Final Report to U.S. Department of Energy

on

CHARACTER AND ORIGINS OF GROUND RUPTURING AND GROUND DEFORMATION DURING THE 28 JUNE 1992 LANDERS, CALIFORNIA EARTHQUAKE

(AS WELL AS THE 1989 LOMA PRIETA AND 1994 NORTHRIDGE EARTHQUAKES)

by

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Supported by
Department of Energy
Grant No. NTP1402
Geosciences Research Program
W.C. Luth, Administrator
Office of Energy Research
ER–64/GTN
Washington, D.C., 20585
17 September 1996

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MOST IMPORTANT ACCOMPLISHMENTS

This is a final report on two years of research funding provided by the Department of Energy, used for research during a period of about three years. The overall objective of the research has been to understand the form and significance of surface rupture produced by earthquakes. Specific objectives are to describe fracturing and other manifestations of broad belts of ground rupture during the Landers earthquake and to mechanically analyze the structures that form along the belts. Through the efforts of three senior researchers, Dr. Robert Fleming of the U.S. Geological Survey, Dr. Kenneth Cruikshank, postdoctoral researcher at Purdue and now at Portland State University, and myself, as well as two graduate students, Wei Wei and Sumaryanto Martosudarmo, a photogrammetist with the U.S.G.S., James Messerich, and two drafting technicians, Kaj M. Johnson and Nils A. Johnson, we have accomplished much that we set out to do. We have learned much about ground rupture during earthquakes, even though we have studied only three earthquakes to date: Loma Prieta, Landers and Northridge. The following papers and manuscripts will be cited below.

General

1. Johnson, A.M., 1995. Orientations of faults determined by premonitory shear zones. Tectonophysics, 247:161,238.

Loma Prieta, California Earthquake of 1989

2. Johnson, A.M., and R.W. Fleming, 1993. Formation of left,lateral fractures within the Summit Ridge shear zone, 1989 Loma Prieta, California, earthquake. Journal of Geophysical Research, 98:21823,21837.
3. Martosudarmo, S.Y., Johnson, A.M., and Fleming, R.W., 1996. Ground fracturing on the southern end of Summit Ridge caused by the October 17, 1989 Loma Prieta, California earthquake. U.S.G.S. Open,file Report 96,xxx, 47 p., 5 plates.

Landers, California Earthquake of 1992

4. Fleming, R.W., A.M., Johnson and J. Messerich, 1996. Growth of a Tectonic Ridge. U.S. Geological Survey, Open,file Report 96,xxxx, 48 p., 5 plates.
5. Fleming, R.W., and Johnson, A.M., 1996. Growth of a tectonic ridge during the Landers earthquake. Submitted to Geology. 4 p.
6. Johnson, A.M., R.W. Fleming, and K.C. Cruikshank. 1993. Broad Belts of Shear Zones as the Common Form of Surface Rupture Produced by the 28 June 1992 Landers, California, earthquake. U.S. Geological Survey, Open File Report 93,348, 61 p.
7. Johnson, A.M., Fleming, R.W., and Cruikshank, K.M., 1994. Broad belts of right,lateral surface . rupture along simple segments of fault zones that slipped during the 28 June 1992 Landers, California, earthquake. Bull. Seismological Society of America, 84:499,510.
8. Johnson, A.M., Fleming, R.W., Martosudarmo, S.Y., Johnson, N.A., Johnson, K.M., and Wei, W. 1996. Analecta of structures formed along strike,slip fault zones during 28 JUNE 1992 Landers, California earthquake sequence. U.S.G.S. Open,file Report 96,xxx, 45 p, 12 plates.
9. Lazarte, C.A., Bray, J.D., Johnson, A.M., and Lemmer, R.E., 1994. Surface breakage of the 1992 Landers earthquake and its effects on structures. Bulletin of the Seismological Society of America, 84:547,561.

Northridge, California Earthquake of 1994

10. Cruikshank, K.M., Johnson, A.M., Fleming, R.W., and Jones, R., 1996. Winnetka deformation zone„Surface expression of coactive slip on a blind fault during the Northridge earthquake sequence, California. U.S.G.S. Open,file Report 96,xxx, 38 p., 4 plates.
11. Johnson, A.M., Fleming, R.W., and Cruikshank, K.M., 1996. Coactive slip on blind faults in San Fernando Valley, California during Northridge earthquake sequence. To be submitted to Geology (or BSSA), 4 p.
12. Johnson, A.M., Fleming, R.W., Cruikshank, K.M., and Packard, R.F., 1996. Coactive fault of the Northridge earthquake„Granada Hills area, California. U.S.G.S. Open,file Report 96, 523, 95 p., 3 plates.

