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The transfer of slip between two en echelon strike-slip faults: A case study from the 1992 Landers earthquake, southern California

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Abstract. Detailed mapping of the fresh surficial ruptures in the right step between the Homestead Valley Fault and the Emerson Fault, two right-lateral en echelon faults that broke in the 1992 Landers earthquake, indicates that the transfer of dextral slip between the faults is accommodated primarily by a series of obliquely striking right-lateral strike-slip cross faults. Right-lateral slip on the cross faults and counterclockwise rotation of the interior blocks are sufficient to transfer virtually 100% of the dextral slip and to accommodate the extension across the jog. Asymmetry of the dextral slip curves along the cross faults indicates that some of them may have been induced to fail by slip on the Homestead Valley Fault, while others were induced to fail by slip on the Emerson Fault. Comparison of the magnitude of slip in 1992 to bedrock and geomorphic offsets suggests that the Homestead Valley Fault and several secondary faults have experienced about 100 nominal Landers events and that the stepover structure originated at the same time as the Homestead Valley Fault, about 1 m.y. ago. Because the Emerson Fault has an order of magnitude greater total offset but only slightly greater surficial slip in 1992, we conclude that it is a significantly older fault. Repetition of 1992-like events should eventually lead to a merging of the Homestead Valley Fault with the Emerson.

Introduction

The fresh surficial ruptures of the Landers earthquake of June 28, 1992, caught the attention of earthquake geologists because of their complexity, length, and large offsets. About 85 km of strike-slip faults, across a sparsely populated but accessible part of the Mojave Desert of southern California, accompanied the M 7.3 earthquake [Sieh et al., 1993]. The superb preservation of the rupture for many weeks following the event and the complex configuration of faults provided a unique opportunity to investigate the nature of strike-slip faulting and to examine both the behavior of individual faults and their interactions.

The Landers earthquake was generated primarily by slip on several distinct faults (Figure 1). These faults are part of the Eastern California Shear Zone, an 80-km-wide zone of right-lateral shear, composed of numerous northwest striking faults that accommodate about 15–20% of the relative plate motion between the North American and Pacific plates [Dokka and Travis, 1990b; Sauber et al., 1994] (Figure 1, inset).

The characteristic en echelon structure of strike-slip faults is observed at all scales along the 1992 rupture. There are three major en echelon stepovers: one between the Johnson Valley Fault and the Homestead Valley Fault, another between the Homestead Valley Fault and the Emerson Fault, and a third between the Emerson Fault and the Camp Rock Fault. All of these are right stepping and hence dilatational, yet each stepover accommodates slip transfer between its bounding strike-slip faults in a distinct manner. The southernmost stepover is discussed by Spotila and Sieh [1995].

Field Methods

To understand the Homestead Valley–Emerson Fault transfer zone, we found it necessary, first, to map the fresh fractures in great detail. We mapped the surface rupture traces onto 1:6,000-scale aerial photographs and 1:12,000-scale topographic maps. The aerial photographs covered most of the field area except a narrow strip down the central section of the stepover zone. Precision and detail in this strip is thus somewhat poorer than in the regions covered by photographs. Fortunately, the surficial ruptures were significantly fewer in this strip. On the photographs, we mapped every observed fault trace as accurately as the scale of the photographs allowed. The mapped traces are thus exact, and not schematic, although in places the ground cracking was so dense that not every crack could be recorded. We measured offsets of magnitudes ranging from zero to several meters wherever possible. We determined lateral and vertical displacement by matching offset linear features such as motorcycle tracks, roads, and stream channels and then measuring the distance between them along the strike of the fault. When good piercing points were not available, we measured vertical separation. We accorded an error to each
Figure 1. Map of the surficial ruptures of the 1992 Landers earthquake. Box outlines the Emerson Fault–Homestead Valley Fault stepover, shown in detail in Figure 2. Inset illustrates location of Landers rupture within southern California. Landers rupture topology after Sieh et al. [1993].

offset measurement based on the range produced by successive measurements of the same feature and an estimate of the possible misfit due to diffuse or nonlinear edges of the offset feature and distance across which the feature was projected. We ranked the general quality of most measurements as excellent, good, fair, or poor.

The pattern of en echelon fracture that is seen on the scale of the entire Landers rupture is also seen at larger scales. Secondary splays and Riedel shears existed on all scales and were so mapped, though only those features that seemed to play a role in the structure of the transfer zone as a whole will be discussed in detail in this paper. The rupture traces were sometimes simple single strands and sometimes comprised wide and complex zones of anastomosing and intersecting strands. The surficial material through which the faults cut played a significant role in defining the location and nature of the surficial rupture throughout the field area. In alluvium, the rupture traces were diffuse but well-defined, having broken through a young, fairly uniform surface. In bedrock, by contrast, they often simply disappeared or dispersed into ill-defined, relatively randomly oriented cracking without any clearly discernible offset. The bedrock in this area is not massive but rather is broken up into large rounded boulders and smaller rubble which tends to disperse and hide evidence of fracture. Much of the energy of fracture went into shifting the bedrock rubble on the surface rather than producing clear surficial fractures. Perhaps below the surface, where the bedrock is more massive and coherent, the faults are better defined.

We measured offsets across the wider and more complex zones in various ways. If the zone comprised several well-defined strands, each of which offset the same feature, we
measured each strand separately and accorded it an error estimation. We then added these measurements to determine the total offset across the zone. We calculated the error by taking the square root of the sum of the squares of the individual errors. In some complex zones, separate measurement of each strand was too complicated. In such cases we projected along the offset linear feature across the whole zone and measured the cumulative offset. In some places we could measure only one or two of several strands in a complex zone. In that case, we recorded the offset but did not include the measurements in the determination of slip along the fault or cumulative slip across the transfer zone because they represent minimum, not total, slip.

**Observations**

**Fault Geometry**

The transfer zone is composed of two primary bounding faults, the Homestead Valley Fault on the southwest side and the Emerson Fault on the northeast. These faults overlap about 5 km along strike and are separated by a 2-km-wide right step. These subparallel en echelon right-lateral faults, which strike approximately N35°W, are linked by about five right-lateral cross faults that cut diagonally across the rectangular area between the main faults. Figure 2 is a simplified map of the faults, including topography and representative lateral (Figure 2a) and vertical (Figure 2b) offsets.

The Homestead Valley Fault, which cuts through thin alluvium in this area, has a very clear, well-defined rupture trace. The fault trace is contiguous throughout its length and is nearly rectilinear, with deviations of no more than a couple of hundred meters. These small bends and kinks do not appear to correlate with the intersections of secondary faults or any other obvious structures. The largest jog in the Homestead Valley Fault, near its northwest end, is, however, associated with a large outcropping of bedrock. The dip-slip component of rupture on the Homestead Valley Fault is predominantly west-side-up.

Secondary cracking and splaying is common in the vicinity of the Homestead Valley Fault. Most of these cracks and splays are on the east side of the fault, within the stepover area. The slip on these varies considerably, from purely tensional cracks to shear fractures with several tens of centimeters of lateral slip. Most shear fractures are right-lateral, but a few have left-lateral offset. In some areas there are several subparallel splays together in a group that alternate in sense of slip. Many secondary fractures are oriented subparallel to the larger transfer faults, but we have found splays at virtually every angle to these faults.

