson fault. Landers Earthquake of June 28, 1992, *Calif. Geol.* 46, no. 1, 23-26.
- Johnson, A. M. and R. W. Fleming (1993). Formation of left-lateral fractures within the Summit Ridge shear zone, 1989 Loma Prieta, California, earthquake, *J. Geophys. Res.* 98, no. 2, 823-837.
- Johnson, A. M., R. W. Fleming, and K. M. Cruikshank (1993). Simple broad belts of surface rupture as the common form of surface rupture produced during the 28 June 1992 Landers, California, earthquake, *U.S. Geol. Surv. Open-File Rept.* 93-348, 61 p.
- Johnson, A. M., R. W. Fleming, and K. M. Cruikshank (1994). Shear zones formed along long, straight traces of fault zones during the 28 June 1992 Landers, California, earthquake, *Bull. Seism. Soc. Am.* 84, no. 3, 499-510.
- Kanamori, H., H.-K. Thio, D. Dreyer, E. Hauksson, and T. Heaton (1992). Initial investigation of the Landers, California, earthquake of 28 June 1992 using TERRASCOPE, *Geophys. Res. Lett.* 19, no. 22, 2267-2270.
- Kratzsch, H. (1983). *Mining Subsidence Engineering*, Springer-Verlag, New York.
- Mori, J., K. Hudnut, and L. Jones (1992). Rapid scientific response to Landers Quake, *EOS* 73, 417-418.
- Segall, P. and D. D. Pollard (1980). Mechanics of discontinuous faults, *J. Geophys. Res.* 85, 4337-4350.
- Sieh, K., L. Jones, E. Hauksson, K. Hudnut, D. Eberhart-Phillips, T. Heaton, S. Hough, K. Hutton, H. Kanamori, A. Lilje, S. Lindvall, S. F. McGill, J. Mori, C. Rubin, J. A. Spotila, J. Stock, H.-K. Thio, J. Treiman, B. Wernicke, and J. Zachariasen (1993). Near-field investigations of the Landers Earthquake Sequence, April to July 1992, *Science* 260, 171-176.
- Toppozada, T. R. (1993). The Landers-Big Bear Earthquake sequence and its felt effects, *Calif. Geol.* 46, no. 1, 3-9.
- Department of Civil Engineering
University of California
Berkeley, California 94720
(C.L., J.B.)
- Department of Earth and Atmospheric Sciences
Purdue University
West Lafayette, Indiana 47907
(A.J.)
- Leighton and Associates, Inc.
Diamond Bar, California 91765
(R.L.)

Manuscript received 3 August 1993.