Our major accomplishments are as follows:

1. We have **rediscovered belts of shear zones** along faults. As a result of theoretical analysis of orientations of faults (paper 1), I anticipated that we might find shear zones, rather than simply fault surfaces, at Landers. Indeed, the relations between the formation of shear zones and faults were particularly clear in ground rupture during the June 1992, Landers, California earthquake, which produced the most spectacular ground rupturing of any earthquake yet this century. In long, straight stretches of fault zones at Landers, the rupture is characterized by the telescoping of shear zones and intensification of shearing characterized by broad shear zones of mild shearing, containing narrow shear zones of more intense shearing, containing even–narrower shear zones of very intense shearing, which may contain a fault (papers 6 and 7). Thus the ground ruptured across *broad belts* of right–lateral shearing with subparallel walls over distances of several kilometers. Each broad belt consists of a broad zone of mild shearing, extending across its entire width (50 to 200 m), and much narrower (a few m wide) shear zones that accommodate most of the right–lateral offset of the belt and are portrayed by en echelon tension cracks and left–lateral fractures (papers 6 and7). Even narrower right–lateral shear zones formed within the narrow shear zones, and some of these were faults. Clearly, the faulting occurred late in the development of the shear zone, and the faulting occurred after a shear zone or a belt of shear zones formed. The belt of shear zones was premonitory to the faulting.

By one of those fortunate accidents, a group of geophysicists collaborating with Keiita Aki have recently begun to recognize low–velocity zones along some earthquake faults, including those at Landers (Li and others, 1994b, 1994c, 1994d). For example, K. Aki, W.G. Li and others presented seismological evidence, at the 1994 American Geophysical Union meeting in Baltimore, MD, that such zones at the surface can be recognized at depth as low–velocity zones 50 to 200 m wide that extend to at least 10 km depth along the Johnson Valley and Homestead Valley fault zones at Landers (Aki, 1994; Li and others, 1994a). Thus the belts of shear zones probably are not merely near–surface phenomena that extend for many kilometers along the ground surface, but extend to depths of at least 10 km.

However, I say that we have rediscovered belts of shear zones, not discovered them, because shear zones were well recognized by inverstigators of the 1906 San Francisco earthquake (Gilbert, in Lawson, 1908; Gilbert, 1928; Reid, 1910). Between that time and now, except for fragmentary descriptions (Philip and Meghraoui, 1983; Armijo and others, 1989) they have been ignored. In paper 6 have reviewed descriptions of coseismic earthquake fracturing prepared by some prominent observers—G.K. Gilbert, Andrew Lawson, and F.E. Matthes on parts of the 1906—San Andreas rupture north of San Francisco; Malcolm Clark on the rupture during the 1968 Borrego Peak earthquake; and Robert Brown and George Plafker on the 1972 rupture in Managua, Nicaragua. Our review suggests that shear zones, or parts of shear zones have been widely recognized, but not singled out for particular emphasis as we have.

Thus, we were not the first to notice shear zones, but we are the only ones to recently call attention to their occurrence and to emphasize their importance in considerations of siting of critical engineering structures.

2. Thus our second contribution is to emphasize that **much of the damage** to man–made structures during earthquakes **is due to highly concentrated, anomalously large strains** that occur in the vicinity of visible or blind faults. This contribution is a recurring theme throughout the sequence of papers we have written (papers 3, 6, 7, 8, 9, 10, 11 and 12). It was the central focus of paper 9, a collaboration among engineers and geologists. At Loma Prieta, much of the damage was in a broad shear zone along a fault that was coactive with the deep, blind fault that produced the earthquake (paper 3). At Northridge, much of the damage is within the high strain zones above the tip of blind faults in at least two areas of San Fernando Valley (papers 10, 11, 12). Again, the faults that moved were coactive with the fault that produced the main shock.

3. **Recognition that ground rupturing** at Loma Prieta **is largely tectonic** (paper 2.) The theoretical work on shear zones (paper 1) and the field study of shear zones at Landers (paper 6) provided a basis for understanding peculiar aspects of ground rupture at Summit Ridge during the 1989 Loma Prieta, California, earthquake and the 1906, San Francisco earthquake (Gilbert, 1907; Lawson and others, 1908; Reid, 1910). Ground rupture along the San Andreas fault zone in the epicentral area of the 1989 Loma Prieta earthquake was described in the first U.S. Geological Survey report on the earthquake (Plafker and Galloway, 1989), but the nature of the ground rupture was baffling (Ponti and Wells, 1991). The fractures were misinterpreted to represent gravitational effects (Ponti and Wells, 1991).