One of the largest splays of the Homestead Valley Fault, which we call the Western Splay (WS), is west of the main fault, at the southern end of the transfer zone (Figures 2 and 3a). The splay cuts along the western base of a low ridge of hills. The Homestead Valley Fault cuts along the eastern side of this ridge. In 1992, the ridge rose along both the Homestead Valley Fault and Western Splay. Substantial right-lateral slip also occurred along both traces. The northern half of the Western Splay is a right-lateral thrust fault that dips 25°–50° northeastward, toward the Homestead Valley Fault. Dextral slip ranges from 30 to 40 cm, and dip slip ranges between 10 and 20 cm. To the south, about halfway along the ridge, the thrust fault ends, and a new splay appears. This structure is up in the hills rather than at the edge of the alluvium, though it cuts down through the hills to the south and breaks out into alluvium at its southern end. This fault has a similar right-lateral component to that of the northern fault, but the fault here is vertical to steeply west dipping and has a normal sense of dip-slip motion. The western side is downdropped about 10 cm relative to the hills. This splay changes from an oblique thrust to an oblique normal fault halfway along its length is unclear. This behavior is probably not related to local irregularities in the Homestead Valley Fault. It does imply, however, a change from near-surface shortening to extension across the Homestead Valley Fault. This, in turn, may imply counterclockwise rotation of the block east of the Homestead Valley Fault about a pole near the change from reverse to normal faulting. Conceivably, this behavior may also be explained by tilting of the block between the Western Splay and the Homestead Valley Fault.

The Emerson Fault is approximately parallel to the Homestead Valley Fault where it cuts through alluvium at the northern end of the stepover (Figure 2). It diverges to a more easterly strike where it leaves the alluvium and runs along the eastern flank of the bedrock hills. The southeastern reaches of the Emerson Fault did not break during the 1992 earthquake, but its continuation to the southeast of the transfer zone is clearly expressed in both the geomorphology and the bedrock [Dibblee, 1967a]. The mapped trace of the Emerson Fault continues some 20–25 km southeastward beyond the 1992 rupture.

The secondary faults that link the Emerson and Homestead Valley Faults strike approximately north-south (Figure 2). They divide the intervening stepover region into a series of parallelogram-shaped blocks. The largest and best defined of these cross faults is the northernmost. This Northern Cross Fault intersects the Homestead Valley Fault about 1.5 km from the Homestead Valley Fault’s northwestern terminus in an extensive and complicated triangular zone of subsidiary cracking and faulting (Figures 2 and 3b). In the southern part of the intersection zone, most of the splays constitute a series of short cracks, oriented subparallel to the cross fault. These die off rapidly with distance from the Homestead Valley Fault. The northern end of the intersection has longer, more well-defined subsidiary faults, which cut at very high angles to the Homestead Valley Fault right where they meet that fault and sweep around in an arcuate shape as they approach the cross fault. Minor cracking in the area of the intersection is pervasive, and in places the alluvial surface presents a shattered appearance. The Homestead Valley Fault does not appear to have been deformed by movement on the Northern Cross Fault in 1992, and there is no obvious warping, cracking or faulting west of the Homestead Valley Fault at the intersection.

The Northern Cross Fault intersects the Emerson Fault at the northern end of the map area (Figures 2 and 3c). Right at the point of intersection is a small hill, the top of which is an uplifted alluvial fan surface. The hill may well have resulted from numerous 1992-1ike strain episodes, at the intersection of the two faults, but its small dimensions imply no regional significance. The Emerson Fault passes along the eastern edge of the hill as two strands that bound a small graben. As at its southern terminus with the Homestead Valley Fault, the Northern Cross Fault does not cut or deform the Emerson Fault at their intersection. The importance of this observation in constraining the kinematics of the stepover is discussed in a subsequent section.
The other cross faults to the south are less well-defined and less significant than the Northern Cross Fault. One and a half kilometers south of the intersection of the Northern Cross Fault and the Homestead Valley Fault, a discontinuous linear zone of minor cracking and faulting strikes northward from the Homestead Valley Fault (Figures 2 and 3d). The largest observed lateral offset is 24 cm, and most offsets are less than 5 cm. The surficial discontinuity of this zone of cracking suggests that the fault zone may be discontinuous at depth as well.

Another, slightly more prominent secondary fault, ES1, intersects the Homestead Valley Fault at the southern end of the field area, about 6 km from the northern terminus of the Homestead Valley Fault (Figures 2 and 3e). Near its intersection with the Homestead Valley Fault, this structure curves around the southern and eastern margins of a small hill. The fact that the fault trace hugs the side of the hill suggests to us that its location is controlled by the presence of the hill. Further north, the fault cuts into the alluvium and assumes the north-south strike of the other cross faults. This fault trace is intermittent also but can be followed into the bedrock hills of the stepover region. In the hills, this cross fault has a small right step (to ES2), around the southern and eastern sides of a
3768-foot-high peak. ES2 intersects the Emerson Fault at the southern terminus of the 1992 rupture of the contiguous part of the Emerson Fault. Discontinuous cracking along the Emerson Fault occurs farther south of here, e.g., on ES4, but it is relatively minor. Unlike the Homestead Valley Fault, which continues with significant offset well past the intersection with the last large splay, the 1992 rupture of the Emerson Fault ends at the intersection with this large splay, ES2. Virtually all the lateral slip on the Emerson Fault is transferred to the ES2 cross fault. Two small faults farther south, ES3 and ES4, splay off the Emerson Fault. They, however, appear to die out in the alluvium and do not intersect the Homestead Valley Fault.

Slip Distribution Along the Faults

The slip on each of the mapped faults is extremely variable along the length of the fault. Despite the short-wavelength variability, however, there is fairly regular long-wavelength behavior. The lateral offset on the Homestead Valley Fault near the southern end of the field area is approximately 3 m, though it varies from 2 to 3.5 m (Figure 4a). This is the average surficial slip along most of the Homestead Valley Fault as it continues to the south [Sieh et al., 1993]. The lateral slip dies off toward the northern terminus at the rate of 0.2 mm/m up to the intersection with the Northern Cross Fault. At this intersection, there is an abrupt decrease by about 1 m in the amount of slip on the Homestead Valley Fault. The concomitant abrupt northward increase in slip on the Northern Cross Fault is about 1–1.5 m. From this we infer that about half the slip from the Homestead Valley Fault was shunted onto the Northern Cross Fault. North of this intersection, slip continues to decrease along the Homestead Valley Fault but over a shorter distance (0.5 mm/m), toward its northwestern terminus, about 1.5 km from the intersection. This rate of slip decrease suggests strains of about $2.5 \times 10^{-4}$ in adjacent crystalline rock. This is
Figure 3. Details of the Landers surface rupture. (a) Detail of the Western Splay (WS), a secondary fault outside (west) of the main Homestead Valley–Emerson Fault stepover. This splay has oblique right-lateral sense of slip. The northern part dips northeast and has a reverse component, and the southern half dips southwest and has a normal component of slip. (b) Detail of the intersection between the Homestead Valley Fault and the Northern Cross Fault. The area of dense shattering occurs in alluvium. The fault trace is less diffuse and more difficult to see where it traverses bedrock. (c) Detail of the intersection between the Emerson Fault and the Northern Cross Fault. Both the hill and the small playa are probably due to very local fault geometries and do not reflect broad deformations within the transfer zone. (d) Detail of the sporadic but linear series of small cracks cutting through the center of the transfer zone, between the larger Northern Cross Fault and ES1/ES2 cross faults. This series of cracks may represent an immature cross fault. The largest offset observed along this trend is 24-cm right-lateral and 15-cm vertical (west side up). (e) Detail of Split Hill and the intersection between ES1 and the Homestead Valley Fault. The Homestead Valley Fault right-laterally displaces the two small hills in the center by about 300 m. From its intersection with the Homestead Valley Fault, ES1 curves around the southern end of the southern hill and offsets a small dike about 10 m right laterally. The fault in the southwest corner is the tail end of the Western Splay.
approximately the maximum strain that can be stored in granite without failure [Handin, 1966; Jaeger and Cook, 1979; Brace, 1964]. We did not observe off-fault fracturing around the northern reaches of the Homestead Valley Fault. The bedrock that outcrops east of the fault, however, could easily have hidden a myriad of sub-millimeter-sized fractures.

