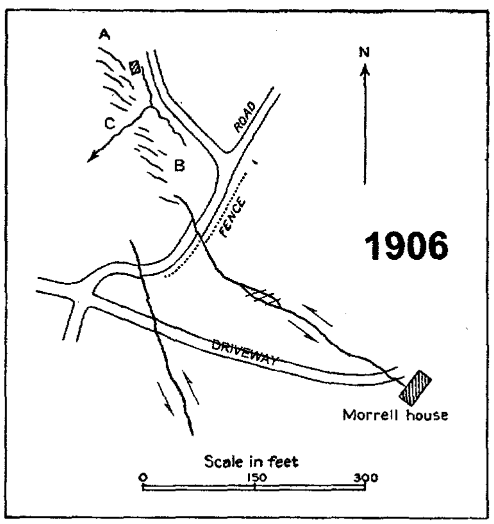
Ground Fracturing at the Southern End of Summit Ridge Caused by October 17, 1989 Loma Prieta, California, Earthquake Sequence

(Maps of Summit Ridge Shear Zones, en echelon tension cracks, complex and compound fractures, and small faults that formed coactively with the earthquake sequence)

Sumaryanto Y. Martosudarmo **Arvid M. Johnson** **Robert W. Fleming**



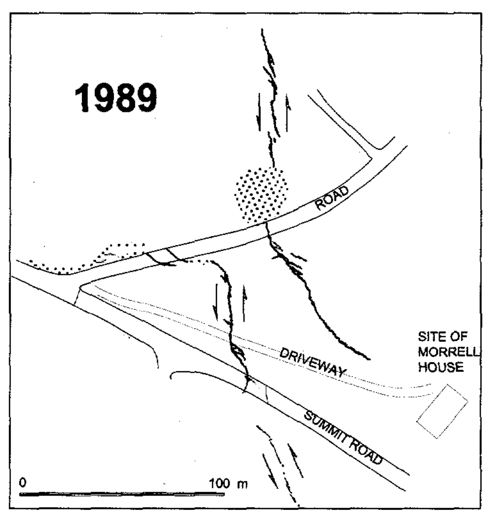


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Table of Contents

List of Figures

List of Plates

Abstract

The Loma Prieta earthquake of 17 October 1989 was the first of three large earthquakes that occurred in California in less than 5 years. The main shock of the Loma Prieta earthquake was deep–seated, the rupture zones of the main shock did not reach the surface, and the earthquake produced enigmatic surface ruptures along the frontal faults of the Coast Range and in the epicentral area that were explained in several quite different ways. The Landers earthquake of 28 June 1992 was near surface and produced more than 80 km of spectacular surface rupture of many different kinematic expressions. Detailed study of fractures at Landers has provided a basis for re–evaluating our earlier work on fractures produced by the Loma Prieta earthquake. This paper is a description of some of the fractures produced by the Loma Prieta earthquake and a discussion of their causes.

Detailed mapping (scale of 1:250) in an area on either side of Summit Road and between Morrell Cutoff Road in the northwest and the intersection of Summit Road and San Jose–Soquel Road in the southeast has provided documentation of fracture orientations and differential displacements required to decipher the ground deformation in that area during the Loma Prieta earthquake. (end)

The fracture ... end of Summit Ridge appear to be the result of two or three different mechanisms. Fracturing due to strong differential response to ground shaking and perhaps landsliding are responsible for the local, arcuate fracture zones and grabens with no or minimal lateral shearing. Deep–seated shearing across a broad, vertical belt is responsible for the Summit Ridge shear zone of tension–cracks/ left–lateral fractures all along the ridge (Johnson and Fleming, 1993). These fractures all have extremely irregular surface traces and rough faces, characteristic of tension cracks in soil. Most of them subsequently accommodated some left–lateral shearing as well as opening, and most are upthrown on their southwest sides. If the fractures had formed as strike-slip faults, shearing in a left–lateral sense, and subsequently opening in tension, the fracture surfaces would be smooth and striated. Instead, they started as tension cracks and sheared in a left–lateral sense as the blocks they bounded were rotated within the broad, right–lateral, Summit Ridge shear zone.

Some of the fracture zones within the Summit Ridge shear zone are *compound*, meaning that the kinematic expression of the fracture changes as the strike of the fracture changes. A part of a curved fracture oriented N65∞W might show pure extensile opening. As the fracture curves to a more northerly strike, it contains a component of left-lateral shear, and as it turns more westerly contains a component of right-lateral shear. The differential displacement across these fractures indicates, however, that overall they accommodated dilation in a direction of N20°- 30°E.

Many other fractures in the Summit Ridge area are *complex*. That is, they accommodated different modes of deformation during their formation. They first opened approximately in the direction N30-40°E in response to extension, and they subsequently sheared in a left–lateral sense (and perhaps opened further) in a direction of about N40°W. These differential displacements are consistent with right–lateral shearing across a broad belt oriented N70°-80°W. Additionally, the southwest side of the fractures were upthrown, producing a deformation consistent with the inferred focal mechanism of the earthquake.

We interpret the fractures and their kinematics as follows: Whereas the San Andreas fault zone southeast and northwest of the Summit Ridge area is oriented about N40°-45°W, the Summit Ridge shear zone is oriented about N60°-70°W, and juts forth nearly 3 km from the southwest side of the San Andreas fault zone. The Sargent fault zone juts forth from the northeast side of the San Andreas with about the same orientation (N70°W) as the Summit Ridge shear zone. Thus, the left–lateral fractures on Summit Ridge, with orientations of about N45°W and parallel to the overall trend of the San Andreas fault zone, appear to be related to right–lateral shearing

along the deep-seated Summit Ridge shear zone. We suggest that there is another broad shear zone to the southeast, the Skyland Ridge shear zone, which accounts for a broad zone of fracturing similar to that at Summit Ridge, and oriented N70°W, but underlying Skyland Ridge.

Finally, we suggest that the Summit Ridge and Skyland Ridge shear zones, the right-lateral ruptures documented by Aydin and others (1992) on the Sargent fault zone, and the range-front thrusting documented by Haugerud and Ellen (1990) all represent deformation on faults that were coactive with the Loma Prieta earthquake sequence, just as happened in the area of the January 1994 Northridge, California, earthquake (Johnson and others, 1996b).

Introduction

The Loma Prieta earthquake, M 7.1, of October 17, 1989, was the first of three large earthquakes that occurred in California in less than 5 years. It was centered in the general area between San Jose and Santa Cruz in northern California (fig. 1) and caused widespread damage from San Francisco and Oakland on the north to Watsonville on the south.

The Loma Prieta earthquake was followed by the Landers earthquake, M 7.5, on June 28, 1992, that occurred in the Mojave desert in southern California between Palm Springs and Barstow. Finally, the Northridge earthquake, M 6.7, on January 17, 1994, occurred in the San Fernando Valley about 30 km north of downtown Los Angeles. The main rupture at the Loma Prieta earthquake was a blind, reverse/right-lateral strike-slip fault. That at the Northridge earthquake was a blind, reverse fault. That at the Landers earthquake was on at least five strike-slip faults that produced more than 80 km of right-lateral surface rupture.

At Northridge, in the San Fernando Valley, there are several belts of enigmatic ground fracturing that are not located in the correct places and lacked appropriate kinematic expression for the thrust-fault mechanism that produced the main earthquake shock. The belts of fracturing contain parallel bands of extension represented by small grabens and of compression represented by buckled sidewalks and thrusts in paved streets that may well be surface expressions of blind reverse faults (Johnson and others, 1997a). The main Northridge earthquake apparently occurred on a south-dipping thrust fault; the belts of extension and compression apparently reflect reverse faults that are antithetic to the earthquake fault.

The Loma Prieta earthquake, likewise, did not produce a throughgoing right-lateral, reverse rupture that could be readily ascribed to the earthquake focal mechanism of the main shock. Instead, a complex pattern of fracturing occurred in Summit Ridge and Skyland Ridge near the epicentral area as well as surface fracturing many kilometers away in Los Gatos, Los Altos Hills, and other places (fig. 2). Preliminary observations of the confusing rupture pattern were described in an early report (Plafker and Galloway, 1989).

The three major earthquakes produced remarkably different patterns of surface deformation, and for both the Loma Prieta and Northridge earthquakes, one could reasonably question whether the observed rupturing was produced by transient strains from strong shaking, ground failure from landsliding and liquefaction, or permanent "tectonic[1]" deformation. It was the spectacular surface rupture at Landers that provided the insights and models required to interpret the surface ruptures at Loma Prieta (Johnson and others, 1997). Here, we document our observations of the surface rupture in the Summit Ridge area (fig. 3) and our interpretation of the origin of the fractures. We also present our methodology, which is based on understanding of fracture mechanics and the kinematics of displacement and strain, and which we largely developed in analyzing structures associated with strike–slip faults that formed within the Aspen Grove landslide in Utah (Fleming and Johnson, 1989).

[1]The use of the term tectonic here follows tradition, although it is somewhat disturbing. What we mean by tectonic fracturing is fracturing at the ground surface produced by differential displacement on faults and shear zones at depth. Since we cannot see the faults or shear zones, the term is necessarily used interpretively. "Tectonic" fracturing is commonly contrasted with "landslide" fracturing.

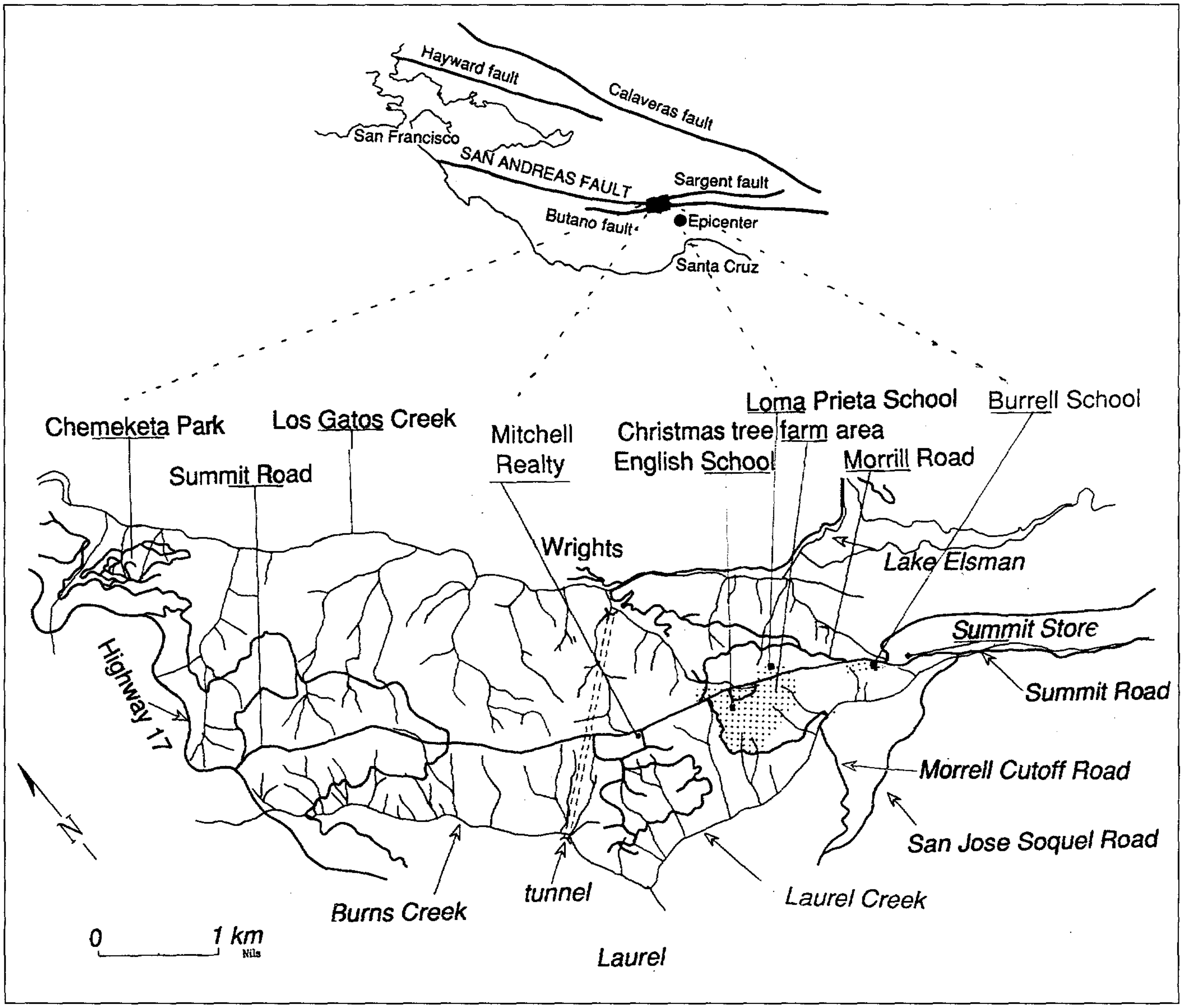


Figure 1. Epicenter of Loma Prieta earthquake, location and shape of Summit Ridge, and geographic features cited in the text. (After Johnson and Fleming, 1993).

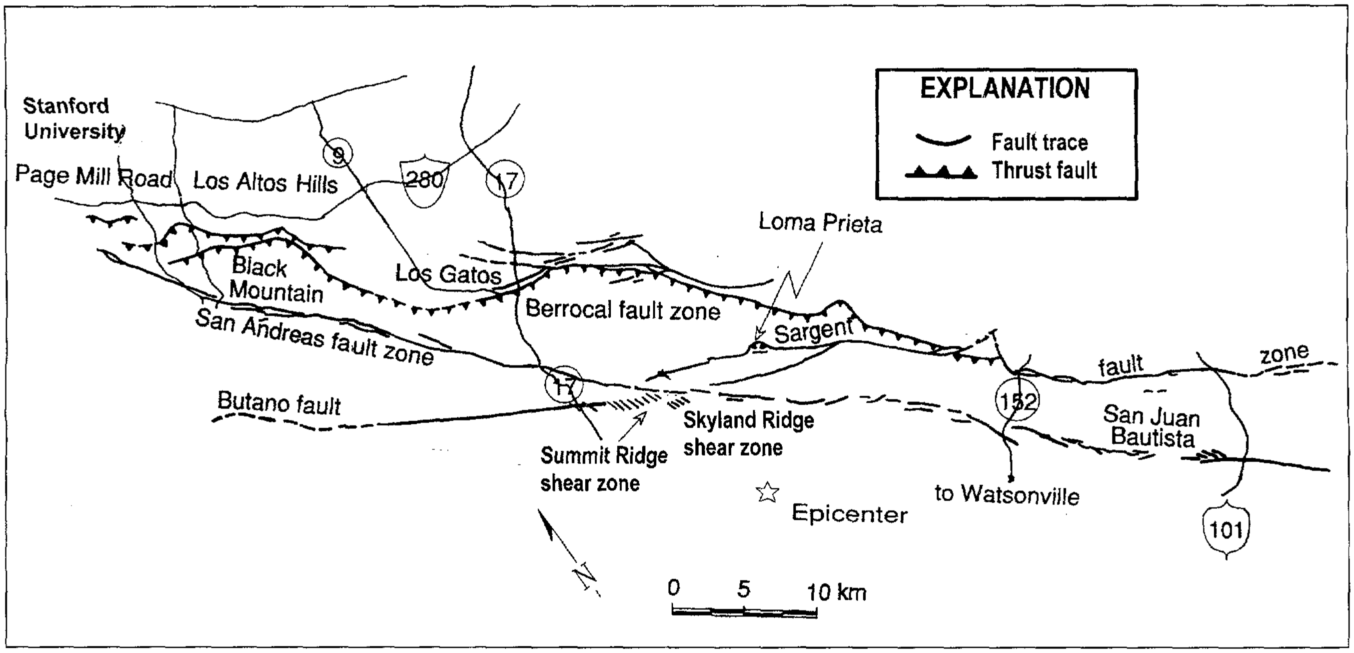


Figure 2. Major faults of the Loma Prieta area, including the Summit Ridge shear zone, along the segment of the San Andreas fault zone between Stanford University and San Juan Bautista. During the 1989 Loma Prieta earthquake there was ground rupture along the San Andreas and Sargent fault zones between Highway 17 and Lake Elsman, and locally along the Berrocal/Black Mountain fault zone between Los Gatos and Los Altos Hills (After McLaughlin, 1974, fig. 1).