Our detailed mapping (paper 3) showed that the fractures at Summit Ridge were straight, long tension cracks of the type which generally accommodated visible left–lateral offsets. The left–lateral offsets appeared to contradict what one would expect along a right–lateral fault (Plafker and Galloway, 1989; Ponti and Wells, 1991). Because these tension cracks and left–lateral fractures were believed to be incompatible with the right–lateral/reverse focal mechanism reported by seismologists, they were either ignored or variously attributed to lurching, arching of the hanging wall of the fault, bedding–plane slip, landsliding, and gravitation sagging (e.g., Ponti and Wells, 1991). As has become clear with further research into fracturing associated with shear zones, however, the tension cracks and left–lateral fractures are to be expected as surficial manifestations of a right–lateral shear zone at depth (papers 2 and 3). Indeed, such fracturing had been recognized, presumably, but its origin was unappreciated (Tchelenko, 1970; Tchelenko and Ambraseys, 1970; King and Vita–Finzi, 1981; Philip and Meghraoui, 1983; Ron and others, 1984; Hancock, 1985; Deng and others, 1986; Sylvester, 1988; Armijo and others, 1989; Scholz, 1990).

Early in our work at Loma Prieta (Aydin and others, 1992), we thought that the fault that produced the Loma Prieta earthquake propagated to the ground surface. We found right–lateral offsets on the order of 10 to 20 cm on fault segments within the San Andreas fault zone (Aydin and others, 1992) and our analysis of the Summit Ridge shear zone (paper 2) indicated that nearly the entire right–lateral offset calculated by seismologists to have occurred near the hypocenter of the Loma Prieta earthquake could be represented by opening and left–lateral offsets along tension fractures within the shear zone. Through detailed mapping, and the understanding provided by the postulate of premonitory shear zones, we then asserted that strands of the San Andreas and Sargent faults broke through to the ground surface during the Loma Prieta earthquake (paper 2).

In retrospect (papers 3), based on our observations and interpretations at Landers (papers 6 and 7) and Northridge (papers 10, 11 and 12), we can readily imagine that the Summit Ridge shear zone, the slip on segments of the Sargent and San andreas faults, and the range–front thrust faulting between Los Gatos and Los Altos Hills could represent coactive fault slip rather than slip on the fault that produced the main shock.

4. Documentation of **Growth and Structural Setting of a Tectonic Ridge** (paper 4 and 5). One of our more spectacular results is, in many ways, an accident. We found a tectonic ridge along the Emerson fault zone that grew distinctly in altitude during the Landers earthquake and determined the structural setting of the ridge. Further, we found surveyor's monuments that were established before the earthquake and resurveyed the monuments in order to determine the deformation in the vicinity of the ridge. The surveys allow, for the first time, the determination of differential vertical and horizontal displacements over a broad area near a growing ridge within a fault zone. In 1993/94 we completed mapping of fractures in the belt of shear zones north of Tortoise Hill ridge and extended the mapping southward where the belt bifurcates and wraps around the ridge. Thus the ridge is **within** the belt of shear zones.

The ridge is a topographic eminence, dome–shaped and measuring some 0.5 km by 1.5 km. In 1995 we used photogrammetry, precision land surveying and leveling to determine deformations at different scales in the vicinity of the rupture zones and across the ridge. The purpose of both types of surveying was to determine changes in angles and changes in lengths of lines so that we could compute strains. As a result of these surveys, we can describe the recent growth of a tectonic ridge; the ridge was pushed upward along bounding shear zones on the NE and SW about 1 m as about 3 m of right–lateral shift was accommodated across the Emerson fault zone during the Landers earthquake. This is a spectacular growth of a ridge during a single earthquake event.

Furthermore, we obtained a new insight into the origin of ridges along strike–slip fault zones. Tortoise Hill ridge is along a relatively straight segment of the Emerson fault zone, so it cannot be a result of a left–step or bend on a right–lateral fault zone (or vice versa), which is the current explanation for such phenomena. We suggest that Tortoise Hill ridge, like analogous ridges that occur in landslides (Fleming and Johnson, 1989), grew as a result of localized dilation of material within a belt of shear zones along the Emerson fault zone.

5. We count among our accomplishments the **preparation and preservation of analytical and synoptic maps of rupture zones** at Loma Prieta and Landers. We have been very fortunate to have the format of the U.S. Geological Survey Open–file report for this purpose. The kinds of descriptions that are possible only with maps are being preserved, for possible future use, in this special format. Unfortunately, very few detailed maps, over the years, have been made of earthquake ruptures. We have made many maps, and nearly all of them are in this report as well as in the Open–file reports cited above.

RELEVANCE OF RESEARCH

I have tried to keep the research relevant to goals of DOE, as I see them, yet maintain a reasonable level of pure scientific curiosity. Most of our results are relevant, I believe.

Our detailed mapping at Landers shows that the earthquake produced some of the most spectacular ground rupturing of any earthquake yet this century. Details are preserved because the earthquake occurred in the desert, and fracture patterns are largely unaffected by houses and roads so they can be interpreted. Our research showed that the ground rupture at Landers was generally not concentrated along surfaces of slip that one would readily identify as faults. Rather, the ground at Landers ruptured primarily along broad belts of shear zones, several m to at least 200 m wide. Although about half of the lateral shift along each rupture belt was accommodated across a narrow shear zone, (perhaps 5 to 10 m wide), there is significant ground breakage over the entire width of the belt.