Slip on the Emerson Fault in this area is at least as variable over short distances as that on the Homestead Valley Fault, but also displays a regular long-wavelength pattern (Figure 4a). It increases northward from zero to about 3 m on the flank of the stepover. Slip on the Emerson Fault continues to increase northward, however, beyond the transfer zone [Sieh et al., 1993].

On all the cross faults, the predominant sense of slip is right-lateral. The Northern Cross Fault has 1–1.5 m of right-lateral offset along most of its length (Figures 2a and 4a). The slip distribution along this fault is markedly asymmetric. Near the intersection with the Homestead Valley Fault, the slip increases abruptly northward from zero to the maximum of 1.6 m within 500 m. It then tapers off gradually to the north. There is a second spike of about 1.4 m right at the intersection of the Northern Cross Fault and the Emerson Fault. The next largest splay, ES2, has about 1.5 m of right-lateral offset near its intersection with the Emerson Fault. Dextral slip on this fault and its continuation, ES1, falls off rapidly as the faults cut through the hills, declining to about 10–20 cm in the alluvium at the southern end of the zone. The asymmetry of the lateral-slip magnitude along most of the splay faults we believe is significant and is discussed later.

The vertical slip on all the faults is quite variable and shows little systematic behavior, although, like the lateral-slip distribution, it is somewhat asymmetric (Figure 4b). Because this
transfer zone is a right-stepping jog between two right-lateral faults, one would expect extensional structures between the faults. We do see vertical slip on the main faults that is consistent with the extensional development of a basin. In general, the sense of slip on the Homestead Valley Fault is down to the east, and that on the Emerson Fault is down to the west. The effect therefore is coseismic subsidence of the hills by an average of about 30 cm with respect to the alluvium outside the transfer zone. Vertical slip on the cross faults is less predictable: on the Northern Cross Fault, ES2, and the northern reaches of ES2, the west side is predominantly down relative to the east side. Figure 5 is a block diagram that illustrates this. Rather than opposing senses of vertical slip on the bounding secondary faults, we see a westward downstepping set of faults.

Cumulative Slip

We calculated the cumulative right-lateral slip across the zone and in the general direction of the primary faults by summing the components of slip on all the faults in the zone along a N35°W strike and plotting the total as a function of distance from the northern terminus of the Homestead Valley Fault (Figure 6). Although clearly the cumulative slip is quite variable along strike, over all, the slope of the curve of slip versus distance is approximately zero, with average slip of about 3 m. There is no significant decrease of slip through the transfer zone. Although this calculation does not address the issue of dynamic rupture, which will be discussed later, Figure 6 shows that virtually all the surface slip on the Homestead
Valley Fault was effectively transferred across the observed structures in the stepover to the Emerson Fault. Thus, in this case, a 2-km step between two en echelon strike-slip faults did not present an impediment to rupture or to the transfer of slip from one fault to the other. Given the lack of significant afterslip at the several locations monitored for several weeks after the earthquake [Sylvester, 1993], we infer that all of the slip was transferred across the zone coseismically.

### Long-Term Offset

How does the long-term history of slip on the faults of the Homestead Valley-Emerson transfer zone compare with the slip in 1992? To make this comparison, we searched for geomorphic and bedrock expression of previous faulting in the area. The Emerson and Homestead Valley Faults and many of the secondary structures show evidence of prior activity. Many have geomorphic indications of 100–200 times the 1992 slip.

We found that the total offset across the Homestead Valley Fault is approximately 300 m. The best evidence of this occurs at the southwest end of the field area (Figures 2 and 3e and Plate 1). There the fault bisects and offsets a small bedrock hill (Figure 7). We call the two resultant knobs Split Hill. Their geomorphic offset is approximately $320 \pm 70$ m, based upon the assumption that the crests of the hills can be used as piercing points (C-C' in Plate 1).

This geomorphic offset equals the bedrock offset. Dibblee's [1967b] 1:62,500-scale map first suggested a bedrock offset of about 300 m. Our mapping at a scale of 1:6,000 shows several bedrock units that have been cut and offset by the movement of the Homestead Valley Fault. Piercing points A-A' and B-B' in Plate 1 indicate a right-lateral offset of $320 \pm 40$ m and $250 \pm 40$ m, respectively. B-B' must be considered a minimum value for the total offset because the contact near point B is
oblique to the fault zone, and diffuse slip occurs across the fault zone there. Total slip could be as much as 60 m greater than the 250-m value.

Since the magnitudes of the geomorphic and the bedrock offsets of Split Hill are indistinguishable, we conclude that the Homestead Valley Fault was first activated subsequent to the creation of the present topography in this part of the Mojave Desert. A hundred nominal Landers earthquakes could account for the total dextral slip.

Several other faults also have geomorphic evidence of previous activity, though in most places the magnitude of the total slip is not recoverable. The Northern Cross Fault crosses a northwest flowing stream channel and appears to have right-laterally offset it about $200 \pm 70$ m. Given that this fault experienced about $1.2$ m of offset at this location in 1992, the total offset could have accrued during about $166 \pm 60$ nominal Landers events. This is approximately the same number of events as have occurred on the Homestead Valley Fault.

The ridge between the Western Splay and the Homestead Valley Fault rose 10–20 cm during the 1992 earthquake. If we assume the ridge was created by coseismic uplift like that in 1992, and we divide the 1992 uplift into the total height of the ridge, which is about 40 m, we calculate that the ridge could have been raised to its present height by 200–400 Landers events. The actual number of such events may well be significantly less than 200–400, because the assumption that the ridge was created solely by coseismic Landers-style uplift is not strong. We know, for example, that Split Hill, just to the south, existed as a landform prior to activation of the Homestead Valley Fault.

The geomorphic evidence along the Emerson Fault is consistent with the other faults. The northernmost major east flowing stream channel south of the Northern Cross Fault–Emerson Fault intersection shows about $260 \pm 50$ m of right-lateral separation across the Emerson Fault. Given that the 1992 right-lateral offset in this area is about 1.5 m, we calculate about $170 \pm 30$ similar events could have produced the offset.