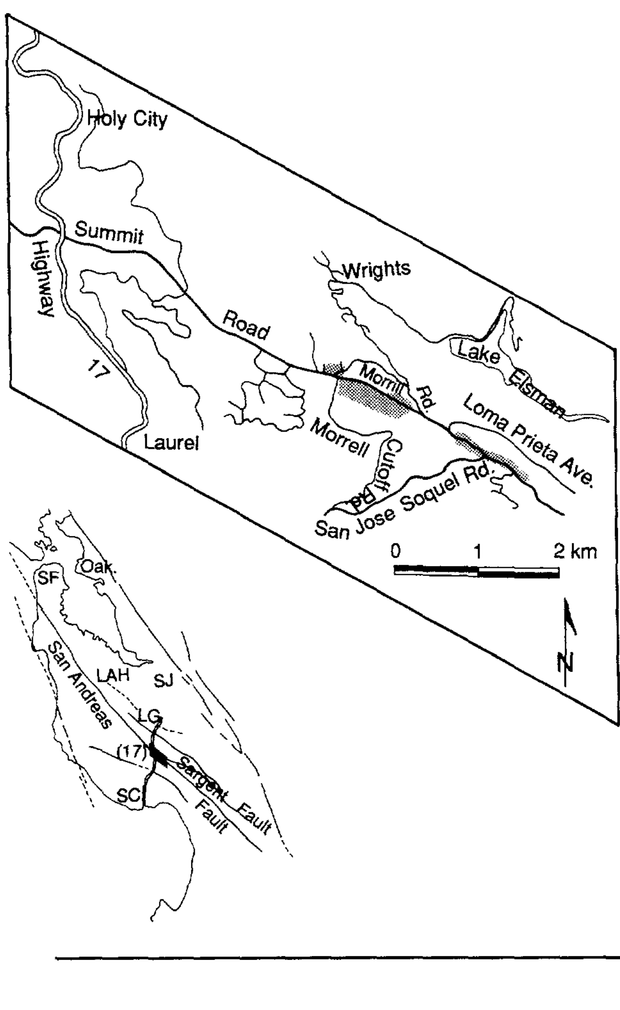


Figure 3. Areas of detailed maps along southern end of Summit Ridge.

Acknowledgments

We thank Atilla Aydin, Stanford University for help with mapping and discussion during the research. Kenneth M. Cruikshank, Portland State University, and Kamil Kayabali, Purdue University, helped with mapping of the topography. The research was supported by NSF Grant EAR–9003678. Fleming's support was from the Nuclear Regulatory Commission. We wish to recognize the reviewers of an early draft of the manuscript, Ed Harp, Dave Keefer, Ray Wells, Carol Prentice, Mike Cleary and Dan Ponti. Ed Harp provided a careful review of the current form of the manuscript. The criticisms have markedly improved the presentation. We thank Jim Gardner for editing the manuscript. Margo Johnson, USGS, Denver, did final layout and formatting.

Background

The ground rupturing from the 1989–Loma Prieta earthquake (fig. 1) produced no single, throughgoing right–lateral / reverse surface rupture along the San Andreas fault zone above the surface of the main fault as defined by the mainshock and aftershocks. Rather, surface fractures with variable kinematic expression were distributed through a broad zone on either side of Summit Road (fig. 1), from Highway 17 in the west to an area near the San Jose–Soquel Road, and Skyland Ridge (Plafker and Galloway, 1989, fig. 9). In addition, there were short segments of right–lateral rupture along the trace of the Sargent fault zone (Aydin and others, 1992). Zones of buckling and shortening of streets, sidewalks, curbs, and other stiff deformation indicators formed in the vicinity of mapped reverse faults from Los Gatos to Stanford University (fig. 2) (Haugerud and Ellen, 1990; Aydin and others, 1992).

Ground fractures along Summit Ridge have been genetically classified as fractures related to landslides or related to tectonism (Plafker and Galloway, 1989, fig. 9; Spittler and Harp, 1990; U.S. Geological Survey Staff, 1990). In general, fractures interpreted to be related to landsliding form broad arcuate traces whereas fractures interpreted to be related to tectonism have relatively straight traces.

Some investigators have proposed that the relatively straight fractures were caused by intense seismic shaking, or by "bending–moment" faulting, that is, fracturing due to stretching of the ground surface, or by slip along bedding planes, or by hilltop spreading (e.g., Cotton, 1990; Cotton and others, 1990; Ponti and Wells, 1991; Prentice and Schwartz, 1991). Some investigators have interpreted the arcuate fractures on hillsides to be results of landsliding (e.g., Spittler and Harp, 1990; Harp, 1990; Ponti and Wells, 1991). In some areas, cracks associated with well–defined, thick landslides opened as large fissures several tens of centimeters wide during the earthquake and cut through houses and roads (Plafker and Galloway, 1989; Spittler and Harp, 1990; Martosudarmo, 1991). Aydin and others (1992), through a program of detailed mapping, recognized three kinds of fractures in the Summit Ridge area: (1) arcuate fractures assumed to be associated with landslides, (2) relatively straight fractures generally open with left–lateral offsets along Summit Ridge, and (3) fractures with right–lateral / southwest–side–up offsets along strands within the San Andreas and Sargent fault zones. Like other investigators (e.g., Plafker and Galloway, 1989; Ponti and Wells, 1991; Spittler and Harp, 1991), Aydin and others associated arcuate fissures with landslide masses, or parts of landslide masses, that moved as a result of ground motions during the earthquake. They suggested, as had other investigators, that the left–lateral fractures all along Summit Ridge were tectonic in origin, but they were uncertain about how the slip on the left–lateral fractures could be related to the earthquake.

The definitive work of Aydin and others (1992) documented that strands of the San Andreas fault zone near Chemeketa Park (fig. 1) and near the south end of Summit Ridge (Plate 1) slipped in a right–lateral / reverse sense on the order of 10 cm. Also, strands of the Sargent fault zone at Lake Elsman (fig. 2), slipped in a right–lateral / reverse sense, with a magnitude of 10 to 20 cm. Thus they interpreted some of the right–lateral fractures to be the surface expression of coseismic, right–lateral, surface slip in the San Andreas and Sargent fault zones connected with the deep rupture zone that produced the main shock. The right–lateral slip, however, is an order of magnitude smaller than the 1.9 m of right–lateral and 1.3 m of reverse slip computed for the main shock at the hypocenter of the earthquake (U.S. Geological Survey Staff, 1990).

We now recognize that the connection between right–lateral slip on strands of the San Andreas and Sargent faults and the main shock of the Loma Prieta earthquake is unlikely because there is no independent evidence that slip propagated to the ground surface. Furthermore, slip occurred on faults well outside the San Andreas fault zone that cannot be attributed to slippage on the rupture that produced the main shock. For example, Haugerud and Ellen (1990) documented slip on strands of thrust faults within the Berrocal fault zone and nearby thrust faults in Los Gatos and near the intersection of Page Mill Road and Interstate 280 in Los Altos Hills (fig. 1). In retrospect, after our research in Northridge, we recognize the evidence throughout the Loma Prieta area for coactive faulting, i.e. slip on faults disconnected from the fault that produces the main shock.

In this paper we focus on the left–lateral fractures and to a lesser extent on the arcuate fractures that have been ascribed to landsliding. Our emphasis is on mapping the morphologies and describing the kinematics of the fractures. We interpret the fractures based on well–established concepts of brittle fracture mechanics (Lawn and Wilshaw, 1975; Cotterell and Rice, 1980; Segall and Pollard, 1983a, 1983b; Cruikshank and others, 1991b). Besides the theory, our research depends on the method of *analytical mapping*[2] of structures. In analytical mapping of fractures, one selects the scale of mapping so that the crucial information required to interpret the fractures is shown on the map. At Summit Ridge we used an alidade and plane table, and the point–reoccupation method, to plot character points and sketch shapes and patterns of fractures and fracture zones at a scale of 1:250.

We mapped the topography, geology and fractures of the study area (fig. 5) several months after the earthquake, during January, February and between late May and the middle of June 1990. We selected two areas of Summit Ridge for analytical mapping because the fractures there were relatively well preserved (and remained so even 6 months after the earthquake). Also, the areas contained excellent examples of associations between fractures and topographic sags and troughs that occur all along Summit Ridge and indicate previous episodes of deformation. One area is termed the Christmas tree farm area, which includes the C.T. English School site and both sides of Summit Road between Morrill Road to the NW and Loma Prieta School to the southeast. The other is a smaller area along Summit Road and northwest of Burrell School (fig. 2). As

[2]*Analytical mapping of fractures is detailed mapping to permit direct kinematic interpretation of the fractures.* In post-earthquake investigations of surface rupture, we have found that a scale of about 1:250 was the smallest that would permit accurate depiction of fracture details where they were well expressed. In general, the scale of the analytical map is *determined by the scale of problem, so it is quite different if* one is studying the formation of the San Andreas fault zone as a plate boundary than it is if one is studying the mechanics of fracturing of ground along a strand of the San Andreas fault or one is studying microcracks in mineral grains in granite.

shown in the cover of this report, the Christmas tree farm area includes two large fractures along Morrill Road that broke in 1906 and again in 1989 (Lawson, 1908; Prentice and Schwartz, 1991). It also contains the head of one of the largest landslide masses in the area, the Morrell Cutoff landslide (Harp, 1990). The study areas also include the place where, according to Johnson and Fleming (1993), the Summit Ridge shear zone meets the main trace of the San Andreas fault, near Burrell School (Plate 1).

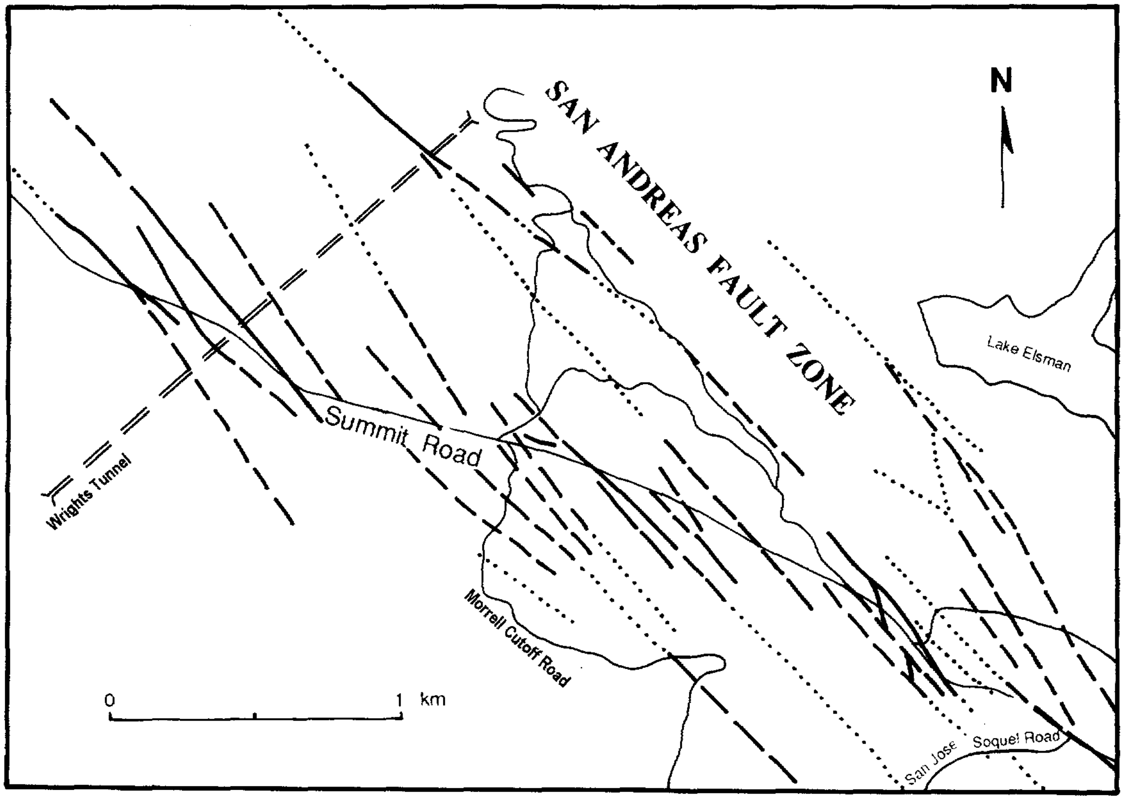


Figure 4. Lineaments and fault traces in Summit Ridge area (based on maps by Sarna-Wojcicki and others, 1975; McLaughlin, 1974; Dibblee and Brabb, 1978; Brabb, 1989; Clark and others, 1989).

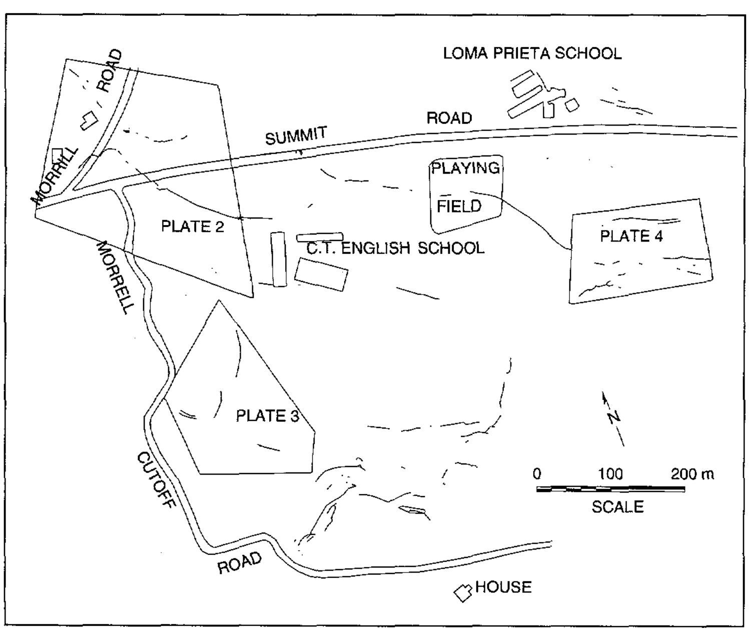


Figure 5. Locations of detailed, analytical maps in Christmas tree farm area of Summit Ridge.