The distribution of shift during faulting across broad shear zones, rather than along fault surfaces, has several major practical and scientific implications: 1). Distributed shift, if it persists to depth, may markedly affect the mechanisms of earthquakes produced by faulting. 2). Shearing across a broad zone must be considered in designs of critical structures to withstand ground rupture during earthquakes, 3). Shearing across a broad zone needs to be considered by earthquake specialists dig trenches across old rupture areas, looking for "strands," and estimating offsets. Our research suggests that much of the offset may be distributed across a rather broad zone. The earthquake specialists who dig trenches need to realize that an earthquake rupture is not really a fault. 4). Shearing across a broad zone must be considered as agencies adopt hazards criteria for the siting of major engineering structures such as nuclear power plants, and dams, as well as critical facilities such as schools, hospitals, and fire departments. An example of such policy considerations is California's landmark, Alquist–Priolo Act, which is concerned with, among other things, setbacks of houses, vital utilities and other structures from active faults. In short,

> Without question, we will be unable to understand ground rupture during earthquakes if we expect it to be expressed as slippage along fault surfaces. For all these reasons, the Landers earthquake and the ground rupture associated with it are important.

In the proposal to DOE I made the following statements about the relevance of the proposed research to the Department of Energy:

> The general topic of our research is the nature of surface rupture during a major earthquake. Two recent earthquakes in California—the Landers earthquake (M 7.5) in 1992 and the Loma Prieta earthquake (M7.1) in 1989—have exposed our lack of understanding of surface rupture caused by earthquakes (Plafker and Galloway, 1989; Ponti and Wells, 1991; Prentice and Swartz, 1991; Engineering and Science, 1992). The central problem at Loma Prieta was that, because the length and width of surface rupturing produced by the earthquake were

unclear, there was considerable confusion about seismic hazard. The confusion resulted from our lack of familiarity with the kind of surface rupture that developed there, in spite of the fact that the same kind of rupture occurred along the San Andreas fault zone during the 1906 earthquake.. Our research strongly suggests that the enigmatic surface fractures at Loma Prieta are tectonic, and that the pattern of fracturing produced there in 1989 was very similar to that of the 1906 San Francisco earthquake (Johnson and Fleming, [1993]; Martosudarmo and others, [1996]). These studies also indicate, however, that estimates of earthquake magnitude and degree of seismic hazard made on the basis of the amount of slip along any given fracture may seriously underestimate the total slip across a shear zone. When conducting siting studies of major earth structures such as dams and power plants, or critical repositories, and for housing developments, schools, and emergency facilities, the practice is to search for "the fault," as though we expect the ground rupture to resemble the planar structure defined, long ago, as a fault (Reid and others, 1913). In investigations of paleoseismicity, earthquake hazards are assessed in large part through information about the length of rupture and the magnitude of offset (Wise and others, 1984). Much of the offset, however, is overlooked in such studies. For example, the oft–cited trenching investigation of Pallet Creek by Sieh (1978) could document only about 25 percent of the expected long–term slip along the San Andreas fault in that area. Perhaps the excavation included only part of the near–surface shear zone, or possibly the shift was accommodated by more obscure forms of deformation that were unrecognized in the trenches.

Our studies of surface rupturing in the Landers earthquake have already demonstrated that "the fault" occupies a zone that is commonly 50 to 200 m wide, but which may be 1 km wide, or wider, under certain circumstances (Johnson and others, [1993, 1994]). Although others have observed the same phenomenon, all of them have assumed that they were seeing more than one fault (e.g., Engineering and Science, 1992). One reason for the dramatic ground rupture produced by the Landers earthquake, the most spectacular of any this century, is that the earthquake's hypocenter was very shallow, one to three km. Another is that the rupture formed in the desert, where details are preserved and the patterns of rupturing are relatively unaffected by houses and roads. The ground rupture is dominated by right–lateral shearing, and extends along segments of no fewer than six distinct fault zones. The segments are arranged broadly en echelon and connected through wide transfer zones by stepovers, consisting of right–lateral fault zones and tension cracks. The total length of the surface rupture was about 80 km.

There are many reasons why the nature of the ground rupture during the Landers earthquake needs to be analyzed and described in detail. The lessons to be learned by studying this earthquake are especially relevant to the energy industry and the U.S. Department of Energy. It is the largest to have occurred in the United States since the Great Alaskan, Good Friday, earthquake in 1964, and the largest in the 48 contiguous states since the 1906 San Francisco earthquake. The Landers earthquake is also the largest since the revolution of plate tectonics and the inception of the National Earthquake Hazards Reduction Program. It has been the most extensive since adoption of many types of hazards criteria for the siting of major engineering structures such as nuclear power plants and dams, and critical facilities such as schools, hospitals, and fire departments. It is the largest and most disruptive earthquake since development of ideas about "capable" faults and segmentation, and since enactment of California's landmark, Alquist–Priolo Act, which is concerned with "setbacks" of houses, vital utilities, and other structures from active faults. The extensive surface rupture at Landers will have major implications for future regulations about earthquake hazards, including the hazards of rupturing of containment structures of nuclear waste and other extremely toxic waste. For all these reasons, the Landers earthquake, and the ground rupture associated with it, are scientifically important. Clearly, the energy industry and the U.S. Department of Energy need to know how ground will rupture along earthquake faults.