All the faults that we can constrain quantitatively show of the order of 100–200 nominal Landers events. This implies that the transfer structure we observed in 1992 has existed for 100–200 events and has not acted as an impediment to rupture during that period. The only exception to the 100-event rule is in the bedrock offset along the Emerson Fault on which both 1992 and cumulative slip are greatest. Bedrock offsets along this fault are of the order of 3–5 km. Dibblee [1964] mapped a quartz monzonite porphyritic dike offset some 3.5–5 km along

Figure 7. Profile of Split Hill. View is toward the northeast. The location of the Homestead Valley Fault is indicated by the white arrows. The fault passes between the hills, behind the left hill and in front of the right hill as viewed from this direction. The two hills are clearly right-laterally displaced along the Homestead Valley Fault.
Plate 1. Geological outcrop map of the Split Hill region on the Homestead Valley Fault. The 1992 rupture is in pink. The dark regions outlined in solid lines are outcrops. The lighter colors outlined in dashed lines indicate the extent of the unit extrapolated from the outcrop distribution. A-A', B-B', and C-C' are piercing points for estimating cumulative lateral slip in this area. The Split Hills are offset geomorphically (C-C') about 300 m. The plutonic and metamorphic rocks underlying the hill display an equivalent offset (A-A' and B-B').

Legend

- **Very fine grained white quartzite; locally shows good bedding**
- **Biotite quartz monzonite; porphyritic intrusive with K feldspar phenocrysts**
- **Green saccharoidal calc-silicate with diopside**
- **Brecciated variation of green calc-silicate, often contact metamorphosed**
- **Variant of brecciated calc-silicate with tan dolomitic marble clasts, locally shows good bedding**
- **Medium grained leucocratic dike with quartz and K feldspar**
- **Coarse plutonic rock with dark green amphibole laths and white feldspar; possibly a contact rock between biotite quartz monzonite and calc-silicate**
- **Fine grained, well-foliated gneiss**
the Emerson Fault about 15 km north of this transfer zone. F. Gomez and K. Sieh (unpublished mapping, 1992) confirm a likely value of about 4.6 km, based upon correlation of plutonic and metamorphic contacts across the fault, also about 15 km north of the stepover. The bedrock offset along the Emerson Fault, therefore, is about an order of magnitude higher than that along the Homestead Valley and associated structures.

Discussion

Transfer Zone Geometry

It is widely held that a right step, or jog, between two right-lateral strike-slip faults produces extension in the region between the two faults. Such extensional jogs and pull-apart basins have been observed, in studies of both individual earthquake ruptures and long-term structural features [e.g., Crowell, 1974; Tchalenko and Ambresys, 1970; Clark, 1972; Clayton, 1966; Sharp, 1975; Woodcock and Fischer, 1986; Aydin and Nur, 1982; Brown and Sibson, 1987; Hempton and Neher, 1986; Sims and Ito, 1990]. Stepovers have also been theoretically modeled [Rodgers, 1980; Segall and Pollard, 1980] and observed in sandbox and clayakoe experiments [Chinnery, 1966; Tchalenko, 1970; Naylor et al., 1986]. Any extensional jog in brittle materials requires the development of secondary structures to accommodate the extension and to transfer the lateral slip from one primary fault to the other. To provide these structural services, various combinations of normal faults and strike-slip structures have been postulated and observed (Figure 8).

Laboratory and theoretical models and field work have found evidence for the development of normal faults cutting through the stepover at high angles to the primary faults, as sketched in Figure 8. Clayton [1966] has mapped a stepover with such a configuration, in which two right-stepping right-lateral strands of the Hope Fault in New Zealand are joined by a series of curving normal faults that depart from the bounding faults at angles from 10ø to 70ø (Figure 8e). Crowell's [1974] model of a pull-apart basin is more complex, with oblique-slip faults at the ends of the bounding faults and a few reverse faults in the interior of the stepover accompanying the normal faults (Figure 8b). The right stepover at Mesquite Lake between the right-lateral Imperial and Brawley Faults (Figure 8f [after Hudnut et al., 1989]) shows oblique-slip and normal faults developing to accommodate extension.

In other cases, both observed and modeled, strike-slip faults develop as significant secondary structures responsible for transferring the slip through an extensional jog. Rodgers [1980] modeled the development of a pull-apart basin between two lateral strike-slip faults. His elastic dislocation model analyzes the development of secondary structures in response to motion along the two master faults. In his models, two small depressions, occupied by normal faults, develop near the ends of the master faults, while strike-slip faults occupy the center of the pull-apart basin (Figure 8e). Basin depth is 10–15% of the lateral offset on the master faults. Sibson [1986] developed a model of a mesh within the stepover composed of extensional fractures linked by short lateral-slip faults of both senses of slip (Figure 8d).

An example of an extensional jog with secondary lateral faults is found in the Dasht-e Bayaz, Iran, earthquake (Figure 8g [from Tchalenko and Ambresys, 1970]). Woodcock and Fischer [1986] describe the stepover configuration there as an "extensional duplex," in which secondary en echelon oblique-slip faults successively peel off from the primary faults to accommodate extension and to transfer lateral slip as the primary faults lengthen and the zone matures over time. Finally, some strike-slip faults are linked by other strike-slip faults with the opposite sense of slip. In the Imperial Valley in southern California, the right-lateral Brawley Seismic Zone and Superstition Hills Fault are separated by a right step. In the 1987 Superstition Hills earthquake, right-lateral faulting on the Superstition Hills Fault was preceded by rupture on a series of left-lateral cross faults oriented at right angles to the two flanking dextral fault zones (Figure 8h [after Hudnut et al., 1989; Sharp et al., 1989]).

Despite the wide range of geometries from previous observations, models, and experiments, none applies exactly to the Homestead Valley–Emerson Fault case. The Homestead Valley Fault–Emerson Fault stepover does not conform to the model of a pull-apart basin depicted in Figures 8a, 8b, 8e, or 8f. In these cases, the two bounding lateral faults are joined at oblique to right angles by normal faults, and subsidence of the plug in the middle accommodates the extension. Although the interior of the Emerson–Homestead Valley stepover is down-dropped an average of about 30 cm relative to the ground outside the bounding faults, as predicted for an extensional jog [e.g., Rodgers, 1980; Segall and Pollard, 1980], we do not see the extensional stepover structure dominated by normal faults (Figure 9a). Rather, the secondary structures are a series of oblique right-lateral strike-slip faults that strike 30ø–40ø from the primary faults into the interior (Figure 9b). Although they possess a normal component of slip, they are primarily lateral-slip faults. For example, on the Northern Cross Fault, the average lateral slip of over 1 m accompanies an average vertical displacement of 10–20 cm. Furthermore, lateral slip across these faults is in the same sense as that across the primary faults, that is, dextral. Thus the secondary and primary faults together have created a right-lateral strike-slip fault-bounded rhombohedral block or blocks that constitute the interior of the transfer zone (Figure 5).

It is clear that the structural configuration of Figure 9b cannot be maintained without change over time. The fault-bounded block of Figure 9a could, theoretically, continue to exist without significant distortion through innumerable earthquake cycles, simply dropping farther and farther down with each event. However, the behavior of the right-lateral strike-slip-bounded block of Figure 9b is constrained by the slip on its bounding faults, and thus the block must necessarily be distorted over successive events.