Geologic Setting

The Summit Ridge area, depicted by a network of stream valleys in figure 1, is underlain by deformed and variably consolidated bedrock, mainly the Butano Sandstone (fig. 6) (Brabb, 1989; Clark and others, 1989). In the northwest part of the ridge, the Butano fault separates the Butano Sandstone (Eocene) from the Vaqueros Sandstone (Lower Miocene). Hall and others (1974), in a study of fault hazards in Santa Cruz County, stated that the history of Butano fault activity is largely unknown. Ponti and Wells (1991, plate 2) show left–lateral fault separation on two faults offsetting the Butano fault in the Christmas tree farm area and about 0.5 km to the west along Summit Road (fig. 6).

The flanks of Summit Ridge are largely covered by landslide deposits, only partly shown in figure 6. Within the Christmas tree farm area, bedrock is covered by man–made fill, slopewash and landslide deposits. Only a small part of the area contains exposures of weathered bedrock.

Along the crest of Summit Ridge in the vicinity of the Christmas tree farm there are linear traces of parallel troughs and ridges trending N32∞W to N42∞W that are shown well on aerial photographs taken in 1939 and 1989. Presumably the linear traces reflect faults in the area, but the faults were nowhere observed in bedrock. These traces were mapped by Sarna–Wojcicki and others (1975) all along Summit Ridge. More than a decade before the Loma Prieta earthquake, Sarna–Wojcicki and others (1975) made a detailed study of the San Andreas fault zone from Page Mill Road in the north to 15 km south of San Juan Bautista in the south (fig. 2) to show locations of historic breaks and other lineaments and features interpreted to be a result of Holocene faulting within the fault zone. They report that fault–related structures in the area between Chemeketa Park and Wrights (fig. 1) are masked by vegetation and massive landslides (fig. 6), but that active faulting appears to splay out to a zone as wide as 1.6 km in some places. Furthermore, during the 1906 earthquake, movement occurred over a zone about 1.5 km wide at the Wrights/Laurel tunnel (fig. 1), and the overall shearing included about 1.5 m of right–lateral offset near the eastern portal of the tunnel. Sarna-Wojcicki and others (1975) conclude

> "...this evidence indicates that movement on the fault was not necessarily restricted to a single plane of fracture but took place within a wide zone of deformation. Indeed, evidence from aerial photographs and from ground inspection indicates that [near Wrights and for about 2 km south of Wrights] no single, continuous, through–going fault line can be seen; instead, this section is traversed by a number of *en echelon* lineaments trending at a low angle to the trend of the fault zone. This style of deformation first becomes visible in [Summit Ridge] about 2 km west of Wrights..."

Immediately southwest and northwest of the Summit Ridge area, the San Andreas fault zone has a general trend of about N45°W. The average trend of the features mapped as fault strands by Sarna–Wojcicki and others (1975) in the Summit Ridge area is about the same (fig. 7).

Hall and others (1974) recognized a zone of multiple subparallel lineaments 400 to 1200 m wide, near Redwood Estates, northwest of Highway 17, and related it to the Butano fault. They suggested that the Sargent and Butano faults are both related to the San Andreas fault:

> "The San Andreas Fault zone becomes very wide north of Skyland Ridge where the Butano fault merges with it from the northwest and Sargent fault merges with it from the southeast. The Butano and Sargent faults appear to have a symmetrical relation to the San Andreas and consequently might have similar histories and seismic potential."

Johnson and Fleming (1993) suggest a similar model of faulting in the Summit Ridge area. The active strands within the San Andreas fault zone

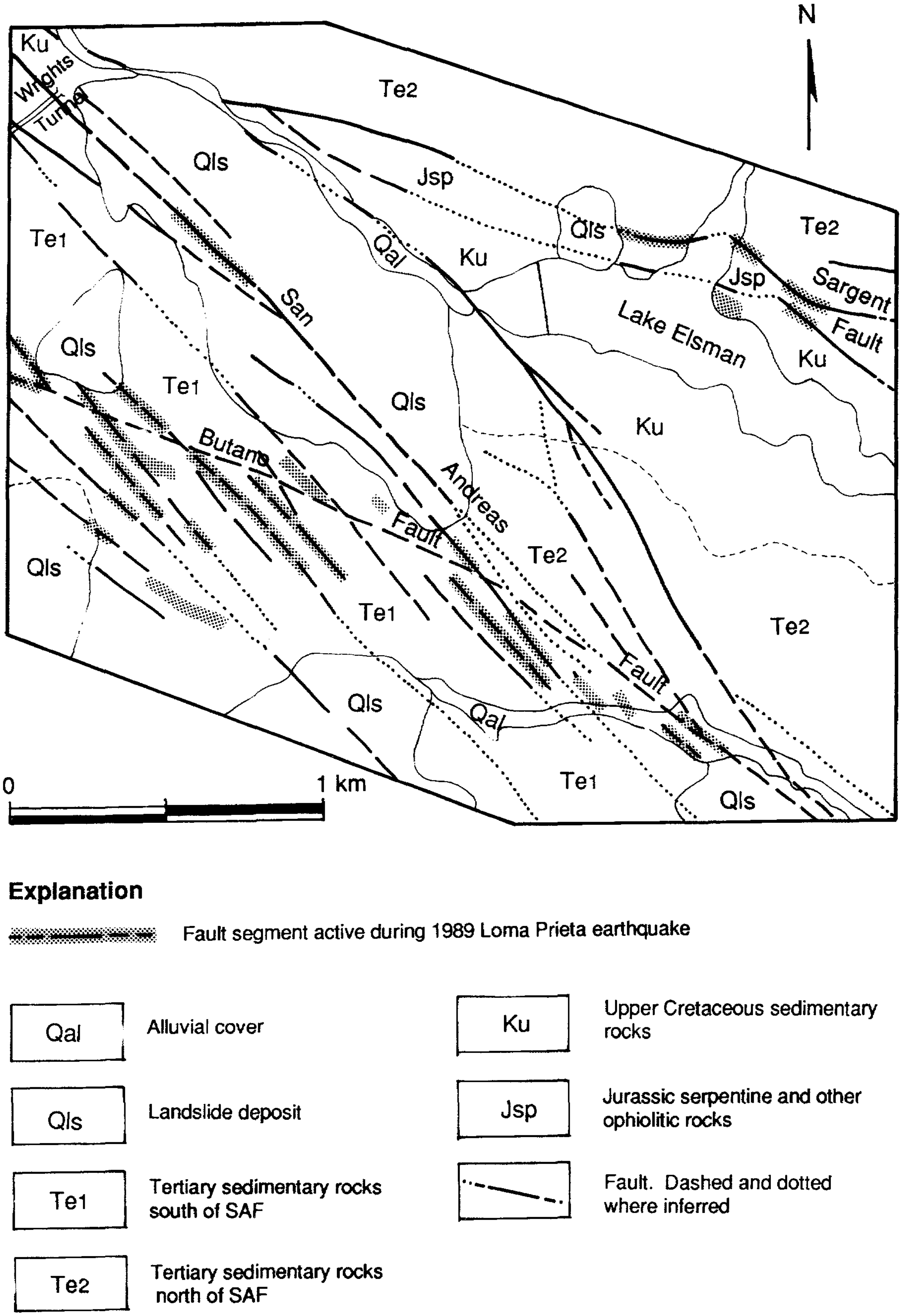
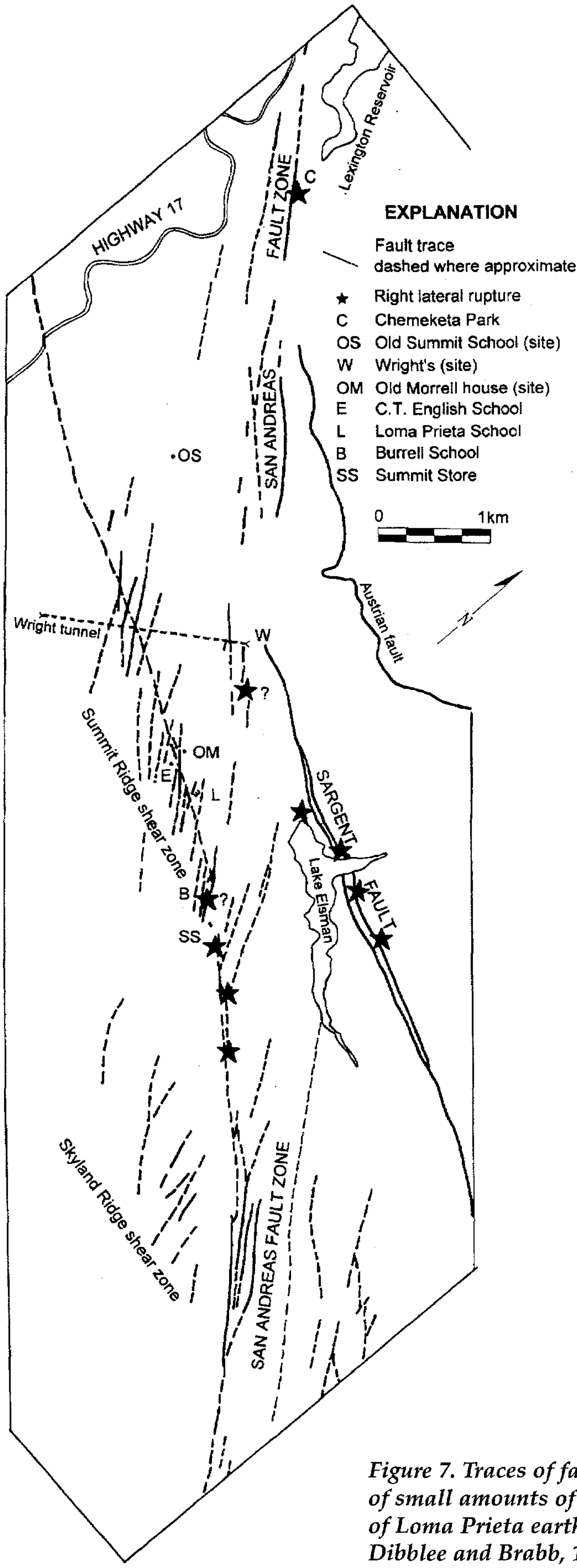
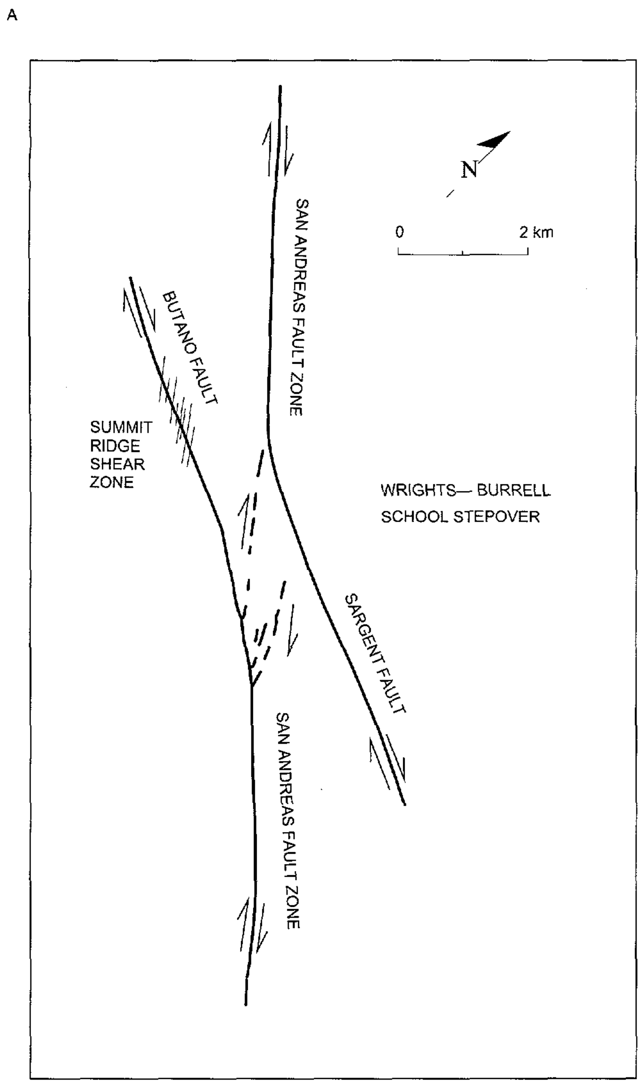


Figure 6. Structural setting of the southern part of Summit Ridge (After Clark, Brabb and McLaughlin, 1989; Dibblee and Brabb, 1978; and Ponti and Wells, 1991, Plate 2).



near Summit Ridge appear to consist of two, right–stepping segments. The segment to the northwest enters the area as a relatively simple break or set of breaks. Near Highway 17 and Lexington Reservoir, the Sargent fault zone appears parallel to this segment and veers off toward the east in the vicinity of Wrights. It has an orientation of about N70°W. (fig. 2 and fig. 7). The segment of the San Andreas fault zone to the southeast enters the area as a set of breaks and veers off toward the west near Burrell School along the Summit Ridge shear zone, essentially along the mapped trace of the Butano fault (fig. 7). According to their interpretation of the various rupture zones, the two segments of the San Andreas fault zone are connected via the Wrights/Burrell School stepover along the northeast flank of Summit Ridge (fig. 8A). They see an analogy between the Summit Ridge area and the area at Landers, California, where the right–lateral, Johnson Valley fault zone to the south connects to the right–lateral, Homestead Valley fault zone to the north through the right–lateral, Kickapoo stepover (fig. 8B).

Figure 7. Traces of faults in the vicinity of Summit Ridge, showing locations of small amounts of right-lateral slip along major faults in epicentral area of Loma Prieta earthquake. (After Clark, Brabb and McLaughlin, 1989; Dibblee and Brabb, 1978; Sarna–Wojcicki, Pampayan and Hall, 1975).