The proposed research will investigate the nature and distribution of the ground rupture that can be expected during a major earthquake along a fault zone. Research into the way faulting occurs is relevant to the energy industry because of the need to avoid damage to energy facilities, and nuclear and toxic materials containment facilities, especially in the western U.S. On the other hand, the proposed research is fundamental because it focuses on the ground fracturing itself, rather than, for example, the interaction of ground deformation and engineering structures. Our research is designed to provide new insights into faulting processes themselves.

In these ways, the proposed research is relevant to the stated goals of the Department of Energy Geosciences Research Program.

OBJECTIVES OF RESEARCH

The proposal to DOE made the following statements about the objectives of the research:

Faults and attendant structures are well–displayed throughout much of the 80–km rupture at Landers. Because the differential displacements are so large, the structures are exaggerated. The maximum differential, right–lateral displacements, up to perhaps 6 m, are comparable to the maximum value of 5.4 to 6.4 m in the 1906, San Francisco earthquake (Gilbert, 1907; Lawson, 1908). They are much larger than the 1971 San Fernando and 1989 Loma Prieta earthquakes, (1 or 2 m); the 1964, Borrego Peak and 1972, Managua, Nicaragua earthquakes, (2 or 3 dm); or the Parkfield earthquake, (5 to 8 cm).

At Landers, one can see virtual *cartoons* of deformation patterns in the field. The scarcity of vegetation, the aridity of the area, the firmness of the alluvium and bedrock, and the relative isotropy and brittleness of surficial materials collaborate to provide a virtually unique display of simple cracks, fractures, faults, and shear zones that define the earthquake rupture zone throughout its length. The difficulty is not in finding a place to describe, but in selecting the place to best invest one's descriptive energy, given one's goals and the relatively limited time before the structures will have faded or vanished. If we fail at Landers to accurately describe the fracturing that characterizes the ground rupture during a major earthquake the shortcoming is both ours and inexcusable!

The proposed research can be described in terms of three general objectives, and several specific parts. The general objectives of the proposed research are: (1) to make detailed maps that characterize the ground fracturing along simple segments, and some complex segments, of the 80–km rupture zone of the Landers earthquake; (2) to determine displacement fields within a few hundred metres on either side of the rupture zones where we have made detailed maps; and (3) to develop theoretical models to explain the fracture patterns we observe and to postulate the character of the fault zones perhaps a few hundred metres beneath the areas we have mapped.

The background and methods of accomplishing the objectives are to:

1. Make detailed maps of rupture zones in order to characterize the ground fracturing produced by the Landers earthquake.
    - a. Along simple segments of the rupture zone.
    - b. Where a simple rupture zone passes from alluvium to bedrock.
    - c. Where a simple rupture zone breaks down into en echelon fault segments.
    - d. In the vicinity of a stepover, from one fault zone to another and from one fault segment to another.

2. Use photogrammetric methods (analytical stereoplotter) to determine displacement fields in the general vicinities of each of the types of structures mentioned in 1, in order to determine the kinematics of the deformation. We will analyze displacements in several areas where we have offset man–made features so that we can check the accuracy of the photogrammetric methods.

3. Perform theoretical analyses of various simple and complex models in order to:
    - a. Explain the fracture and fault patterns described in various areas.
    - b. Determine the near–surface stress state as the rupture zone evolves.
    - c. Explain different orientations of tension cracks within a shear zone and in ground outside the shear zone.
    - d. Explain the controls of orientations of en echelon shear zones.
    - c. Infer the probable conditions at depths of a few hundred metres beneath the ground surface.

The data that we gather in reaching objectives (1) and (2) will be valuable for analyzing processes of faulting and for discussing various types of regulations concerning hazards due to faulting. The theoretical analyses we propose in objective (3) will provide a basis for understanding our observations in (1) and (2), as well as other investigator's observations, and will provide a basis for extrapolating what we observe at the ground surface to a depth of perhaps a few hundred metres beneath the ground surface

THE SIX RESEARCH PROBLEMS

In my proposal to DOE, three years ago, I stated that I wished to address six major questions or topics with funding from DOE. Before presenting our published results, I wish to review "what we promised."