That all of the faults are dextral-slip faults requires counterclockwise rotation of the interior block(s). Without such rotation, right-lateral strike-slip motion along the cross faults would produce pronounced deformation of the master faults. Geomorphic and bedrock features described earlier indicate that several of these faults, including the Northern Cross Fault, have been active through many rupture events but have not deformed the principal bounding faults. If the interior block had slipped 200 m or so by pure translation along the Northern Cross Fault, it should have deflected the trace of the Homestead Valley Fault and/or the Emerson Fault by 200 m. We do not observe such deflections. Pure translational slip could occur on the cross faults without affecting the primary faults only if the slip vector for the cross fault were parallel to the strike of the bounding faults. However, when we combine a N35øW slip vector azimuth with the offset data along the Northern Cross Fault, we find that the plunge of the slip vector must change along strike from about 20ø in the south to 0ø in the
Figure 8. Examples of modeled and observed dilational stepovers. (a) Model of a pull-apart basin created by two right-stepping right-lateral faults. The area between the faults drops down along the major faults and along intervening normal faults that develop in response to the extensional stresses created by the jog. (b) Idealized model of a pull-apart basin, with normal and oblique-slip faults developing as secondary structures to accommodate extension. After Crowell [1974]. (c) Sketch of an extensional jog based on an elastic dislocation model of overlapping faults where the overlap is twice the separation. Sketch shows the location of right-lateral secondary faults that might develop. The possible conjugate left-lateral faults are not shown. The regions labeled “N” are zones of possible normal faulting. After Rodgers [1980]. (d) Sketch of linked tensile cracks and strike-slip faults within an extensional jog. Normal faults, with ticks on downthrown side, bound the jog. From Sibson [1986]. (e) Map of observed structures in a right step of the right-lateral Hope Fault in New Zealand. After Clayton [1966]. (f) Map of the right-lateral Imperial Fault–Brawley Fault Zone extensional jog. The main secondary structures are normal faults with a dextral component of slip on some. After Johnson and Hadley [1976]. (g) Map of rupture traces from the 1968 Dasht-e Bayaz, Iran, earthquake. The left-stepping traces of the sinistral fault are linked by another left-lateral fault, and a series of small fractures of unknown slip occupy the intervening area. After Tchalenko and Ambraseys [1970]. (h) Map of the faults in the region of the 1987 Superstition Hills earthquake. The right step between the right-lateral Superstition Hills Fault (SHF) and Brawley Seismic Zone is traversed by left-lateral cross faults such as the Elmore Ranch Fault (ERF). After Hudnut et al. [1989].
Figure 9. (a) Simplified sketch of an idealized right-lateral step between two dextral faults linked by normal faults at right angles. (b) Simplified sketch of the Homestead Valley–Emerson Fault stepover. The two primary right-lateral strike-slip faults are linked by a series of smaller obliquely striking right-lateral strike-slip cross faults. One cross fault (NCF) is continuous across the whole stepover, while the others (the Eastern Splays) are discontinuous.

north and that the dip of the cross fault at the northern end must be shallower than the topographic slope, which is clearly impossible (see the appendix). So the observed slip constraints and dip of the faults indicate that the slip vector is not in fact parallel to the primary faults. Therefore there must have been some counterclockwise rotation of the blocks.

If the interior blocks are so rotating, they should produce compression and extension at the NW-SE and NE-SW corners of the block, respectively. There is no incontrovertible evidence of such compression and extension, except possibly at the ridge between the Western Splay and the Homestead Valley Fault. The north to south transition from reverse-oblique to normal-oblique slip on the Western Splay may be caused by the counterclockwise rotation of one of the blocks east of the Homestead Valley Fault.

**Evolution of the Stepover Geometry**

Continued slip along these preexisting structures and continued counterclockwise rotation of the blocks over time will alter and distort this stepover zone from its present configuration. Long-term counterclockwise rotation should contribute to narrowing and lengthening of the stepover zone (Figure 10). The cross faults should rotate toward the primary faults, their strikes becoming less oblique. The Homestead Valley Fault and the Emerson Fault should draw closer together and ultimately coincide. This would be consistent with modeled and observed behavior of extensional jogs, where discontinuous and stepped en echelon fault strands merge and become continuous with increasing offset [e.g., Wesnousky, 1988; Wilcox, 1973; Segall and Pollard, 1980].

We expect to see the individual faults composing the

Figure 10. Model of the stepover evolving over time. Counterclockwise rotation and dextral slip on primary and secondary faults causes the stepover zone to lengthen and become narrower. The bounding faults are deflected into the zone and approach coincidence.
stepover evolve over time as well. We may see signs of this evolution already. The Northern Cross Fault, which is the only throughgoing cross fault and which carries the most slip, is currently the primary transfer structure. Its large offset and its continuity indicate that it is probably the most mature of the observed cross faults. It has experienced approximately the same number of events as the Homestead Valley Fault and is likely as old as that fault. By contrast, the Eastern Splays, though we have no quantitative measure of their age, appear significantly less well developed. They are discontinuous, with less slip than the Northern Cross Fault. We propose that these small faults are immature versions of the Northern Cross Fault. As the transfer zone evolves, we might expect to see increasing coherence of these faults, perhaps the linking of ES1 and ES2 into one throughgoing fault like the Northern Cross Fault. The intermittent zone of faulting though the center of the zone might then develop into a full-fledged fault, and/or other new, similar faults might initiate within the stepover. Thus in the Emerson Fault–Homestead Valley Fault stepover, we may be seeing the incipient stages of the strike-slip duplex structure suggested by Woodcock and Fischer [1986].

Structure at Depth

The surface configuration of faulting leads us to speculate on the three-dimensional structure of the stepover. We have been discussing the stepover region as one or more rhombohedral blocks, bounded by vertical, right-lateral-slip faults. Is this, in fact, a justifiable assumption? To what degree does the strike-slip duplex configuration of faulting that we have mapped at the surface represent the three-dimensional structure of the stepover? Does the surface geometry extend relatively unchanged throughout the brittle crust? Or is it replaced by other geometries at depth, such as a single, continuous curved fault cutting diagonally across the stepover?

Though we cannot answer these questions conclusively, direct observations and inferences can help illuminate the issue. For the surface geometry to continue to depth relatively unchanged requires that the dips on the faults be approximately vertical. Measurements of dips at the surface and aftershock locations are our only direct indicators of fault dip. In the shallow subsurface, the dips of the Homestead Valley and Emerson Faults must be vertical or nearly so, because the 1992 fault planes, where exposed, are steeply inclined. Unfortunately, these dips cannot be extrapolated with confidence to depths of several kilometers.

Vertical cross sections of aftershock distribution in several places along the 1992 Landers rupture show that aftershocks of the earthquake delineate a near-vertical plane that extends to depths of 10–15 km [Hauksson et al., 1993]. The clearest examples of this occur on segments such as the Johnson Valley Fault and the Emerson Fault north of the transfer zone, where there is a single-well-defined fault trace at the surface. However, many of the cross sections, especially in areas like the Emerson Fault–Homestead Valley Fault stepover which have a complicated surface geometry, show a cloud of aftershocks that do not clearly define planar fault structures. Hauksson et al. [1993] have interpreted the aftershock cloud as evidence that the Emerson Fault–Homestead Valley Fault stepover comprises a broad band of right-lateral shear rather than a single fault at depth. Such a broad shear band could be the continuation of the strike-slip duplex that we see at the surface. However, the diffuse aftershock pattern is in part due to errors in aftershock locations, and we cannot precisely determine the locations and dips of the faults at depth from aftershock data alone. Thus we cannot argue conclusively from aftershock locations that the duplex maintains its surface geometry at depth or that it does not. On the other hand, the relatively greater scatter leads us to believe that there probably remains some complexity at depth and the surface faults do not merge into a simple planar fault at depth.