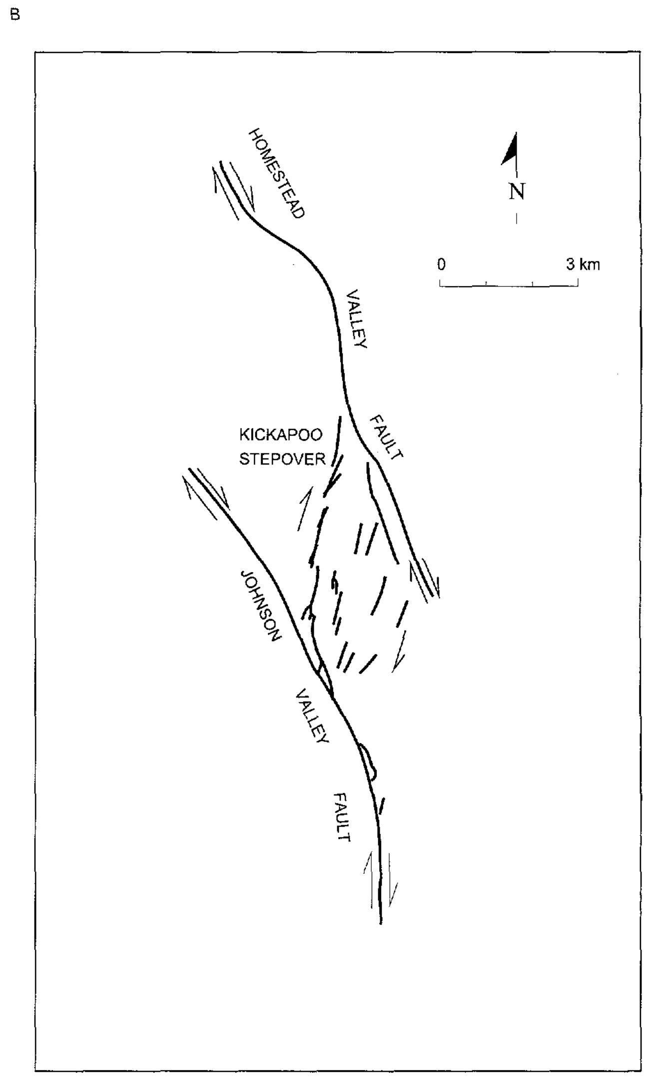


Figure 8. Similarities between the 1989 rupture elements of the San Andreas fault zone in the Summit Ridge area and the 1992 rupture elements of the Johnson Valley/Homestead Valley fault zones at Landers, in southern California.

A. A stepover along the San Andreas fault zone near Summit Ridge. San Andreas fault zone enters the area from southeast and bifurcates into traces within the Wrights/Burrell School stepover and along the Summit Ridge shear zone. The Summit Ridge shear zone is continued to the northwest by the Butano fault. The San Andreas fault zone enters the area from the northwest and bifurcates into traces within the Wrights/Burrell School stepover and along the Sargent Fault zone. The two segments of the San Andreas are thus joined via the broad, Wrights/Burrell School stepover. (Interpretation mostly due to Johnson and Fleming, 1993). All the elements are right–lateral fault zones.

B. A stepover at Landers, California. Johnson Valley fault zone enters map area from south and turns about 30° to northwest, where its slip during 1992 terminates. Homestead Valley fault zone enters area from north and the slip during 1992 terminates (fault zone continues). The two fault zones are connected via the Kickapoo stepover. All the elements are right–lateral fault zones.

Ground Fracturing Caused by the Loma Prieta Earthquake

The preceding overview of the geology, fracture patterns and interpretation provides a framework to describe the fractures produced by the Loma Prieta earthquake in the area of the southern part of Summit Ridge. Before describing the fractures, we will introduce terms and concepts that we use to classify and interpret the fractures.

The ground in the Summit Ridge area ruptured along distinct *fracture zones* during the Loma Prieta earthquake. The fracture zones occur as belts of individual fractures or cracks that have various orientations and relations to one another and that have accommodated various amounts of opening, lateral and vertical differential displacements. The fracture zones are separated by more or less unfractured ground. The trace of a fracture zone may be grossly arcuate, or it may be relatively straight, or it may consist of arcuate parts and straight parts, or it may be segmented and step laterally, *en echelon*. There are examples of all of these that were created during the Loma Prieta earthquake.

The pattern of individual fractures within a fracture zone may be diagnostic of the shearing deformation to which the ground was subjected. A simple pattern of *en echelon fractures* is one of the best indicators that the ground was subjected to lateral shearing across a fault or a shear zone at depth. Thus, if the fracture zone consists of a band of *en echelon tension cracks* (typically oriented about 45° to the walls of the zone, e.g., Pollard and others, 1982; Nicholson and Pollard, 1985; Cruikshank and others, 1991b), the fracture zone formed under conditions of lateral shearing. The angle of the *en echelon* cracks relative to the trend of the shear zone reflects the stress state at the time the cracks formed. For example, if there was tension normal to the shear zone, the angle will be less than 45° and if there was compression normal to the shear zone, the angle will be greater than 45° (Johnson and others, 1997). If the cracks step left, the fracture zone reflects right–lateral shearing and if the cracks step right, the fracture zone reflects left–lateral shearing.

Alternatively, the fracture zone may consist of *en echelon fault segments* (Gilbert, 1928; Brown and others, 1967, fig.12; Fleming and Johnson, 1989, p. 66; Cruikshank and others, 1991b) rather than tension cracks. The relations between the stepping direction and the direction of lateral shearing across the zone is the same as for *en echelon* tension cracks, so the interpretation of the sense of shearing remains straightforward (Gilbert, 1928, p. 13). The fault segments, though, generally form at a small angle, commonly 5° to 15° (e.g., Fleming and Johnson, 1989; Wallace, 1990) to the walls of the *en echelon* zone. The angle between the fault segments and the walls of the shear zone reflects the orientation of the stresses as well as the dilatancy of the faulting ground (Johnson and others, 1993, 1997; Johnson, 1995).

Where the ground is subjected solely to tension, or to a combination of tension and compression in the case of pure shear, *tension cracks* form. Tension fracturing is the most common kind of fracturing that we observed in the Summit Ridge area. Tension fracturing is reflected in highly irregular and interlocking traces of fractures and extremely rough fracture surfaces. Where there is compression as well as tension, the traces of individual tension cracks, and zones of tension cracks, should have a strong preferred orientation, parallel to the maximum compression direction (Cotterell and Rice, 1980; Cruikshank and others, 1991b).

In describing the fractures at Summit Ridge, it is important to distinguish simple fractures and complex fractures. *Complex fractures* are defined as fractures that form in one kinematic regime and stress state and then accommodate a different kind of deformation in a subsequent kinematic regime and stress state. Examples of tension cracks that subsequently accommodated oblique differential displacements were thoroughly documented in landslides in Utah (Fleming and Johnson, 1989), but examples of tensile fractures—joints—that become faults and of faults that become joints are also common (e.g., Segall and Pollard, 1983b; Zhao and Johnson, 1992).

En echelon tension cracks and faults that form as complex fractures are especially difficult to interpret and require special consideration. In a shear zone, *en echelon* fault segments originate as faults then subsequently open, at least near the ground surface (Fleming and Johnson, 1989). The surfaces of the fault segments are slickensided and striated, but the fracture is open. The sense of shear is indicated by the stepping direction of the fractures—left stepping for right–lateral shear and vice versa. In contrast, *en echelon* tension cracks start as opening–mode fractures (fig. 10) and then accommodate further opening as well as shearing (Johnson and Fleming, 1993).

At Summit Ridge, long fractures with highly irregular and interlocked traces clearly reflect a tensile origin (Johnson and others, 1993). Subsequent to opening, though, many of them accommodated left–lateral shearing as well as further opening, and are therefore excellent examples of complex fractures. Thus, complex fractures provide valuable information about the *sequence* of events. Most of the tension–cracks and left–lateral fractures that we saw at Loma Prieta are of the complex type (fig. 9A).

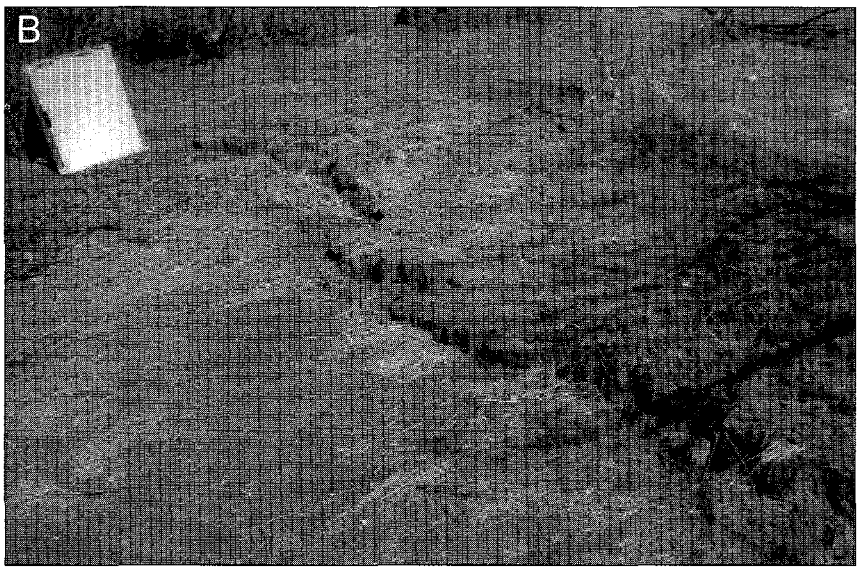
Some of the fractures in the Summit Ridge area are *compound fractures*. Compound fractures are defined as fractures that change orientation along their trend, but everywhere accomplish the same kind of differential displacement of adjacent blocks or plates of ground (Fleming and Johnson, 1989, p. 55). A compound fracture can change with change in fracture orientation from pure opening along part of its trend, to combined opening and lateral shift along a different part of its trend. The important aspect of compound fractures is that the relative displacement accommodated by the fracture is everywhere the same (Fleming and Johnson, 1989).

A familiar example of a compound fracture is the ridge–transform combination recognized in plate tectonics, where opening along a pair of offset ridges is transformed to right–lateral or left–lateral faulting connecting the offset ridges. Some other well–known examples are head scarps and flank faults of landslides, strike–slip faults and thrusts or folds, and steps that produce ramp folds along thrust faults (Fleming and Johnson, 1989). Clark (1972, p. 62) described compound fractures in several places along ruptures associated with the 1968 Borrego Peak earthquake in southern California, where he noted that the relative components of opening and lateral differential displacements across the fractures appeared to be strongly correlated with the strikes of the fractures. Wallace (in Brown and others, 1967, fig. 12) mapped compound fractures consisting of combinations of stepping fault segments and associated depressions and bulges along the trace of the San Andreas fault that ruptured at Cholame and Parkfield, California.

It is crucial to recognize compound fractures and fracture zones in the field because they must be "read" differently from simple fractures. Along a simple fracture, the fracture surface has a single attitude and the differential displacements are measured normal to the walls of the fracture. Along a compound fracture, the mode of deformation changes and so does the mechanics of the structure. A fracture, including a fault, is defined in terms of local differential displacement and the orientation of the fracture. If either change along the fracture—either the orientation or the magnitude or direction of differential displacement—then the fracture is compound. In this respect a fracture is defined similar to stress, that is, in terms of point quantities. However, as with stress, single measurements of point quantities define a field only if the field is constant. This is why a compound fracture cannot be described in terms of a spot measurement. Compound fractures must be described by a field of measurements of point quantities. Analogously, a *compound fracture zone* might be composed of individual simple fractures if the orientations or differential displacements across the component simple fractures change along the zone.

Morrell Fractures—Examples of Compound Fracture Zones

Fractures that extend from the intersection of Summit Road and Morrill Road to the northeast side of the C.T. English School provide an excellent example of a compound fracture zone. These fractures were sketched in 1906 and were mapped in 1989.



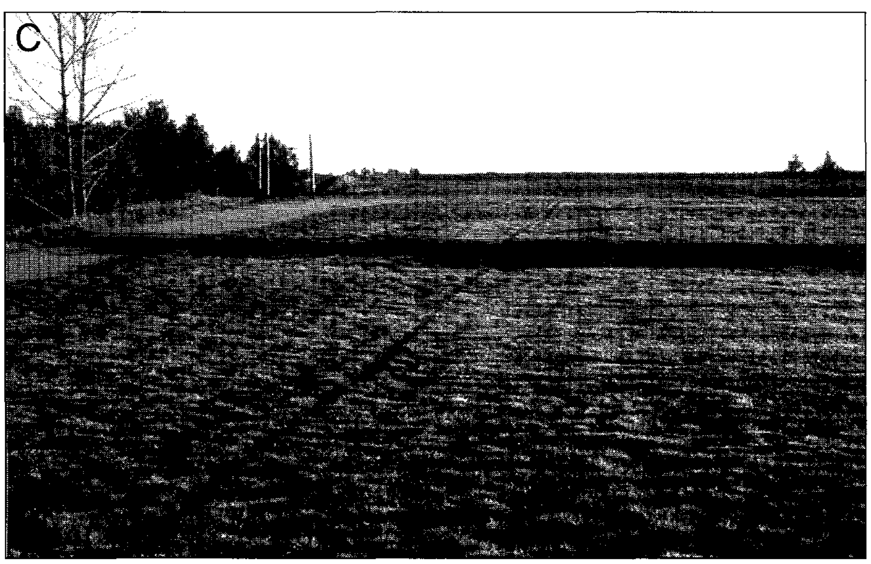


Figure 9. Examples of "tectonic" ground breakage.

A. View northwest from near site of old Morrell house across Morrill Road to house on northwest side of Morrill Road (Plate 2). Fracture zone in foreground has a zig–zag trace, indicative of tensile origin, although the fracture subsequently accommodated left–lateral shearing and downthrowing to the east (right). In the distance, the fracture zone becomes a series of crudely en echelon breaks that reflect left–lateral shearing. This fracture zone offset Morrill Road in 1989: 40 cm left–lateral, 30 cm opening, and 10 cm downthrowing (southwest-side-up). A fracture zone formed at the same place during the 1906 earthquake, but offset Morrill Road 1.1 m in left–lateral sense. Ground was opened and downthrown on northeast side in 1906 also.

B. View north-northeast of north-trending, stepping, left–lateral fractures along second fracture zone between Summit and Morrill roads (Plate 2). About 50 m southwest of fracture zone shown in A and 35 m north of Summit Road. Right–stepping en echelon cracks reflect combination of shearing and opening at the time the cracks formed.

C. View southwest in afternoon from near baseball backstop. In shadow is scarp of fracture cutting across playing fields of English School. On left is running track, offset by upthrowing of about 10 cm of ground to southwest. Fracture open generally 5 cm. Lateral offset was not visible here but is left-lateral (10 cm) about 150 m to northwest along trend of this fracture.

1906 Ruptures

Mr. G.A. Waring examined the 1906 ruptures in the Summit Ridge area (Lawson, 1908, p. 109) and described the left-lateral ruptures as follows:

> "At Patchin, 3 miles west of Wright Station, there are fissures over a foot wide trending mainly in the direct line of the fault (S. 33° E.). Several stretches of numerous small cracks alternating with a few long, continuous fissures, mark the course from Patchin to Wright Station. Thru the Morrell ranch it is especially evident. (see plate 64B)."

> "...The fault past a little west of Wright, tearing up the public road at several places (plate 65A) especially the blacksmith shop, near Burrell School-house."

The photo in plate 64B cited in the quote shows a left-lateral offset of 3.75 feet according to Reid (1910, p. 35) of a wooden fence along the southwest side of the road called "Road" in the figure on the cover of this report, and now known as Morrill Road. The photo in plate 65A shows *en-echelon* ruptures in a zone of rupture 2 to 3 m wide crossing the "Road."