First Research Problem

According to our analytical mapping of the deformation within a broad shear zone, about 160 m wide, in one of our study areas, the deformation first consisted of a combination of pure right–lateral shearing parallel to the walls and dilation normal to the walls of the shear zone. The shearing and dilation are reflected in the orientations of the tension cracks. After the tension cracks formed, the mechanical behavior of the ground was changed profoundly, and it sheared readily. As overall right–lateral shearing continued, some blocks of ground bounded by tension cracks rotated in a clockwise direction, causing left–lateral offsets across the fractures and changing some of the fractures to left–lateral faults, just as in the Summit Ridge area during the Loma Prieta earthquake of 1989. Although the formation of tension cracks and their subsequent transformation into left–lateral faults are interesting, we understand, qualitatively at least, how left–lateral shearing is developed within a right–lateral shear zone (Johnson and Fleming, in review).

An interesting problem, though, concerns the control of the orientations of the tension cracks themselves, and this is one of the issues we propose to research. The fundamental fractures in the broad shear zones are the tension cracks, not the small, left–lateral faults. The distribution of the tension cracks throughout the broad shear zone, and their virtual absence in ground on either side, indicates that the ground within the shear zone was subjected to *localized deformation* vis a vis the ground on either side of the shear zone. The reason for the localization is unclear, but I believe that much can be learned about the deformation by interpreting the tension cracks, which are oriented about 30° clockwise from the walls of the shear zone. We know that the deformation responsible for the tension cracks was not pure shear, oriented parallel to the walls of the shear zone, (as we commonly associate with simple shear along a fault zone, for example), because, in that case, the tension cracks would be oriented 45°, not 30°, from the walls of the shear zone.

A possibility that we propose to investigate is that the stresses in the ground within a few m of the ground surface were due largely due to shearing, plus dilation, across a broad zone, (about 200 m wide), at greater depths. This would explain, qualitatively, why the tension cracks are localized within a distinctive zone and are absent in ground on either side of the zone. What we would suggest, then, is that a combination of pure shear and dilation normal to a shear zone, at depth, is responsible for the stress state and the resulting orientations of tension cracks within the structure that we have called a *broad shear zone* at the ground surface.

In the proposed research we will investigate these concepts more thoroughly and solve boundary–value problems for a shear zone at depth, below a layer of different properties, in order to quantify the predictions of orientations of tension cracks in a layer over a shear zone.

[Note: Our work has provided additional documentation of this phenomenon, and we have published some relevant field measurements and theoretical analyses.]

Second Research Task

The second research task we propose is to make detailed maps of the broad belt of shear zones about 0.5 km toward the SE and 0.5 km to the NW of the Two Ranches area, along the Homestead Valley fault. One reason is to show the extent of damage such as we observed in the Two Ranches area. A second purpose is to see how the belt of shear zones changes as the character of the shear zone in the NE wall of the belt changes into en echelon segments, toward the SE. The Two Ranches map area is transitional—between a fully–developed, en echelon fracture zone to the SE, and a fully–developed, simple fracture zone to the NW—so it will be particularly interesting to extend our mapping along the belt of shear zones here. A third objective is to see how the belt of shear zones changes as the fault zone passes from compact alluvium, in the vicinity of the Two Ranches area, to bedrock to the NW.

Many of the smaller fractures will have vanished due to weathering and human activities by the time we are able to make the maps, but, because we already have experience with mapping fresh fractures, we will know what we are missing as we make more maps. The larger fractures, those associated with the narrow shear zones we have described, will survive, and it is these that we will be able to map.

[Note: We did complete this mapping, extending our detailed maps for about 0.5 km south and 1.5 km north of the Two Ranches area. The results are presented in "Analecta......."]

Third Research Problem

The third research problem is relevant to all of the proposed study areas at Landers. The problem is that, in order to determine the kinematics of a belt of shear zones, we need to have detailed information about the relative displacements within the belt. We selected the Two Ranches area for detailed study, in part, because the offset fence lines there enabled us to observe relative displacements across various shear zones. As we extend the mapping to the NW and SE, however, we will not have detailed information on relative displacements. For this reason, we propose to use a method, developed primarily by Robert Fleming, utilizing aerial photographs taken before and after the Landers earthquake. The intent would be to determine displacement fields, and, perhaps, strain fields, in and near the broad belts of shear zones at Landers. Robert Fleming, in collaboration with the Geologic Division Plotter Laboratory at Denver, already has tested the method on two landslides in Utah and one in Hawaii (Fleming, Johnson and Baum, 1991; Baum and Fleming, 1991), and has shown its exciting potential.

Although the technique has not yet been tried for determining displacements along active faults, there is every reason to believe it would work. For the Landers earthquake, we have aerial photographs (1:20000) taken in 1988, before the earthquake, and aerial photographs (1:6000) taken shortly after, in 1992. Because neither set of photographs contains targets with known ground control, it will be necessary to establish control in the field on points that can be identified in both sets of photographs. The points will be surveyed precisely using a Total Station surveying instrument. Coordinates in both deformed and nondeformed ground will then be measured using an analytical stereoplotter, available for use at the U.S. Geological Survey in Denver, Colorado. On the 1:20000 aerial photographs, the limits of measurements for position is plus or minus 10 cm on the ground; we commonly observed amounts of displacement from 2 to 40 times this large across many of the breaks.