It is tempting to use measurements of the vertical deformation within the stepover to try to ascertain the shape of the stepover at depth. Whereas volumetric constraints initially suggest a shallow stepover structure, they do not preclude continuation of the duplex to deeper levels. A simple mass balance calculation, using only the observed surficial slip, indicates a mass deficit in the interior. If the surface structures continued to depth, then 3 m of right-lateral slip on the Homestead Valley Fault and the Emerson Fault should produce a mass deficiency in the stepover of 3 m times the width of the zone (about 2 km) times the thickness of the fault block (say 15 km), or 0.09 km³. The observed 30-cm downdropping alone accounts for a volume of 30 cm times the width of the zone (2 km) times the length of the zone (about 5 km), or about 0.003 km³, only 3% of the required mass. However, this admittedly crude calculation is too simplistic and does not account for possible narrowing of the zone that we postulated was likely to occur with the counterclockwise rotation of the interior block. How much narrowing would be required to account for the other 97% of the volume? The entire volume of 0.09 km³ could fit in a block 5 km long by 15 km deep by 1.2 m thick. Thus the amount of narrowing required to accommodate the missing mass is a mere 1.2 m, an amount impossible to resolve in the field. Even over the course of 100 earthquakes of this nature, we would see only 120 m of narrowing. Given the irregularities of the fault, it seems highly possible that 120 m of narrowing could have occurred across this stepover. Thus we find that we cannot use the vertical component of slip in 1992 to quantify the depth to the base of the duplex structure.

Seismological studies of the Landers earthquake are inconclusive regarding the continuity of surficial structures to depth. Cohee and Beroza [1994] used near-source displacement recordings to model the Landers rupture and found no disruption in the propagation of rupture through this stepover. They suggest that rupture occurred as if on a throughgoing fault. Studying shear waves trapped in the Landers fault zone, Li et al. [1994] found evidence for a fault discontinuity at the Johnson Valley–Homestead Valley Fault stepover but none at the Homestead Valley–Emerson Fault stepover. However, using strong motion, teleseismic, geodetic and geologic data from the Landers earthquake, Wild and Heaton [1994] find that at both of the major stepovers, the Johnson Valley–Homestead Valley and the Homestead Valley–Emerson, there is a clear slowing down of the rupture front as it navigates the jump. This rupture retardation may indicate a fault discontinuity at depth. We cannot know, of course, if such a discontinuous fault geometry is identical to the surficial geometry.

Nor do comparisons with other stepovers help us here. Some studies [e.g., Barka and Radinsky-Cade, 1988; Harris et al., 1991] have concluded that stepovers less than 1 km wide are likely to merge, while others [e.g., Bakun et al., 1980; Rymer, 1989] have suggested that fault stepovers of even a few 100 m width can continue to depth. While the complete transfer of slip through this stepover might seem to argue for continuity across the zone, there is no real need to have a throughgoing
fault in order to transfer slip across a step of only 2 km. Using a two-dimensional finite difference model of rupture propagation through a fault step that continues to depth, Harris and Day [1993] find that earthquake ruptures can propagate across steps as wide as 5 km without any linking cross structures. Finally, Sibson [1986] finds that while an extensional jog can impede rupture on timescales of seconds, a small jog is nevertheless unlikely to prevent rupture on quasi-static timescales.

If the surficial geometry does not continue to depth and the principal faults merge, we suspect that it is the Homestead Valley Fault that bends at depth to join the Emerson Fault, rather than the converse. As mentioned in the preceding section, the Emerson Fault has about an order of magnitude more total slip than the Homestead Valley. We believe this implies a substantially shorter lifetime for the Homestead Valley Fault. If this is correct, then the Emerson Fault has acted alone, without the Homestead Valley Fault during most its existence. We have no reason to believe, then, that the dip of the Emerson Fault in the stepover would deviate from its dip elsewhere along strike.

A more reasonable hypothesis is that the younger of the two faults, the Homestead Valley, would have formed with a contorted, nonplanar shape near its intersection with the older, throughgoing Emerson Fault. It is beyond the scope of this principally descriptive paper, however, to create continuum-mechanical models that might quantify such shapes. Thus, in lieu of more definitive data, we argue only for a nearly vertical Emerson Fault. The subsurface shape of the Homestead Valley Fault is not well-constrained.

Comparison With Seismological and Geodetic Inversions

We have observed that through the stepover, slip decreases northward on the Homestead Valley Fault and increases northward on the Emerson Fault. Figure 6 shows that the cumulative surficial lateral slip on all the faults remains relatively constant across the stepover at a value of ~3 m.

Wald and Heaton [1994], Cohee and Beroza [1994], and Hudnut et al. [1994] used observations similar to those of Sieh et al. [1993] and Ponti [1992], smoothed over wavelengths of several kilometers, as constraints in the inversions of seismological and/or geodetic data for fault slip and rupture history. Within a factor of 2 or 3, their best fitting inversions reproduce the observations of surficial slip within the stepover region. The surficial data are superior to the modeled slip values at the surface, because they are directly observed and because they provide finer resolution of structural detail. The inversions, however, provide important clues to the behavior of the faults at depth, which cannot be deduced from our measurements of surficial offsets.

All of the best fitting inversions produce two broad-scale features that are relevant to understanding the stepover between the Homestead Valley and Emerson Faults. First, all reveal that the patch of very high surficial slip (3–6 m) north of the stepover, on the Emerson Fault, does not extend below a depth of about 8 km. Second, all the inversions produce a patch of very high dextral slip (3–8 m) about 10 km in diameter on the Homestead Valley Fault, near the southern edge of the stepover and 5–10 km beneath the surface.

The slip in this region as determined by surficial offsets is half to one third the slip determined by seismological and geodetic methods that sample a wider window of deformation. Perhaps the discrepancy is due to the narrow aperture of the geologic measurements. We cannot see off-fault and subsurface deformation. Alternatively, the geodetic and seismological models may suffer from nonuniqueness. In either case, this discrepancy suggests that strict extrapolation of surficial geological offsets to depth and the assumption of no large off-fault deformation may be inappropriate.

Nevertheless, geological observations do place important constraints on the analysis of fault behavior. In the following, we discuss the possible role of geologic data in analysis of earthquake rupture dynamics.

Sequence of Rupture Through the Duplex

What we know of the dynamic rupture of the Landers earthquake comes largely from seismological observations. Inversions of seismological data show unequivocally that the Landers earthquake was produced by nearly unilateral rupture from south to northwest. The details of the progression of the rupture are, however, very difficult to resolve from the seismological data, alone, and remain controversial and ambiguous. (Note, for example, the significant differences between the rupture progressions modeled by Cohee and Beroza [1994] and Wald and Heaton [1994]. In large measure, the ambiguities in the seismological records arise because only the longer-period (2–15 s) components of the records can be utilized in the inversions. These periods contain little information bearing on the details of the rupture history over fault lengths shorter than several kilometers. Unfortunately, the two major stepovers have dimensions of only a few kilometers. At this scale of seismological ambiguity, then, it would be useful to have information bearing on the details of the rupture history.

The seismological inversions, plus the nature of slip we see in the field, lead us to speculate that we may be able to see patterns of dynamic rupture in the static slip signature left on the ground surface. We have noted above that one aspect of the surface ruptures within the stepover is the asymmetry of their dextral-slip functions. Figure 4a shows that along most of its length, slip on the Northern Cross Fault diminishes away from the Homestead Valley Fault. Slip on the Eastern Splays decreases predominantly away from the Emerson Fault. We think these asymmetries may bear upon the issue of rupture dynamics across this stepover.