H.R. Johnson (Lawson, 1908, p. 276) apparently made the map of the fractures shown on the cover of this report:

> "...The Morrell ranch is located 1 mile south of Wright's and is on the line of the fault...The house itself was built exactly on the fissure, which opened up under the house at the time of the earthquake..."

> "A feature associated with the movement of soil along the fault-line is shown in the accompanying sketch, fig. 57 [shown on cover of this report]. The 'splintering' of the main fracture raised a long, low ridge across which a creek had been forced to cut its way thru a vertical distance of 1.5 feet to get down to its original level."

The same location is described by D.S. Jordon (Lawson, 1908, p. 277):

> "At Morrell's ranch, about 4 miles above Wright's, a large 2-story house with a wing stood on the slope of a hill. The east side of the house was much higher above the ground that the west, and stood on wooden piers about 7 feet high. The earthquake crack past thru this ranch, a branch of it going under the house. The main body of the house was thrown to the east, away from the crack, the ground there slumping several feet and the house being almost totally wrecked. All thru the orchard the rows of trees are shifted about 6 feet, those on the east side being farther north, and the east side, which is downhill, seems to have fallen. The crack is largely open and in one place is filled with water. This should be attributed to slumping."

In a footnote on page 35 of his part of the report on the 1906 earthquake, Reid (1910) indicated that"Fig. 57 [shown herein on cover] is badly drawn and shows the offset in the wrong direction."

1989 Ruptures

Although the map made by H.R. Johnson in 1906 (shown on cover of report) is only a sketch, and he did show the offset of Morrill Road incorrectly, it is remarkable how similar the 1989 ruptures were to the 1906 ruptures. Not only are the traces in similar places, but details are similar. Thus, the *en echelon* fractures northwest of "Road," and the overlapping and stepping segments between "Road" and the Morrell house appear both in 1906 and 1989. This is a truly remarkable example of repetition of rupturing during subsequent earthquakes. We can only wish that more maps of ground rupture had been made following the 1906 earthquake.

Along the northeast side of the C.T. English School (Plate 1), a fracture zone consists of segmented tension cracks trending about N70°W. Traced toward the southeast, the zone turns easterly and dies out. Traced toward the northwest, the fracture zone trends about N45°W and passes through the Christmas tree farm (right–hand edge of Plate 2). Differential displacements along various segments of the zone are variable, but the right–stepping of the segments indicates some left–lateral shearing as well as tension at the time of fracturing (Plate 2 and fig. 9B). The predominant differential displacements are *mode I* or dilational (fig. 10), ranging up to 20 cm, but generally 5 cm, as well as vertical shearing, with the southwest side upthrown as much as 30 cm. The amount of left–lateral shift was quite small, probably 2 or less cm. The fracture zone crosses Summit Road in several places (fig. 11) into the open ground between Summit Road and Morrill Road, and its trace reorients to about N25°W (Plate 2). Here the left–stepping and the characteristic diamond–shaped, pull–apart openings along the fracture zone indicate stronger left–lateral shearing, but the amount is probably less than 10 cm (not measured). As the fracture zone approaches Morrill Road, the trace of the zone abruptly turns about 60° counterclockwise, and sense of shear in the fracture zone changes from left lateral to right lateral. The fracture zone was poorly preserved by the time we mapped, but could be traced intermittently trending about N80°W to Summit Road where it offset the road in a right–lateral sense in two places (Plate 2).

Thus this single fracture zone changes from a predominantly tensile zone near the C.T. English School, to a left–lateral zone near Summit Road, to a right–lateral zone along Morrill Road. The different kinematic signatures along the strike of the zone are due entirely to different fracture orientations. Similar complexities are reported by Plafker and Galloway (1989) and Ponti and Wells (1991) for fracture zones throughout Summit Ridge.

The horizontal component of the direction of relative displacement of ground to the northeast of the fracture zone was essentially constant, toward the north-northeast along the entire fracture zone at Summit Road. Thus, regardless of the trace (dips were generally nearly vertical) of the fracture zone, and regardless of what may be controlling the orientation of the fracture zone—including pre–existing faults or joints, or bedding planes—the compound fracture zone, overall, accommodated predominantly dilation in the north-northeast—south-southwest direction. Thus, the deformation produced by the fracture zone is simple. The kinematic nature of fracturing changes along its length, but the orientation of the net horizontal component of differential displacement is about constant.

Gross Pattern of Fractures

The gross pattern of fractures in the Christmas tree farm area along Summit Road is shown on the compilation of more detailed, analytical maps (Plate 1). Fracture zones are generally represented by single lines and thus are only shown schematically at this scale.

Two fracture zones are shown crossing Morrill Road in the northwest part of the map area. Both of these fracture zones are apparently reactivations of fracture zones that last formed in 1906 during the San Francisco earthquake (see cover of this report; also, Lawson, 1908, fig. 57; Reid, 1910). The zone to the east occurred near the same place as a large left–lateral, *en echelon* fracture zone accommodating about 1 m of left–lateral offset in 1906 (Lawson, 1908; Reid, 1910; Prentice and Schwartz, 1991). The southeast end of this fracture zone turns toward the east and dies out about 100 m southeast of Morrill Road. A few tens of meters west of this fracture zone is the second fracture zone that we described above as an example of a compound fracture.

Both of these fracture zones trend about N50°W and accommodate some left–lateral shearing. Similarly oriented fracture zones occur in the Christmas tree farm west of the C.T. English School and in the playing fields east of the school (Plate 1); there the southwest-side-up displacement is clearly visible (fig. 9C).

In the steep slopes to the southwest, south and southeast of the C.T. English School are several groups of fracture zones that form arcuate patterns (Plate 1). The largest group coincides with the head of the Morrell Cutoff landslide identified by Harp (1990). About 150 m south of Loma Prieta School, at the eastern end of the area, is a pair of parallel fracture zones that trend northwest-southeast (Plate 1). The northern fracture zone of the pair occurs along the base of a scarp, which has the morphology of a landslide scarp with its downthrown side to the south. Thus, this fracture zone also may be bounding a landslide mass.

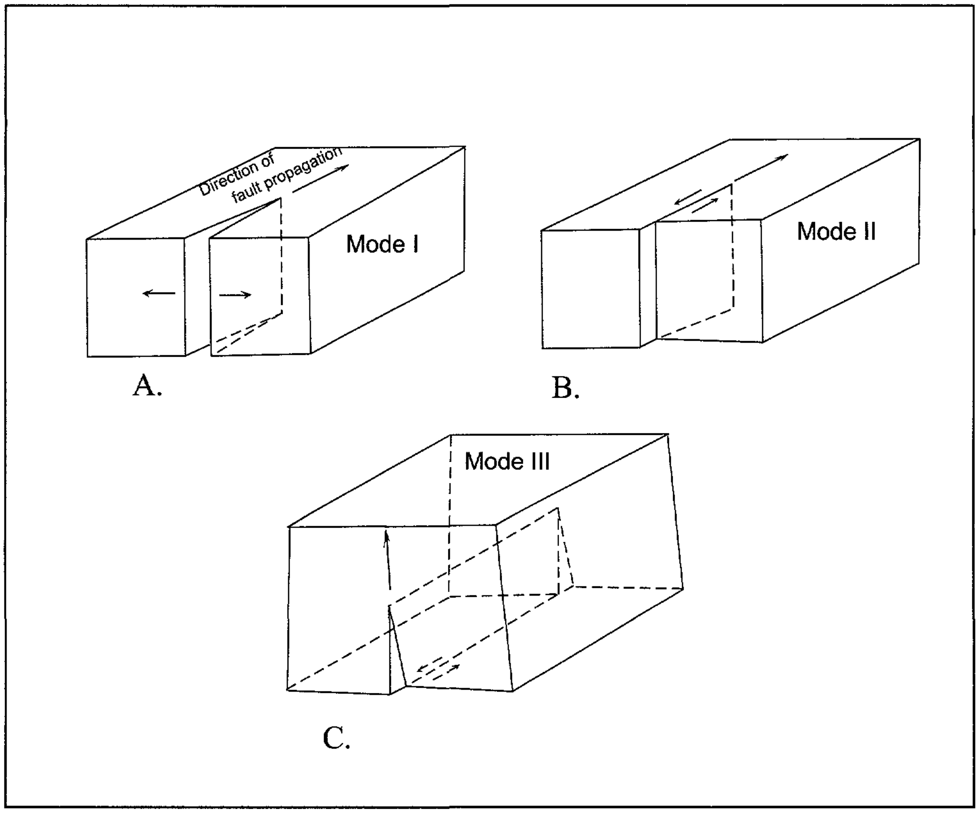


Figure 10. Definition of modes of deformation at the edge of a fracture front (after Lawn and Wilshaw, 1975). The modes are illustrated with a vertical fracture, but they are unrelated to fracture orientation. In mode I deformation, the fracture surfaces separate normally to produce an open crack. In mode II deformation, the fracture surfaces slip at right angles to the fracture front. In mode III deformation, the fracture surfaces separate parallel to the fracture front. The differences between mode II and mode III deformations is the direction of propagation of the fault front relative to the direction of displacement of the fault. A. A joint or tension crack forms in mode I. The fracture propagation is horizontal in the example shown. B. A strike-slip fracture or fault. The fracture in mode II propagates horizontally in the example shown. C. Another strike-slip fracture or fault, but propagating toward the ground surface. This seems to be the typical way that strike-slip faults propagate near the ground surface, and the fracture patterns at the ground surface are diagnostic of this mode of propagation.

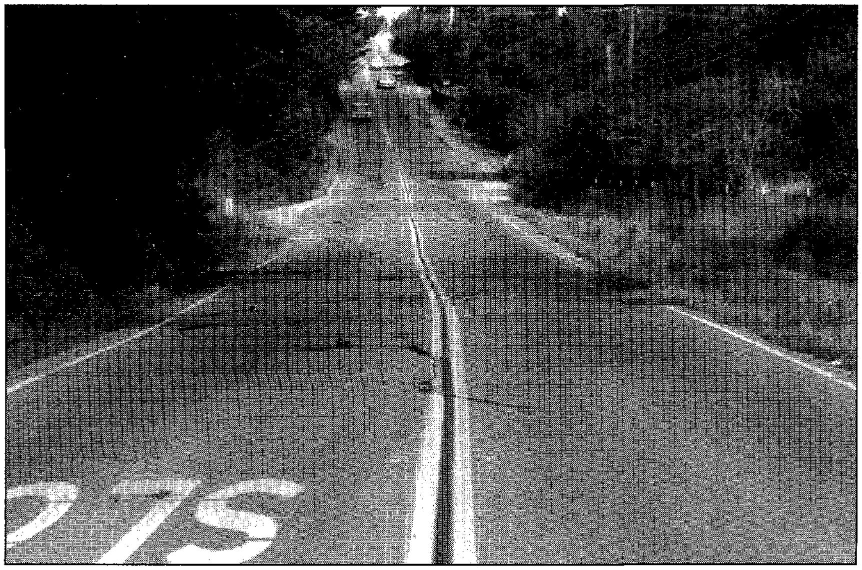


Figure 11. View west of Summit Road, showing left-lateral offset of centerlines across fractures. Fractures were patched with tar and asphalt. Photograph taken about 50 m east of entrance to Christmas Tree farm (on left). Intersection with Morrell Cutoff Road shown in middle distance, left. Intersection with Morrill Road shown slightly farther away on right. Fractures close to automobiles are right-lateral. Ground on right was an orchard in 1906.

Apparently, the fractures shown on Plate 1 are of three groups. One group is downthrown on the southwest, with arcuate fracture patterns and generally located in the heads of old landslide masses. These may be bounded by a right–lateral fault on one side of an arc and a left–lateral fault on the other. Another group of fractures is downthrown on the northeast and, where lateral offset is visible, is left–lateral. A third group consists of fractures that form on either side of grabens oriented parallel to fractures of the second group. Those on the northeast side are downthrown on the southwest and those on the southwest side are downthrown on the northeast. These three fracture zones can be analyzed using the analytical maps (Plates 2, 3, and 4) that show the essential fracture elements in true position, and orientation, and length (but generally exaggerated in width).

Detailed Pattern of Fractures

Christmas Tree Farm—North

Analytical maps were made by plane–table methods at a scale of 1:250 and compiled at 1:500 to derive kinematic information from the fractures in the Summit Ridge area. Three of the fracture zones in the northern corner of the Christmas tree farm area (Plate 1) are shown in Plate 2. We have already briefly described the two fracture zones in Plate 2 that cross Morrill Road. The northernmost zone corresponds with the zone that also fractured in 1906. Then, it was several meters wide, contained internal tension cracks indicative of left–lateral shearing, and offset Morrill Road about 1 m (Lawson, 1908, plate 55A). In 1989, the fracture zone offset Morrill Road about 41 cm in a left–lateral sense; the vertical differential displacement was about 10 cm (southwest-side up) and the opening was about 33 cm (differential displacement vector plunges 11° in the direction N7°E) (C. Prentice, oral communication, 1993). We round the values to even tens of centimeters in Plate 2. The net, horizontal differential displacement across the fracture would be approximately north-south.

The map (Plate 2) shows that this fracture zone extends about 100 m southeast of Morrill Road and ends on the southwest side of an orchard, apparently near the site of the old Morrell ranch house (Sarna–Wojcicki and others, 1975)[3]. To the northwest of Morrill Road this fracture zone was obliterated in the area between the road and a house. But beyond the house, it could be traced at least 150 m northwest, beyond the limit shown in Plate 2, along the flank of a small valley. This fracture trace turned more westerly and was expressed as a tension crack with the southwest-side up.

Examination of the fracture pattern within the 50 m stretch of the northwest end of the fracture zone, northwest of Morrill Road, between the house and the gully (Plate 2), we see that the fracture formed in response to left–lateral shearing, and perhaps tension normal to the *walls*[4] of the fracture zone. At the northwest end of the mapped part of the zone, the zone is defined by *en echelon* cracks, 0.5 to 2 m long, and oriented about 20° to 45° counterclockwise with respect to the walls of the zone. Thus the crack traces step right, so the shearing was left–lateral. There are several other, shorter traces of *en echelon* cracks within the fracture zone. The longer traces also step right, so their pattern reflects left–lateral shearing, whether the fractures are faults or tension cracks. The fractures are generally southwest-side up, which is also typical of long, straight fracture zones in other parts of the Christmas tree farm area. Vertical displacement along the entire fracture zone ranges up to 20 cm.

[3]According to our detailed mapping, this fracture zone does not cross Summit Road, which is contrary to suggestions of other investigators, who have mapped and stated that this fracture zone crosses Summit Road and extends for a couple of hundred meters to the southeast in the vicinity of C.T. English School. We specifically searched for but found no connection between this fracture zone (fig. 9A) and the fracture zone (fig. 9C) that passes through the playing fields of the C.T. English School. The way the two fracture zones are curving at their proximal ends (Plate 1)—both toward the northeast—also suggests that they do not connect.

[4]The *walls of a fracture* are simply the two faces of the fracture. A fracture zone generally lacks bounding fractures and instead consists of a group of subparallel fractures in a zone that is much longer than it is wide. The walls of this zone are, in 2-dimensions, represented by parallel lines that enclose the traces of the fractures in the zone.