[Note: We did use the photogrammetric method in the area of Tortoise Hill ridge, along the Emerson fault zone. We obtained spectacular results, on distribution of shearing across a rupture zone and distribution of horizontal and vertical differential displacements within a ridge (papers 4 and 5). We used 1:6000 photos taken before and after the earthquake, and control points surveyed before and after the earthquake. In this way we were able to determine strains and differential vertical displacements across Tortoise Hill ridge, along the Emerson fault zone.]

Fourth Research Problem

As we were surveying control points for a detailed map of the shear zones in a field area on the Emerson Fault zone, we discovered an interesting complication. We found a belt of tension cracks, about 50 or 60 m wide, trending N20 to 30E and extending NE toward the Camp Rock fault zone. The fractures appear to be an expression of the deformation in the transfer zone, between the segments of the Emerson and Camp Rock fault zones that ruptured during the earthquake. The orientation of the tension cracks within the transfer zone have a distinctly different orientation than those cracks within the broad shear zone along the Emerson fault. The tension cracks within the broad shear zone are typically oriented 30° clockwise to the walls of the broad shear zone, whereas those within the transfer zone are typically oriented 60 to 70° clockwise to the walls of the broad shear zone.

As part of the proposed research, we intend to map, in detail, the zone of tension cracks between the Camp Rock and Emerson faults, and to perform the theoretical analysis that will explain how the stress state can differ within the shear zone and between the shear zones. Evidence of a marked change in stress state over relatively–short horizontal distances appears to support our interpretation of the tension cracks within the broad shear zones as a result of shearing and dilation within a zone of *localized* shearing, a shear zone about 60 m wide on the Emerson fault and about 160 m wide on the Homestead Valley fault. If the shearing and dilation are localized, the stresses generated in the near–surface materials would also be localized. In contrast, the stresses responsible for the fractures within the transfer zone would result from interaction between two relatively–widely–spaced fault zones, in this case, interacting across the valley.

[Note: The mapping proposed could not be done. The preservation of the fractures was extremely poor, so by the time we returned to this area to do the detailed mapping, the fractures could not be found. However, measurements of lateral offsets across the rupture zone show that the tension cracks accommodated at least one m of offset, that is, transferred at least 1 m of offset from the Emerson fault zone to the Camp Rock fault zone (or vice versa). Further, leveling of control points in the study of Tortoise Hill ridge indicates that the pullapart basin, of which the tension cracks are part, dropped at least 0.3 m relative to a point about 5 km south of the ridge. Thus the band of tension cracks turned out to be as interesting as we thought they would, and we were fortunate to have mapped them immediately after the earthquake while they remained preserved.]

Fifth Research Question

One of the difficulties in interpreting en echelon fractures is that fault segments arranged en echelon can superficially resemble similarly–arranged tension cracks. Faults that have partially broken through to the ground surface are often expressed as fault segments, arranged en echelon. According to our experience, en echelon tension cracks tend to form at 45±15°, and en echelon fault segments at 15±10° to the walls of the shear zone.

While we have no theoretical basis for explaining the orientation of en echelon fault segments, we do have all the theoretical equipment required for doing so. One part of the proposed research is to investigate the orientations of echelon fault segments and shear–zone segments, and to compare and contrast these orientations with those of tension cracks. Thus, we can determine conditions of these related, but quite different, types of en echelon fractures. Preliminary analysis indicates that the angle between the fault segments and the walls of the shear zone should reflect the orientation of the principal stresses, in addition to the dilatancy of the faulting ground.

[Note: We have completed mapping of three areas where the fault segments are arranged en echelon. These results are described in paper 8, "Analecta.....". In one area, along the Homestead Valley fault zone, the en echelon faults are the short, connecting faults of a releasing duplex structure. In two other areas, within the Kickapoo fault zone, there are en echelon fault segments. In the Charles area there are at least 4 levels of en echelon faults, at different scales, suggesting a fractal relationship. We do not yet, however, understand these observations.]

Sixth Research Problem

Part of the proposed research is to document the patterns of fracturing ground deformation within, and adjacent to the Kickapoo stepover, in as much detail as is available. Within a belt of en echelon shear zones, the shift is transferred from one segment to another. We propose to use the photogrammetric method to determine the relative displacements in the vicinity of en echelon segments of shear zones that we map in the Kickapoo stepover.