We suggest that the slip asymmetry may indicate the direction in which rupture propagated along the cross faults. That is, the slip is highest near the site of rupture initiation and lowest near its termination. We believe that the Northern Cross Fault failed because of stresses induced by failure of the Homestead Valley Fault and that the Eastern Splays failed because of stresses induced by failure of the Emerson Fault. Calculations of stresses at the ends of cracks in elastic media show that edge dislocations produce increases in shear stresses in the region surrounding the crack tip [e.g., Chinnery, 1963, 1966; Jaeger and Cook, 1979; Segall and Pollard, 1980; Rodgers, 1980; Stein et al., 1992; Harris and Simpson, 1992]. These shear stresses are greater at the crack tip and diminish away from it. If a favorably oriented second crack, located near the tip of the first crack, has uniform strength along strike and is then induced to fail, slip on the crack will initiate at the point nearest the first crack tip and propagate away (S. Ward, written communication, 1994). Furthermore, the magnitude of slip on that crack should diminish away from the tip of the first crack (S. Ward, written communication, 1994). Admittedly, calculations for cracks in an isotropic elastic medium do not perfectly mimic
those in the faulted Earth, during the propagation of a major earthquake rupture. They do, however, suggest that the asymmetry of slip on the faults of the stepover may reveal both the source of the stresses that produced failure of these faults and the direction in which slip propagated along them.

Let us assume, then, that asymmetry in slip distribution correlates with propagation direction. Figure 11 is our speculative reconstruction of rupture propagation through the stepover, based upon our observations of and assumptions about the asymmetry of surface slip, in the broader context of the seismological and geodetic inversions [Wald and Heaton, 1994; Cohee and Beroza, 1994]. According to the model of Wald and Heaton [1994], during the period from about 10 to 12 s after initiation of the earthquake, rupture propagated very rapidly northward along the Homestead Valley Fault to the southern edge of the stepover (Figure 11a). At that point, there was an abrupt decrease in the rupture-front velocity from about 4 to 1.4 km/s at the stepover (Figures 11b–11f). Between 12 and 16 s, rupture occurred principally within the region of the stepover. Their data do not allow them to resolve the detailed sequence of fault rupture within the stepover. However, we propose that their slow (1.4 km/s) propagation of the rupture front northward through the stepover may reflect the complex rupture sequence we deduce from the slip asymmetries.

In the early part of this 4-s-long period, rupture propagated...
to the northern end of the Homestead Valley Fault (Figure 11b). As it neared the end of the fault, slip decreased dramatically on the Homestead Valley Fault (Figure 4a), while rupture velocity may also have decreased. The shear stresses produced near the end of the Homestead Valley Fault by this slip function then caused south-to-north failure of the Northern Cross Fault (Figure 11c). Shear stresses produced by failure of the Northern Cross Fault induced rupture of the Emerson Fault near their intersection (Figure 11d). We suggest that since dextral slip on the Northern Cross Fault should have increased the normal stress on the Emerson Fault north of the intersection and decreased it to the south, the southern tail of the Emerson Fault ruptured next, propagating toward the southeast. This rupture would best fit into Wald and Heaton's [1994] sequence within the period 14–16 s. Next, the Eastern Splay accommodates the strains built up at the southeastern end of the Emerson Fault and begins to rupture southward, back toward the Homestead Valley Fault (Figure 11e). Stresses produced by failure of that portion of the Emerson Fault south of the Northern Cross Fault induced slip on the Emerson Fault north of the stepover about 16 s into the earthquake, at which time the rupture front accelerated and resumed its rapid northwestward propagation at about 4 km/s (Figure 11f). This sequence of faulting might account for Wald and Heaton's [1994] observation of some rerupturing toward the southeast on some fault(s) in the stepover area as the main rupture front continues northwest past the stepover.

This scenario is, of course, speculative, but it is consistent with the seismological inversion of Wald and Heaton [1994] and the static slip data. Ostensibly, this model conflicts with the best fitting inversions of Cohee and Beroza [1994]. Cohee and Beroza [1994] also have the rupture propagating south to north through the stepover 11–15 s into the earthquake, and the rupture front on the Homestead Valley Fault slowing down slightly as it approaches the stepover region and accelerating again across the region of highest slip. However, they have rupture fronts moving simultaneously along both the Homestead Valley and the Emerson Faults in the stepover. They interpret this to mean rupture occurred on a throughgoing fault. However, it may also mean simply that rupture occurred simultaneously on two or more independent faults. At any rate, the resolution of seismological data is such that they cannot rule out the possibility of back rupture.

If slip asymmetry does correlate with propagation direction and indicates the source of the shear stresses that induced failure, then perhaps the surficial slip signature can help resolve some of the details of rupture dynamics that seismological methods cannot.

**Implications of the 1992 Rupture for Long-Term Fault Behavior and Earthquake Recurrence**

As noted above, several offset geomorphic and bedrock features on the faults constituting the transfer structure indicate that the faults have experienced a total of 100–200 times the amount of slip associated with the 1992 event. Table 1 summarizes these long-term offsets and compares them with the 1992 values.

<table>
<thead>
<tr>
<th>Fault</th>
<th>1992 Offset</th>
<th>Geomorphic Offset</th>
<th>Bedrock Offset</th>
<th>Number of Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>HVF</td>
<td>3 m</td>
<td>300 m</td>
<td>300 m</td>
<td>100</td>
</tr>
<tr>
<td>NCF</td>
<td>1.2 m</td>
<td>200 m</td>
<td>⋯</td>
<td>160</td>
</tr>
<tr>
<td>WS</td>
<td>20 cm</td>
<td>40 m</td>
<td>⋯</td>
<td>200</td>
</tr>
<tr>
<td>EF^a</td>
<td>1.5 m</td>
<td>260 m</td>
<td>⋯</td>
<td>170</td>
</tr>
<tr>
<td>EF^b</td>
<td>3 m</td>
<td>⋯</td>
<td>4 km</td>
<td>1300</td>
</tr>
</tbody>
</table>

The approximate number of 1992-like events that have occurred on each fault segment was calculated by assuming the 1992 offsets to be “average” and dividing the 1992 slip into the cumulative offset.

^aWithin the stepover region.

^b15 km north of the stepover.

The similarity in the number of 1992-like slip events required to create the total offsets on the Homestead Valley Fault, Northern Cross Fault, and Western Splay suggests they and the stepover structure as a whole have been behaving as a system since their inception. It seems reasonable to assume that when the Northern Cross Fault ruptures with the Homestead Valley Fault, the northern Emerson Fault also ruptures, and slip transfer, in general, is as complete as it was in 1992. Whether the northern Emerson Fault also always ruptures with the Homestead Valley Fault is another matter, since we believe its much larger total offset suggests that the Emerson Fault is older and had a distinct history prior to inception of the Homestead Valley Fault and the stepover.

Only the northern half of the Emerson Fault ruptured during the 1992 earthquake. The half that lies south of the stepover has been active in the late Holocene (D. P. Schwartz, personal communication, 1994) but did not rupture in 1992. We suggest that early on, before the initiation of the Homestead Valley Fault and the stepover, the southern and northern portions of the Emerson Fault must have formed a solitary, throughgoing fault. More recently, perhaps in response to changing stress fields or overall rotation of the Mojave block [Dokka and Travis, 1990a; Nur et al., 1986], the Homestead Valley Fault developed. This fault then siphoned all or a portion of the slip rate that had been carried by the southern half of the Emerson Fault. Thus the long-term slip rate of the Emerson Fault north of its juncture with the Homestead Valley Fault would now equal the sum of the slip rates of the southern Emerson and the Homestead Valley Faults.