Most cracks are wide open, one of them about 40 cm and several 10 to 30 cm wide. We infer that this part of the fracture zone formed via a combination of northeast-southwest tension and northwest-southeast shearing accompanied by vertical shearing.

Southeast of Morrill Road[5], the fractures in the zone have the distinctive pattern of *complex fractures*, consisting of tension cracks that have subsequently accommodated left–lateral shearing. Traces of the longer fractures are sawtoothed or zig–zaged with irregularities resulting in an interlocking pattern (fig. 9A). Fracture traces trending east-west are wide open and fracture segments trending northwest-southeast are closed, indicating left–lateral shearing. This sawtooth pattern containing open and closed portions is distinctive and diagnostic of a fracture that opened in tension and then subsequently sheared (in this case in left lateral).

We have already mentioned, as an example of a *compound fracture* zone, the fracture zone that crosses Morrill Road about 30 m west of the fracture zone we have just described. This fracture zone breaks the area north of the C.T. English School (Plate 1), crosses the Christmas tree farm, breaks Summit Road with left–lateral offset, runs into open ground, changes its direction to the northwest before it meets Morrill Road, turns west subparallel to Morrill Road, and crosses Summit Road again, but this time offsetting the road in a right–lateral sense. Within the Christmas tree farm area, this fracture zone has a general trend of N38°W and occurs along the northeast limb of a broad (100–200 m wide), northwest–plunging ridge (Plate 2), and on the southwest limb of a narrow (10 m wide) northwest–plunging trough. The zone consists of *en echelon* cracks 1 to 20 m in length, with steps of 5 to 20 m to the right. Across these fractures the differential displacement was 5 to 30 cm vertically upward (southwest-side up), and there is a maximum of 3 cm of left–lateral offset. The dip of the fractures was observed in several places to be southwestward, implying that they have a reverse component at the ground surface. The fractures are open, high–angle, left–lateral, reverse or normal fractures[6]. The amount of opening ranges from a few cm to 30 cm. In some places, the fractures were destroyed by disking by the time we mapped, and their vicinity is shown as disturbed ground in Plate 2.

On this same fracture zone, about 10 m to the northwest of Summit Road, there is an 8 m left step in the trend of the rupture belt. This left step is a *transfer zone* or stepover; such structures serve to transfer displacement between parallel but not coincident fracture zones. Within the transfer zone are fractures that superficially resemble a left–lateral duplex structure (e.g., Cruikshank and others, 1991a). A duplex structure, however, would contain connecting fractures that are left lateral. The sense of stepping of the fractures in the transfer zone identifies them as right lateral. This transfer zone is analogous to the Summit Ridge shear zone, itself (Johnson and Fleming, 1993), being composed of blocks bounded by fractures that rotate as the overall left-lateral shearing occurs. The connecting fractures trend east-west and form counterclockwise angles of 45∞ to 60∞ to the traces of the main fractures. The character of this part of the fracture zone indicates that it formed in response to a combination of shearing in the direction N30°W and dilation normal to this direction.

Beyond the transfer zone to the north, the individual fractures step right, reflecting left–lateral shearing as they formed (fig. 9B).

[5] Mapped by Atilla Aydin, February 1990.

[6]Everywhere in the Christmas tree farm area, however, the fracture elements of the fracture zones were essentially vertical at the ground surface, so it makes no sense to call fracture zones reverse or normal there (e.g., the "left–lateral/normal" of Aydin and others, 1992). Just as fracture zones in plan view are compound, changing orientation along strike, so are fracture zones as viewed in the vertical view, here being normal and there reverse. Just as most fractures in plan view cannot be described by a single, point measurement, but must be described by a field of measurements, so most fractures in vertical section can be described by the similar fields of measurements.

The next fracture zone to the southwest is at the lower middle part of Plate 2. The zone continues to the southeast beyond the map area where it crossed the school grounds and basketball court and damaged the buildings of the C.T. English School. It trends N34°W, and can be traced on Plate 2 to within about 20 m of a farm road and about 40 m from Morrell Cutoff Road. The pattern of the fracture traces of the third fracture zone, at the southwest edge of Plate 2, indicates left-lateral shearing and opening when the fractures formed. The left–lateral offsets along some of the zig–zag segments suggest a complex fracture zone that opened predominantly in tension directed about N30°E and then subsequently sheared in a left–lateral sense combined perhaps with further opening.

Thus, study of the analytical maps of all three fracture zones shown on Plate 2 indicates opening in a direction of N30°E and subsequent, minor, left–lateral shearing. Where the traces of the fracture zones are oriented about N55°W, we see evidence of early predominant opening in the pattern of fractures. Where the traces of the fracture zones have a more northerly trend, we see evidence for early left–lateral shearing and opening. This is precisely what we would expect where a block of ground northeast of each fracture zone is moving relatively northeasterly with respect to the block of ground southwest of the zone. The pattern of relative displacement of blocks of ground, therefore, is thus far remarkably simple.

Christmas Tree Farm—Southwest

The fracture zones in the southwest part of the Christmas tree farm area (fig. 5, Plate 3) include three arcuate fracture zones, concave toward the west or southwest, and two relatively straight fracture zones trending N50°W. The two relatively straight fracture zones are similar in some respects to the fractures we have just described. One of the straight zones bounds a graben about 3 m wide and about 5 to 10 cm deep, which have accommodated a few cm of left–lateral differential displacement in addition to vertical shift. Thus the graben accommodated opening in the direction N40°E, which is crudely similar to the direction of extension deduced from the pattern of fracturing within the longer fracture zones described above.

The graben continues a few meters northwestward, beyond the boundaries Plate 1 and 3, where it transforms into a single large break, which cuts Morrell Cutoff Road and a log cabin. The southwest side of the single fracture is up, and the amounts of vertical offset and opening increase toward the northwest[7]. The paired fractures in the graben are unusual, but the left–lateral offset and orientation is typical of the fracture zones we have already described along Morrill Road.

The other straight fracture zone on Plate 3 is characterized by pull–apart openings of 20 to 30 cm. Left-lateral shift of 12 cm was measured near the mid-length of the rupture by matching points on opposite sides of the fracture. The fracture pattern is, however, ambiguous with respect to strike-slip displacement, and it is apparently principally a tension fracture zone that accommodated opening. The trend of the fracture zone, N50°W, is the same as the graben, and the trace of this fracture zone likewise projects toward the graben. The block of ground to the southwest of the fracture zone moved relatively upward as much as 15 cm. Only about 40 m of the fracture zone remained at the time of our mapping; the northwest end of the fracture zone is in the small farm road shown on the map, and only small remnants of the fracture zone are preserved to the southeast, where the fracture zone was destroyed by disking.

[7]We note that at least one investigator reported that this graben defines the right flank of a large landslide mass; however, this is unlikely because the right flank of a landslide is characterized by right–lateral shearing, not the left–lateral shearing observed here.

Arcuate Fracture Zones

The arcuate fracture zones of hyperbolic shape in the northern part of Plate 3 can be directly correlated with topographic bowls in the hillside, apparently representing positions of landslide deposits. The outermost fracture zone has a southwest–trending arm and a northwest–trending arm. The southwest–trending arm is composed of right–stepping, *en echelon* tension cracks and perhaps fault segments that reflect left–lateral shearing, as one would expect in the left flank of a landslide mass. The northwest–trending arm consists of parallel segments, apparently reflecting simple opening in the northeast-southwest direction. Note that if the structure is a landslide, there is no right–flank for these fracture zones. The movement on this zone of fractures is principally opening of up to 50 cm with the west side down. The southwest-trending arm carries a small component of right-lateral shift that was not measurable at the time of mapping.

Nestled within this outer fracture zone is another fracture zone trending east-west, and extending from the outer fracture zone to the upper dirt road. The fractures are arranged *en echelon* and step left, reflecting the right–lateral shear one would expect on the right flank of a landslide mass. Thus the inner fracture zone, in combination with the southwest–trending arm of the outer fracture zone, appears to bound a soil mass that moved generally westward.

Downhill and across the upper dirt road from this arcuate fracture zone is a large area of disturbed ground that masks any evidence of the continuation of fractures. Another arcuate fracture zone between patches of disturbed ground contains the same fracture patterns as the zone farther uphill. The fractures are essentially opening and down to the west. A small, unmeasurable component of left-lateral slip was recognizable in the fracture pattern on the southwest-trending part of the fracture zone. The continuation of the fractures to the southwest was masked by regrading the ground downhill from the lower dirt road.

A small arcuate fracture zone of hyperbolic shape formed in the southwest part of the area of Plate 3, in a slope lacking evidence for landsliding. Several fractures, each less than 15 m long, compose this zone, and the fractures have openings in the range of 10 to 20 cm wide. No lateral differential displacement was observed along the fractures, but their arrangement in *en echelon,* right–stepping pattern reflects some left–lateral shear. The position of the left–lateral shear is consistent with a left flank of a landslide. But again, the feature lacks the right flank and toe of a fully developed landslide. The most striking aspect of this arcuate zone is again the amount of opening and downdropping to the west or southwest. This condition is opposite that of the long, straight fracture zones described above that have smaller opening, southwest-side-up and a left-lateral strike-slip component.

Other arcuate fracture zones occur in the southern and southeastern parts of the Christmas tree farm area (Plate 1). A long, arcuate fracture zone occupies most of the southwestern edge of Plate 1 just north of the Morrell Cutoff Road. The fracturing occupies an area of about 200 m by 150 m on a south–facing slope. Most of the large fractures occur along the base of a topographic feature that resembles an old landslide scarp. The region of large cracks extends 80 m laterally along the base of a northwest–trending scarp. The arcuate flanks occur on the west and the east sides, on either side of a north–south trending farm road that can be located by nicks in the map contours on Plate 1. The west flank has a more complicated fracture pattern than the east flank. The west flank is dominated by a throughgoing fracture nearly 100 m long, with a large opening (up to 60 cm). This fracture has accommodated right–lateral differential displacements of as much as 20 cm and is downthrown by up to 1 m. The position of the downthrown side is consistent with landslide movement. The fractures extend vertically at least 4 m, as indicated by their exposure in the deep gully parallel to the farm road. As shown in the map compiled by Spittler and Harp (1990), the right (west) flank of the complex of arcuate fracture zones terminates a few meters south of Morrell Cutoff Road in a northwest–trending fracture zone with the southwest-side up (op. cit., loc. 23–24, Plate 5).

The east flank fracture zone consists of several subparallel fractures trending to the southeast. About 70 m downslope from the position of the head, the east flank fracture forms a zone 8 m wide and 20 m long. Left–lateral differential displacement of 5 cm and a maximum opening of 35 cm were measured within this zone. This arcuate fracture zone carries part of the morphology of a landslide, but is incomplete. Deformation in the upper part (head) and flanks are consistent with landslide morphology. However, the structure lacks a toe or evidence of convergence of the flanks that might suggest landsliding[8].

Some relatively straight fractures occur in the eastern part of the Christmas tree farm area (Plate 1) about 200 m south of Loma Prieta School and about 500 m northeast of the arcuate fractures just described. Even though these fractures are straight, they extend for about 170 m along the base of a horseshoe–shaped scarp about 8 m high (Plate 4). The scarp appears to be the headscarp and walls of an old landslide mass, and the fractures are apparently more closely related to the arcuate fractures associated with landslide topography than with the straight, tectonic fractures. In some places the fracture zone is a fresh scarp, and in others it appears as a thin crack. The ground south of the fracture zone is downthrown as much as 20 cm, and individual cracks are open up to 40 cm. The fractures end where the old scarp ends. At the east end of the scarp the fracture zone steps to the right, suggesting left–lateral shearing. Differential displacement of up to 20 cm is directed downslope.

About 50 to 75 m downslope from the headscarp, but still within the area bounded by the right flank of the horseshoe-shaped scarp, is a graben, about 25 to 30 m wide, and at least 200 m long. The position of the graben defined by tension cracks oriented about N80°W, open up to 1 m, but generally 5 to 20 cm, and downthrown as much as 30 cm on the north or south sides. The graben ends at the projected position of the right flank of the old scarp.

These fractures are also distinctly different from those described in the relatively straight fracture zones in the western part of the Christmas tree farm area. Fractures step either right or left with respect to neighbors, and thus do not reflect either right– or left–lateral shearing. Fractures are downthrown either to the north or south, and they did not subsequently accommodate left–lateral shearing. Instead, these fractures represent southward differential lateral movement of a block of ground on the south side of the graben.

The fractures in the graben may be connected with the arcuate zone near Morrell Cutoff road via a strike-slip fracture zone that serves as a right flank of a landslide. A zone of fractures trending northeasterly between the left (southeast) side of the arcuate fracture zone near Morrell Cutoff road and the graben that is near the Loma Prieta school has the characteristics of a right flank of a landslide. Some of the fractures in the zone carry 50 cm of right-lateral strike slip with the southeast-side down. The unmapped area farther to the southeast (Plate 1) of these loosely connected strike-slip fractures is a large, densely vegetated basin that also may contain fractures. Perhaps the graben, the arcuate fractures near Morrell Cutoff road and the right-lateral strike-slip fractures represent a part of the complex headscarp and right flank of the Morrell Cuttoff landslide identified by Harp (1990).

The fractures in the vicinity of the buildings and playing fields of the C.T. English School and the Loma Prieta School (Plate 1) were mapped at a scale of 1:1200 and do not show the details required to interpret the conditions responsible for their formation. The general relations, however, are similar to those northwest and north of the C.T. English school described above.

[8]E. Harp, 1997, written communication, reports that he observed compressional folds consistent with a toe on the downhill side of Morrell Cutoff Road and southeast of the arcuate fractures. At the time of our mapping, we looked for and did not find evidence of a toe in expectable places. Without detailed mapping of the entire area, the presence of a fully developed landslide here remains, in our view, unproved.

Straight Fractures Associated With Distinctive Geomorphic Features

If we exclude from consideration the fracture zones in the Christmas tree farm area that are arcuate or in other ways appear to be associated with parts of old landslide masses, the remaining fractures shown are closely associated both in position and orientation with distinctive topographic forms. These forms include plunging troughs, or elongated depressions with axes that trend obliquely to the axis of Summit Ridge. Figure 12 shows that the orientations and positions of fracture zones in the southeast end of Summit Ridge are essentially coincident with the lineations mapped by Sarna–Wojcicki and others (1975). Except for one lineation on the hillside about 75 m southwest of the C.T. English School, all the troughs contain coseismic fractures.