During our preliminary field study of the Kickapoo stepover, we noted that the clockwise angle between the segments and the overall trend of the Kickapoo stepover is small, about 10°, in the south, increasing to perhaps 30° in the north, near where it joins the Homestead Valley fault zone. We noted that the vertical offsets accommodated by the shear zones is very small in the south, and that they increase to perhaps 1 m in the north. Through detailed mapping, we can document such a relationship.

[The note above applies here as well.]

By investigating these six problems, we should contribute significantly to the knowledge of rupture zones of major earthquakes and the deformation that occurs in the vicinity of faults as they rupture during an earthquake. We should also be able to contribute to the methodology of studying and deciphering the patterns of fractures associated with earthquake ruptures. We will add to the understanding of shear zones, the formation of broad bands of tension cracks, and the formation of en echelon shear zones and faults; all of these structures are commonly observed within rupture zones of earthquake faults, but no one has yet explained their formation.

Other Research Questions

It is inevitable, it seems, that some research questions one proposes to investigate turn out to be uninteresting, or inadequately displayed in the study area, or too difficult to address, and new, unanticipated, research questions and opportunities present themselves in the course of the investigation. Such is the case with the present research. Our research at Landers is no exception. We describe many of these problems in paper 8, our U.S.G.S. Open–file Report entitled "Analecta of structures....." Our second session of mapping uncovered very nice rifts at the intersections of the Kickapoo fault zone with the Johnson Valley and Homestead Valley fault zones, where two right–lateral belts of shearing cross. The rift appears to be a result of the intersection of belts of shearing. They provide further examples of the causative conditions of rifting identified on a theoretical basis in paper 1. Also, as indicated above, one of our most exciting results is the documentation of an active tectonic ridge on the Emerson fault zone. We did not recognize the ridge at the time of the proposal to DOE nor did we know of the land survey that had been done prior to the earthquake. It was the resurvey of the monuments set during the first survey that provided the first quantitative analysis of growth of a tectonic ridge during an earthquake, a phenomenon that had been long suspected, but never documented.

PRODUCTS OF THE RESEARCH

The following papers and manuscripts are entirely or in part based on research supported by the DOE grant. Copies of the papers and manuscripts are in following pages.

General

1. Johnson, A.M., 1995. Orientations of faults determined by premonitory shear zones. Tectonophysics, 247:161,238.

Loma Prieta, California Earthquake of 1989

2. Johnson, A.M., and R.W. Fleming, 1993. Formation of left,lateral fractures within the Summit Ridge shear zone, 1989 Loma Prieta, California, earthquake. Journal of Geophysical Research, 98:21823,21837.
3. Martosudarmo, S.Y., Johnson, A.M., and Fleming, R.W., 1996. Ground fracturing on the southern end of Summit Ridge caused by the October 17, 1989 Loma Prieta, California earthquake. U.S.G.S. Open,file Report 96,xxx, 47 p., 5 plates.

Landers, California Earthquake of 1992

4. Fleming, R.W., A.M., Johnson and J. Messerich, 1996. Growth of a Tectonic Ridge. U.S. Geological Survey, Open,file Report 96,xxxx, 48 p., 5 plates.
5. Fleming, R.W., and Johnson, A.M., 1996. Growth of a tectonic ridge during the Landers earthquake. Submitted to Geology. 4 p.
6. Johnson, A.M., R.W. Fleming, and K.C. Cruikshank. 1993. Broad Belts of Shear Zones as the Common Form of Surface Rupture Produced by the 28 June 1992 Landers, California, earthquake. U.S. Geological Survey, Open File Report 93,348, 61 p.
7. Johnson, A.M., Fleming, R.W., and Cruikshank, K.M., 1994. Broad belts of right,lateral surface rupture along simple segments of fault zones that slipped during the 28 June 1992 Landers, California, earthquake. Bull. Seismological Society of America, 84:499,510.
8. Johnson, A.M., Fleming, R.W., Martosudarmo, S.Y., Johnson, N.A., Johnson, K.M., and Wei, W. 1996. Analecta of structures formed along strike,slip fault zones during 28 JUNE 1992 Landers, California earthquake sequence. U.S.G.S. Open,file Report 96,xxx, 45 p, 12 plates.
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10. Cruikshank, K.M., Johnson, A.M., Fleming, R.W., and Jones, R., 1996. Winnetka deformation zone,,Surface expression of coactive slip on a blind fault during the Northridge earthquake sequence, California. U.S.G.S. Open,file Report 96,xxx, 38 p., 4 plates.

11. Johnson, A.M., Fleming, R.W., and Cruikshank, K.M., 1996. Coactive slip on blind faults in San Fernando Valley, California during Northridge earthquake sequence. To be submitted to Geology (or BSSA), 4 p.
12. Johnson, A.M., Fleming, R.W., Cruikshank, K.M., and Packard, R.F., 1996. Coactive fault of the Northridge earthquake„Granada Hills area, California. U.S.G.S. Open,file Report 96, 523, 95 p., 3 plates.