This structural evolution, the partitioning of slip rates between the two faults, and the 1992 slip values suggest several scenarios for the long-term interaction of the Homestead Valley and Emerson Faults. One possibility is that the Homestead Valley Fault and northern half of the Emerson Fault usually fail in a single earthquake sequence, as they did in 1992. Palaeoseismic data do indicate that the last prehistoric events on both faults were within a thousand years of each other in the early Holocene [Rubin and Sieh, 1993; Hecker et al., 1993; Rockwell et al., 1993; D. P. Schwartz, personal communication, 1994; T. K. Rockwell, personal communication, 1994]. If this is the case, then the Homestead Valley Fault should provide 3 m of slip to the Emerson Fault. However, in 1992, north of the stepover, the Emerson Fault had 6 m of slip or 3 m that did not come from the Homestead Valley Fault. Obviously, this slip distribution cannot continue indefinitely without producing a slip deficit. Therefore we need another source of slip. One possibility for that source is the southern segment of the Emerson Fault. Thus interspersed between earthquakes of the Landers-1992 type would be earthquakes on the Southern Emerson Fault only. A typical slip function for a southern Emerson event might then exhibit a northward decrease in slip...
where the fault bounds the eastern flank of the stepover (Figure 12a). The frequency of events on the southern Emerson Fault and the average offsets associated with them would depend on the average rate of slip on the southern half of the fault and on the strength of the fault. None of these quantities is known, although we use 3 m per event for illustrative purposes in Figure 12. Other possibilities include the rupture of the entire Emerson Fault north of the stepover fails alternating with Landers-type events and Southern Emerson events (Figure 12b), and events in which the Homestead Valley Fault ruptures alone after a full Emerson Fault rupture (Figure 12c). Finally, the slip discrepancy between the Homestead Valley and Emerson Faults could be accommodated by having Homestead Valley events twice as often as Emerson events without involving the Southern Emerson at all. However, given the paleoseismological evidence that the southern Emerson is still active (D. P. Schwartz, personal communication, 1994), we prefer to include it in our favored scenarios.

Recurrence Intervals

If indeed the 1992 Landers earthquake is a “typical” event, knowledge of the average recurrence interval would enable one to determine how long the Homestead Valley Fault has been active. Sauber et al. [1994], using geodetic data to compare the coseismic strain release in the Landers earthquake to the interseismic strain accumulation in this region, estimated a recurrence interval of 3500–5000 years for Landers-type events. This is markedly shorter than recurrence intervals inferred from paleoseismic studies of individual faults in and near the stepover. Paleoseismic studies on the Homestead Valley Fault south of the study area by Hecker et al. [1993] reveal two faulting events, one 5700–8500 years ago and one 12,500–14,000 years ago. If 7000 years is a typical recurrence interval, then it implies that the Homestead Valley Fault has been active for about 1 m.y. This is consistent with an age of 1.5–0.7 m.y. for the series of NW striking faults throughout the Mojave block determined by crosscutting relationships [Dokka and Travis, 1990b]. Paleoseismic studies by Rubin and Sieh [1993] in the playa on the Emerson Fault in this area (Figure 3c) likewise indicate two previous events, one about 9000 years ago and the other between 14,800 and 24,000 years ago. The Emerson Fault ages are slightly older than Homestead Valley Fault ages but still imply an age of about 1 m.y. for the Homestead Valley Fault.

According to these paleoseismic studies, the Homestead Valley Fault slip rate of 0.4–0.6 mm/yr [Hecker et al., 1993] is similar to that of the Emerson Fault, 0.2–0.6 mm/yr [Rubin and Sieh, 1993], yet the cumulative offset on the Emerson Fault is an order of magnitude higher than that on the Homestead Valley Fault. This similarity of modern rates supports our previous suggestion that the Emerson Fault acted alone until the Homestead Valley Fault was born.

The above exercise is useful for placing general constraints on the age and activity of the faults in this area. On the other hand, if this earthquake teaches us anything, it is that we should be wary of assuming characteristic and repetitive faulting behavior. Patterns in space are clearly complicated and irregular, so there is no reason to expect patterns in time to be any different. We can say, however, on the basis of large-scale offsets, that while the details of timing may elude us, rupture patterns do repeat over long periods and are responsible for creating large-scale geomorphic and tectonic features.

Summary and Conclusions

We measured surface offsets in the area of the Landers 1992 rupture where the Homestead Valley Fault stepped over to the Emerson Fault. We found that these two primary faults were linked by a series of obliquely striking right-lateral strike-slip faults. This stepover structure appears to be a developing strike-slip duplex in which the northernmost cross fault is the most mature transfer structure, and the other cross faults are less mature. The secondary faults and rotations effectively transferred all the slip from the Homestead Valley Fault to the Emerson Fault. The stepover discontinuity may have presented a small impediment to rupture over a 5-s period but did
The observation that slip distribution on the cross faults is asymmetric leads us to speculate that the asymmetry may indicate the source of the stresses which induced failure on the faults in the stepover and may correlate with propagation direction, with slip decreasing in the direction of rupture propagation. Using seismological models of rupture evolution, we propose a scenario for rupture within the stepover, and speculate that possibly geological observations of surficial slip can provide insights into rupture dynamics.

Finally, we compare long-term bedrock and geomorphic offsets along the faults in the stepover region to 1992 offsets. The Homestead Valley Fault and several smaller faults show evidence of having been active through 100–200 nominal Landers events. This, in turn, indicates that the cross faults have effectively transferred slip across the stepover since its inception and that the step has not presented an impediment to rupture. The Emerson Fault, which has an order of magnitude greater total offset, appears to be a much older fault than the other faults making up the stepover. On the basis of preliminary paleoseismological studies of recurrence intervals on the faults in the area, these long-term offsets indicate that the faults in the area have been active of the order of one to a couple of million years.

Appendix

With reference to Figure 13, use the offset measurements $r_\ell = 154$ and $v = 36$. The strike of NCF is N5°E, and we assume the slip vector azimuth is N35°W, parallel to the strike of the HVF. Then $\alpha = 40^\circ$. Thus

\[ h = (r_\ell) \tan (\alpha) = (154) \tan (40) = 129 \]

\[ \tan (\phi) = \frac{v}{h} = 36/129 \]

so $\phi = 16^\circ$

\[ b = \frac{v}{\sin (\phi)} = 134 \]

\[ \tan (\beta) = \frac{b}{r_\ell} = 134/154 \]

so $\beta = 41^\circ$

\[ D = \frac{r_\ell}{\cos (\beta)} = \frac{154}{\cos (41^\circ)} = 204 \]

so $\Theta = 10^\circ$; i.e., the trend and plunge of the slip vector must be N35°W/16°N and the strike and dip of the NCF must be N5°E/10°N.

Similar calculations elsewhere along the NCF yield even shallower fault dips and slip vector plunges, e.g., midway along, where the offsets are 120 cm right lateral, 21 cm east side up, the dip and plunge are $8^\circ$ and $12^\circ$ respectively. Given that at this point the fault cuts across steep terrain with a topographic slope of greater than 20°, such fault dips are clearly impossible. We conclude then that the slip vector azimuth of the NCF is not in fact parallel to the HVF.

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