The correlation between the elongated depressions or plunging troughs and the co–seismic fracture zones in the Christmas tree farm area (Plate 1) is so strong that, when we mapped the tree farm around the C.T. English School area, we anticipated finding each fracture zone. As we walked between the trees and spotted a plunging trough ahead, we would anticipate finding a fracture zone not in the axis of the trough, but on the southwest flank of the trough. The fracture zones typically were where we expected them to be. We found the two fracture zones bounding the C.T. English School buildings on the northeast and southwest sides, as well as the short fracture zone about 75 m southeast of the larger building of the C.T. English School, in this position relative to the troughs plunging. We found a fracture zone defined by only a few aligned cracks on the southwest flank of the trough

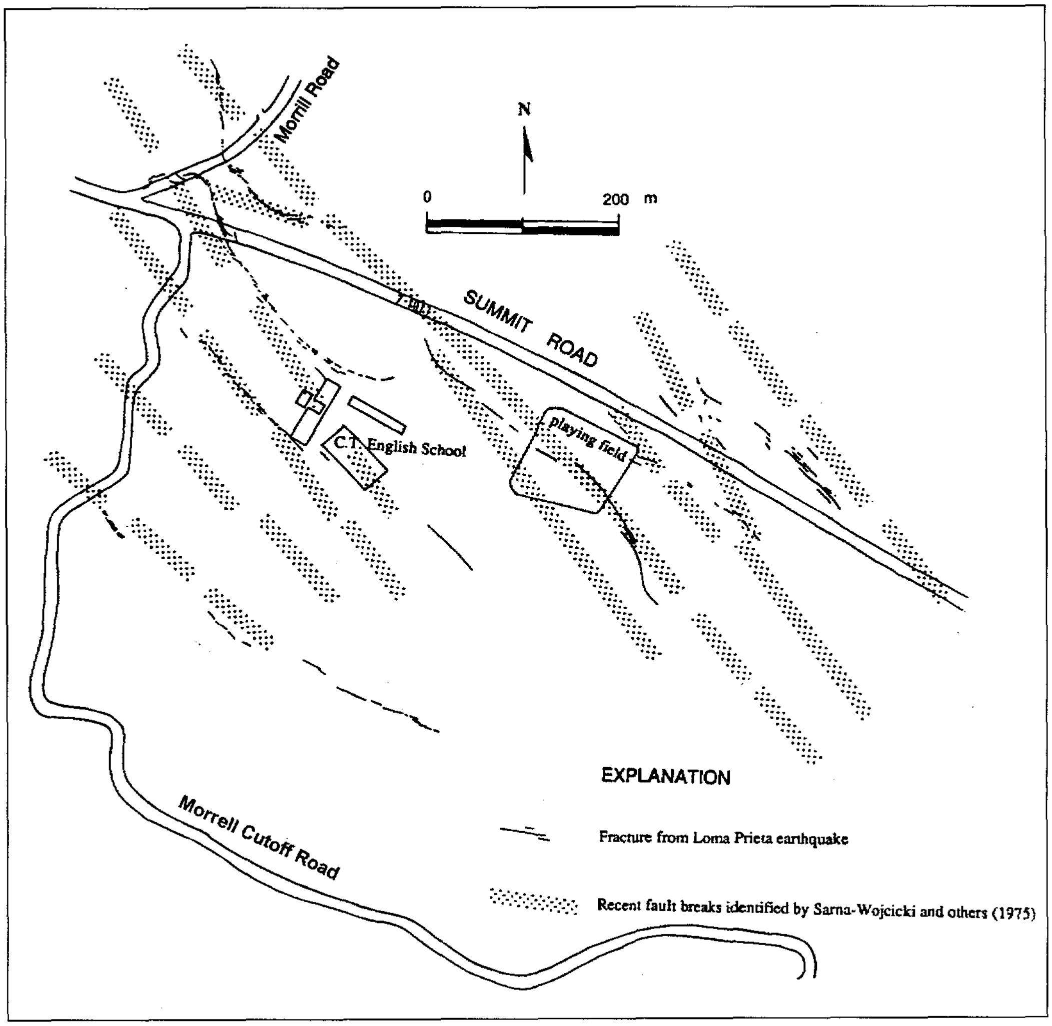


Figure 12. Comparison of synoptic map of traces of fracture zones (narrow lines) apparently unrelated to differential movement of landslide masses in the Christmas tree farm area (mapped in 1990 after the Loma Prieta earthquake) and enlargement of map of lineaments (broad, dotted dashes) mapped by Sarna–Wojcicki and others (1975), based on a field and photogrammetric study of fault–related topographic features along the San Andreas fault zone.

immediately adjacent to Summit Road, about 60 m southwest of Loma Prieta School (Plate 1) only because we expected a fracture zone in that location and persisted in criss–crossing the grass– and tree–covered hillslope, looking for cracks in the grass. Thus we are impressed with the correlation between the positions and orientations of the fracture zones with plunging troughs.

Two other fracture zones of the same type are associated with an elongated depression and a plunging trough near the Burrell School (Plates 1 and 5). The fracture zone in the elongated depression had been largely obliterated by the time we mapped in January 1990, but the one next to the Burrell School was intact. Both fracture zones occurred on the southwest sides and wrapped around their respective troughs. The ground to the southwest side of each fracture zone was relatively upthrown.

The main fracture zone was about 150 m long and occurred along the southwest side of the elongate depression. It trended about N47°W on the Stanton property (Plate 5), and at the northwest end, turned abruptly clockwise about 70° and crossed Summit Road. It offset the center line of Summit Road about 1 cm (left–lateral) and produced a vertical offset of about 3 cm. A few tension cracks formed on the northeast side and parallel to the long dimension of the depression. Another fracture zone, composed of nearly straight, parallel cracks, cut through an orchard to the west of the depression. One of these fractures cut through a low retaining wall near the gate to the Stanton's, and offset the wall about 10 cm left–lateral, 10 cm opening and 10 cm vertical (southwest-side downthrown) differential displacements (Plates 1 and 5).

The fracture zone immediately northwest of Burrell School was a minimum of 100 m long. It probably extended farther to the northwest, but the ground in that area was regraded. A house that was situated between Burrell School and the Stanton property was demolished after the earthquake. Individual fractures within the remaining traces of the fracture zone at Burrell School were arranged *en echelon*, stepping right, reflecting a combination of northeast-southwest opening as well as left–lateral shearing.

There is some evidence that the fracture zone on Summit Ridge extends even farther northwest than we have heretofore recognized. A similar association between fracturing and depressions and troughs west of Highway 17 (fig. 2) (Spittler and Harp, 1990, Plate 1), exists in the area between Stagecoach Road and Citation Road. The fractures show a right–stepping echelon configuration, and according to the geologic notes accompanying the map, the fracture zone accommodates a maximum opening of 20 cm, and southwest–side–up vertical differential displacement of 12 cm. Furthermore, Harp (oral comm., 1997) reported the presence of several straight fractures that were generally parallel to the straight fracture zones on Summit Ridge with southwest-side-up farther down the hillside and southwest of Morrell Cutoff Road.

Possible Origins of Fractures on Summit Ridge

The concepts of simple, complex and compound fractures, as well as understanding of the stress–controls of orientations of individual tension cracks and fault segments, combine to provide a theoretical base for understanding the fracture patterns. The detailed map information on position, orientation and kinematics of individual fractures and groups of fractures provides the documentary evidence for interpretation. Judgments can be made whether the fractures were produced by ground shaking, by spreading of ridges, by general shearing, by faulting, by landsliding, or by some mysterious agent heretofore unobserved. The fracture patterns and the differential displacements across the fractures are like stress indicators. An advantage of analytical maps of fractures here or anywhere is that interpretations of the causes of fractures are separable from documentation of the fractures. Interpretations are necessarily temporal but, in principle, documentary evidence should not be.

One of the difficulties in interpreting the fracturing that occurs during an earthquake is identification of the *dominant* deformation processes causing the fracturing. This is clearly an area that needs additional work, including theoretical analysis, because the imaginable deformation processes are many. Deformation processes relevant to the Christmas tree farm area, however, are landsliding, differential ground shaking, general shearing (and concomitant dilation) at depth, and faulting at depth.

Origins of Arcuate Fractures

Many of the arcuate fractures that formed during the Loma Prieta earthquake have been interpreted to be landslide features. Generally, these fractures form a characteristic, *partial hyperbolic shape* that conforms to topographic expression (Spittler and Harp, 1990; Aydin and others, 1992). There may be several viable explanations of the origin. The fractures are clearly different from the long, straight compound and complex fractures at Morrill Road (Plate 2). Data are insufficient, however, to state definitively whether the structures are some special type of shaking phenomenon or are early stages of landslide movement. The fracture zones are so distinctive in their kinematics and locations that they should be viewed as an unknown form of surface rupture until their processes of formation are better understood. By describing the arcuate structures and refraining from identifying or naming them, perhaps they will receive more intense study when produced in a future earthquake.

Landslides are common features in the Santa Cruz Mountains, and the topography in several places in the Christmas tree farm area strongly suggests past landsliding of various scales. The arcuate fracture zones that opened during the Loma Prieta earthquake occur in sloping ground that is generally associated with pre–existing landslide scarps and within old landslide deposits. The major displacement of the fractures is opening, and crack widths are as large as 1 m. The arcuate fractures have significant vertical displacements with the downslope side downthrown except where grabens occur. There, the downdropped block occurs in the heads of the old landslide masses with an uphill–facing scarp on the downslope side of the graben.

There are four zones of arcuate fractures and one zone of straight fractures and graben in the Christmas tree farm area that are located near the scarps of old landslide masses. Three of the arcuate zones are shown on Plate 3 and are characterized simply by opening amounting to several tens of centimeters. These zones contain a very small component of left-lateral shear on what appears to be a developing left flank of a landslide, but even there, the fractures are mostly gaping tension cracks with the downhill side of the fractures dropped down. The left-lateral component of the offset can be deduced from the stepping sense of the fractures. The notion that the curving portion of the fracture zone is a developing landslide flank, however, is uncertain. Small amounts of right-lateral or left-lateral offset across a curving crack may indicate only opening. If the trace of a large fracture zone, characterized by pure opening and down-to-the-west differential vertical displacement, curves either to the left or right, the fractures become compound, and the zone carries a small component of left- or right-lateral shear that is only a consequence of fracture orientation.

The fourth arcuate zone is more complicated than the three shown on Plate 3. This zone, shown on Plate 1, consists of an arcuate fracture zone near Morrell Cutoff Road that is loosely connected to a relatively straight fracture zone and graben near Summit Road with a large-displacement, right-lateral fault zone. The structure is more than 700 m long, and the right-lateral fault zone appears to serve as a stepover between the two "arcuate" zones. Unfortunately, the right-lateral fault zone was mostly in a densely vegetated, topographic basin that could not be effectively mapped by plane-table methods; so the detailed information needed to interpret the structure is lacking. Again, there is a strong temptation to interpret the right-lateral fault zone as the right flank of a landslide, and indeed, the case for basal slip on a landslide failure surface is stronger here than for the other arcuate fracture zones. Nonetheless, the kinematics of the fractures do not require a basal failure surface to achieve the fracture pattern as we mapped it.

If we accept the notion that slip on a basal surface is a requirement for landsliding, then none of the observations of cracks and their relationships to old landslide boundaries are diagnostic. Because there are not flanks or toes, we can deduce only that the principal direction of differential movement of the ground is normal to the average direction of the arcuate fracture zone opening. The differential movement might be a result of differential acceleration of adjacent blocks of ground, rather than sliding of the block on the concave side of the fracture zone.

On the one hand, perhaps the arcuate fractures are associated with incipient landslide masses that were beginning to propagate a slip surface, from the head toward the ultimate toe, as Fleming and Johnson (1989) described in the Aspen Grove landslide in Utah. Assuming that to be the case, the observations at Loma Prieta may be relevant to the earliest stages of earthquake-induced landsliding where the landslide masses did not become fully mobilized. If so, the earthquake-induced landslide process is one of progressive failure, and conventional methods of stability analysis that add a force component in the analysis to account for the effect of shaking are incorrect.

On the other hand, perhaps the arcuate zones are a result of differential ground acceleration that produces ground lurching. Perhaps the ground in the old landslide masses and the ground surrounding them shook differentially so that the fractures appear to be a result of landsliding. In this interpretation, the differential displacement across the arcuate fractures was absorbed in the landslide debris in the vicinity of the fissures, but did not reflect slippage on a basal shear surface and, therefore, was not landsliding.

The fracture shapes are so peculiar and distinctive that we wonder whether landslides generally activated in the southern part of Summit Ridge during the Loma Prieta earthquake.

Origin of Other Fractures

The non-arcuate fracture zones in the Christmas tree farm area are candidates for an origin that was driven by the differential displacement on faults and shear zones. These fracture zones are shown synoptically, along with the lineations and scarps recognized photogrammetrically by Sarna–Wojcicki and others (1975), in figure 12. The topographic features occur in a band about 3 km long and 0.5 to 1 km wide that extends from as far southeast as Burrell School and as far northwest as the intersection of Old Santa Cruz Highway with Summit Road, about 1.75 km southeast of Highway 17 (fig. 2). Sarna–Wojcicki and others (Sheet 2, 1975), even before the 1989 earthquake, singled out for special emphasis the lineations within the San Andreas fault zone in the Summit Ridge area, including lineations along the left–lateral fractures that cut across Morrill Road at the old Morrell Ranch in 1906:

> "...Dr. Jordan attributed the [left–lateral] displacement at the Morrell Ranch to slumping. An alternative explanation is that left–lateral movement took place along subsidiary left–lateral *en echelon* faults formed in a wide zone of deformation between two right laterally moving rigid blocks..."

and thus they proposed a general mechanism, a localized shear zone beneath the area, as compared to relatively rigid rocks on either side. Ponti and Wells (1991, p. 1502) also suspected that there was overall right–lateral shearing in the Summit Ridge area, but they were puzzled by the contradictory, left-lateral offsets across long fractures:

> "...the geometry and sense of displacement of most of the linear fissures are...hard to explain by simple tectonic models. The crude left–stepping pattern of the Summit Road fissures implies dextral shear consistent with the earthquake mechanism, yet most displacements on the fault–parallel fissures have sinistral components of motion."

This was the status of our understanding of the left–lateral fractures on Summit Ridge until the June 28, 1992, Landers earthquake. At Landers, there was no question about whether coseismic fault displacement had propagated to the ground surface, and we saw many examples of left--lateral shearing along *en echelo*n fractures within right-lateral shear zones.

In retrospect, three essential ideas about deformation and fracturing associated with faults needed to be understood in order to recognize the origin of the left–lateral fractures at Loma Prieta. First, we know that fractures commonly are complex, even during a single deformation—fractures form under one state and then accommodate a different state (Fleming and Johnson, 1989; Johnson and others, 1993). Second, we have begun to realize that many faults are intimately related to shear zones (Aydin and Johnson, 1978, 1983; Johnson, 1995). Third, we have relearned (following Gilbert, 1928) to distinguish between *en echelon* faults and *en echelon* tension cracks forming within shear zones (Fleming and Johnson, 1989).

On the basis of these three ideas, Johnson and Fleming (1993) were able to understand many fracture zones that formed during the Landers earthquake and were able to suggest a rational explanation for the left–lateral fractures at Loma Prieta. We are not suggesting that the mechanism is new; we are only indicating that others did not recognize the probable connection between the left-lateral shearing observed on fractures and an underlying right-lateral shear zone. Indeed, the interpretations of left–lateral fractures within right–lateral fault zones[9] was suggested by Professor Omori, according to Reid (1910) as well as by Tchelenko (1970); Tchelenko and Ambraseys (1970); Peng and Johnson (1973); Freund (1974); Sarna–Wojcicki and others (1975); Wernicke and Burchfield (1982); Philip and Maghraoui (1983); Quidong and Peizhen (1984); Ron and others (1984); Deng and others (1986); Sylvester (1988); Armijo and others (1989); Ponti and Wells (1991); Young and others (1985) and certainly many others.

The left–lateral fracturing at Loma Prieta formed in the right-lateral, *Summit Ridge shear zone* (Johnson and Fleming, 1993) which is about 0.5 km wide, at least 3 km long and centered on Summit Ridge. The shear zone juts forth with an orientation of about N70°W from the San Andreas fault zone which has a trend of about N45°W in this area. Thus, as shown in figures 2 and 4, the connection between the Summit Ridge shear zone and the San Andreas fault to the southeast of Burrell School is similar to the connection between the Sargent fault and the San Andreas fault to the northwest of Wrights. Aydin and others (1992) documented 10 to 20 cm of right–lateral rupture along part of the San Andreas at Chemeketa Park and along the Sargent fault on the northeast side of Lake Elsman during the Loma Prieta earthquake, which suggests that these segments were activated together in 1989. They documented about 10 cm of right–lateral rupture at the intersection of Summit Road and San Jose/Soquel Road and near Summit Store, and Johnson and Fleming (1993) document that the Summit Ridge shear zone could contain right–lateral shift as large as one or two meters, which suggests that these segments were activated together in 1989. Although we mapped in detail Morrill Road and the winding road that passes through the Wrights/Burrell School stepover (fig. 8A) and extends down the hillside to Wrights (Aydin and others, written comm.), we found only one short stretch of road that might have been ruptured along the stepover (fig. 13). Apparently in this area in 1989 the San Andreas fault did not form a single rupture zone, but rather two. One zone extends into the area from the southeast, turns counterclock-

[9]The phenomenon is so widely known among earthquake and fracture-mechanics specialists that it is surprising that they (and we) did not immediately recognize the phenomenon at Loma Prieta!

wise and terminates in the Summit Ridge shear zone; the other extends into the area from the northwest, turns counterclockwise along the Sargent fault (fig. 8A). This rupture pattern is apparently different from that in 1906 when the ruptured parts of the San Andreas to the southeast and northwest were connected by rupture of the Wrights/Burrell School stepover. The Wrights/Burrell stepover is quite similar to the Kickapoo stepover and the Emerson/Homestead Valley stepover that ruptured during the Landers earthquake (Fleming and Johnson, 1993; Johnson and others, 1997).

The Summit Ridge shear zone closely resembles the several similar structures formed within belts of right–lateral surface rupturing at Landers (Fleming and Johnson, 1993; Johnson and others, 1993). Within these right–lateral shear zones the tension cracks formed first, as a result of shearing within the zone, then the blocks of ground between the tension cracks rotated with further right–lateral shearing of the zone, causing the blocks to slip relative to each other in a left–lateral sense. According to this mechanism, tension cracks that transform into left–lateral, complex fractures are *expected* forms of fracturing and faulting within a right–lateral shear zone.

Our own interpretation of the controls of the orientations of fracturing in the southern part of Summit Ridge is somewhere between the interpretation suggested by Johnson and Fleming (1993), that the orientations of the fractures are controlled by the stress state within a broad shear zone, and the interpretation suggested by Ponti and Wells (1991), that the orientations of fractures are controlled by orientations of bedding, pre–existing faults and fractures in the bedrock. According to Johnson and Fleming (1993), the orientations of the fractures are controlled by the orientation of the shear zone, within which the fractures occur, and the dilatancy of the material within the shear zone. According to Ponti and Wells (1991) the orientations of fractures reflect the orientations of discontinuities. According to Johnson and Fleming (1993) the cause of fracturing was the shearing within the broad shear zone. According to Ponti and Wells (1991) the cause of fracturing was by gravity–driven, hilltop spreading. Our view is that the occurrence of *compound* fractures—one of which, for example, changes from an opening fracture zone to a left–lateral fracture zone to a right–lateral fracture zone along strike—indicates that some of the fracturing occurred along pre–existing discontinuities. In this limited sense we agree with the conclusion by Ponti and Wells (1991). Our view, however, is that the orientation and opening of the relatively straight, complex fracture zones were controlled by shearing and dilation within a shear zone along Summit Ridge.

Discussion and Conclusions

Incompleteness of Documentation

The haunting similarities shown on the cover of this report between the pair of left-lateral fractures that appeared on Summit Ridge in front of the Morrell home in 1906, and the pair of left-lateral fractures that appeared in the same places with the same orientations and even the same complexities, make one frustrated that fractures have not been mapped in detail routinely during each earthquake in historic time. The sketch of the fractures in 1906 is one of the few detailed descriptions of fractures in the 1906 earthquake report (Lawson, 1908; Reid, 1910). Unfortunately, the situation has not improved in recent times in spite of the marked improvement in our understanding of the formation of fractures. If one looks for detailed descriptions and analyses of ground ruptures produced during subsequent earthquakes one is similarly frustrated.

Specifically, documentation of earthquake rupturing at Loma Prieta by us and others was imperfect. First, we did not realize, until late in the field work, that, in order to describe a fracture or fault *at a point* one must specify the orientation of the

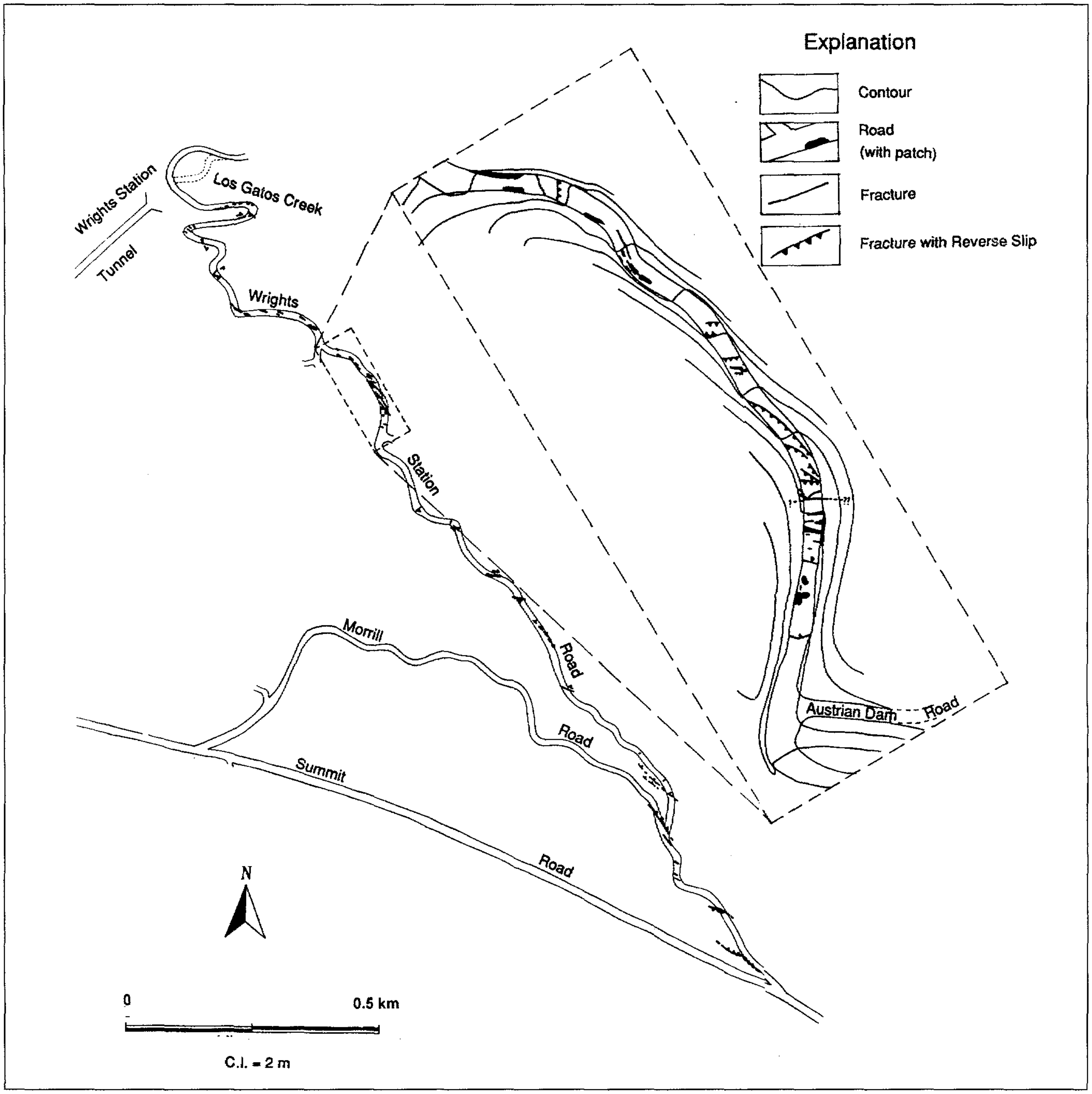


Figure 13. Simplified plane-table map of Wrights Station Road, between Morrill Road and Los Gatos Creek. Besides the ruptures near the intersection of Morrill Road and Wrights Station Road, the fractures that most likely are related to deep-seated deformation along faults or shear zones are in an arc about 250 m long immediately northwest of Austrian Dam Road (inset figure).

fracture surface(s) *and* the magnitude and orientation of the vector of differential displacement. Thus one must specify a unit vector for orientation of a fracture surface and a complete vector for differential displacement at each point. The differential displacement, for example, must include the magnitude and sense of the component normal and the two components tangential to a fracture.

Second, in order to describe a complete fracture, one must specify the vector *fields* of this information at points along the surface of the fracture. Thus, a complete description of a fracture consists of two fields of quantities just like a complete description of the tractions on a surface must specify the vector of the components of traction and the vector of the orientations of the surface everywhere along the surface. Without all this information, a fracture is only partly documented, and its origin and kinematic role in gross deformation generally cannot be understood.

The analytical maps described herein can provide the necessary description of a fracture. The analytical maps record the traces of fractures, and the fractures are essentially vertical, so the maps provide the necessary information about the attitudes of the fractures. However, unless a map shows three vector components of differential displacement at each point, each component with a specified magnitude (including zero), the description of the fracture is incomplete. Unfortunately, in many places we specified only one or two components.

A third problem is that we were unable to begin our research until a few months after the earthquake, after considerable evidence had been destroyed. Fortunately, a few spot measurements were made by others in the area of the Christmas tree farm so we could use these data, where they appeared to be accurate, to supplement ours.

A fourth problem is that we should have prepared analytical maps for the entire areas of rupture at Los Altos Hills, in Los Gatos, along the ruptured parts of the Sargent fault zone and along the ruptured areas in the Summit Ridge/Skyland Ridge areas. These maps would have provided the documentation needed to understand the ground rupture along several fault zones during the Loma Prieta earthquake, and would have been of immense value to geologists studying the next major rupture along this part of the San Andreas fault zone.

The documentation of deformations in this area following the 1906 San Francisco earthquake was also incomplete and so poor that deformation from the 1989 Loma Prieta earthquake could be compared only in the area of the Morrell home, and there with some lingering ambiguity because the offset was shown as right lateral on the sketch map whereas all verbal accounts and photographic documentation indicate left lateral.

We urge earthquake geologists to make truly detailed, analytical maps of earthquake ruptures as part of the basic documentation of ground deformation during earthquakes. We have described the essential features of such maps and provided illustrations of such maps in previous pages.

Review of Interpretations

Based on our analytical mapping at Loma Prieta we make the following interpretations and draw the following conclusions:

1. The arcuate fracture sets in the vicinity of Christmas tree farm area are related to superficial landsliding or differential ground shaking (lurching). We have no basis for selecting a single explanation, but we are infused with the notion that many of the arcuate fracture zones are results of differential ground shaking and do not include basal shearing which characterizes the movement of landslide masses.

2. The complex, left–lateral fractures at Summit Ridge apparently formed within the right–lateral, Summit Ridge shear zone, a shear zone centered on Summit Ridge and caused by deep–seated faulting. If we discount the arcuate fracture zones in the Christmas tree farm area so that we are left with the residue of fracture zones shown in the synoptic map in figure 12 then we have sets of *compound* and *complex* fractures. The compound fractures mainly indicate extension approximately in

the direction N30°E. The complex fractures have the following three properties: (a) They have extremely irregular surface traces and rough faces, characteristic of tension cracks in soil, and reflect tension in the direction N30°E. (b) They all subsequently accommodated some left–lateral shearing and perhaps further opening, indicating that the net extension direction was more northerly, perhaps N20° to 30°E. This extension direction deduced for the southern end of Summit Ridge is consistent to the average direction of horizontal differential displacement reported by Ponti and Wells (1991), about N22°E, for the entire Summit Ridge. (c) The complex fractures all are upthrown on their southwest sides. These three properties are all consistent with right–lateral shearing across a broad zone trending N70°W plus upthrowing on the southwest side.

Although all of these observations are consistent with right–lateral shearing and southwest–side–up thrusting attributed to the main shock of the Loma Prieta earthquake (Plafker and Galloway, 1989) we are not insisting, as we did in our earlier paper (Aydin and others, 1992), that the fault rupture that produced the main shock reached the ground surface at Summit Ridge. The major tectonic rupture zone along Summit Ridge as well as the small right-lateral faults along the San Andreas fault zone and the Sargent fault zone and the thrust faults at the mountain front stretching from Los Gatos to Stanford, all probably represent highly localized straining associated with deformation that was *coactive* with the deep fault that produced the main shock. We do not, of course, know how this works, but the evidence is quickly accumulating that it in fact has happened at Loma Prieta, at Landers (Johnson and others, 1997) and at Northridge (Cruikshank and others, 1996a; Johnson and others, 1996b).

Possibility of Skyland Ridge Shear Zone

There is also evidence for a broad right–lateral shear zone beneath Skyland Ridge as well as beneath Summit Ridge. The fracture map of the Skyland Ridge area prepared by Spittler and Harp (1990, Plate 2) shows a sub–parallel fracture zone trending to the northwest, which suggests a shear zone with that orientation. According to Plafker and Galloway (1989, p.15) :

> "Ground cracks in the Skyland Ridge area exhibit nearly the same trend and sense of displacement as the cracks located along Summit Road. Displacement of the Skyland cracks is largely extensional but with a component of left slip. Displacement is generally less than that observed near Summit Road, and the cracks are less continuous along trend...Many cracks in the Skyland area cut obliquely across the ridge crest. They tend to follow pre–existing linear scarps and troughs, suggesting repeated motion along the zone of cracking."

On the basis of the similarities, and the parallelism between the earthquake fractures and the topographic lineation in Skyland Ridge (Sarna–Wojcicki and others, 1975, Clark and others, 1989) we suggest the existence of the Skyland Ridge shear zone in addition to the Summit Ridge shear zone recognized by Johnson and Fleming (1993). The approximate locations and orientations of the shear zones are indicated in figure 7.

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