RECONNAISSANCE FIELD INVESTIGATION OF THE LANDERS EARTHQUAKE (M_S 7.5) OF JUNE 28, 1992, SAN BERNADINO COUNTY, CALIFORNIA, USA

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Background

The Landers earthquake (M_s 7.5) occurred at 4.58 am local time, and was located about 10 km north of the town of Yucca Valley, close to the small town of Landers, and about 170 km ENE of Los Angeles (Fig. 1). At the time the author was in Reno, Nevada, involved in a field study of the 1915 rupture of the Pleasant Valley fault. Fieldwork was completed on July 8, and on July 9 the author drove with a Reno-based colleague, Dr. Steven Wesnousky, firstly to Los Angeles to consult with seismologists and geologists at U.S.Geological Survey (Pasadena) and California Institute of Technology (Caltech), and then to Yucca Valley to inspect surface faulting and damage in the epicentral area. We reached Yucca Valley at about 6 pm on July 10, and remained in the area until the evening of July 14.

Some objectives in inspecting the fault rupture were to look at the distribution of slip along the length of the fault break; the relationship of faulting to pre-existing traces; and the relationship of the fault rupture to the total length of each of the faults that ruptured. The earthquake magnitude and total rupture length are similar to what has been proposed for the segment of the Wellington fault that runs through the Wellington metropolitan area.

Geological and Seismological Setting

The Landers earthquake and related events occurred on NNW- and NW-striking faults to the east of the southern San Andreas Fault system, within the seismotectonic province known as the Mojave block. Not a great deal is known of the past activity of these faults although total right-lateral displacement across each of the faults of only a few kilometres, and average Holocene slip rates of perhaps 1-3 mm/yr. are generally accepted.

Since about 1986 there has been a marked change in the incidence of moderate to large earthquakes in the region of the southern San Andreas Fault (Fig. 2). Between 1932 and 1986, the only known earthquake of $M > 5.8$ was the M6.0 Desert Hot Springs earthquake of 1948. In this period the southern section of the San Jacinto Fault was very active. Since 1986 activity has switched from the San Jacinto system to the San Andreas system and the Mojave block. There have been four earthquakes of M5.8 or greater within 150 km of the Landers earthquake epicentre since 1986, either on strands of the San Andreas or to the east within the Mojave block. The latest of these was the M6.1 Joshua Tree earthquake of April 22, 1992, which was a right-lateral strike-slip event on a north-striking fault to the south of the Landers earthquake epicentre. The aftershock zones of the Landers and Joshua Tree earthquakes overlap, although the Joshua Tree zone is about 2 km east of the Landers aftershock zone. No surface rupture has been found for the Joshua Tree event (M. Rymer, USGS -pers comm).

There has been a clear inter-relation between the Joshua Tree and Landers events. Aftershocks in the M2-3 range were continuing along the northern part of the Joshua Tree zone up until about 6-12 hrs prior to the Landers mainshock when they shut-off and a sequence of 3 or 4 M4 foreshocks occurred in the Landers epicentral area.

Another recent earthquake that appears to have been significant to the 1992 events is the M5.2 Homestead Valley earthquake of March 15, 1979 (Hill *et al.* 1980, Hutton *et al.* 1980, Stein and Lisowski, 1983). Up to 80 mm of right-lateral strike-slip displacement occurred on a 3 km-long trace of the Homestead Valley Fault, and 10 or 20 mm of right-lateral displacement occurred on the Johnson Valley Fault (Fig. 3). Importantly, the aftershock zone did not follow either of the faults but instead had a marked north trend between the two faults, the area that ruptured with right-lateral movement of at least 2.5 m in the 1992 event. The ruptures mapped in association with the 1979 event might be better regarded as triggered slip. It is interesting to note that the 1979 earthquake began the rupture process in a transfer zone between the Johnson Valley and Homestead Valley Faults. Without the 1979 earthquake it may be that the 1992 event might have been restricted to the Johnson Valley Fault, preventing the second major subevent in 1992 along the Homestead Valley/Emerson Faults.

Seismological Aspects

The Landers earthquake had a very shallow focal depth estimated to be only 2-5 km, with a first motion focal mechanism of almost pure right-lateral strike-slip motion on a vertical fault oriented 10° west of north. The earthquake was a complex event with two major subevents. The first is taken as the epicentre and was located about 10 km north of Yucca Valley and the second was about 10 seconds later and located 40 km further north of Yucca Valley. The second subevent had a moment approximately 1.5 times that of the first subevent and together contribute to a Moment Magnitude (M_w) of 7.4. Hiroo Kanamori has done a preliminary inversion of the seismological records, which indicates there was about 4 m of strike-slip displacement at the focus of the first subevent, and about 6 m at the second subevent focus. This ties in quite well with the amounts of surface rupture discussed below.

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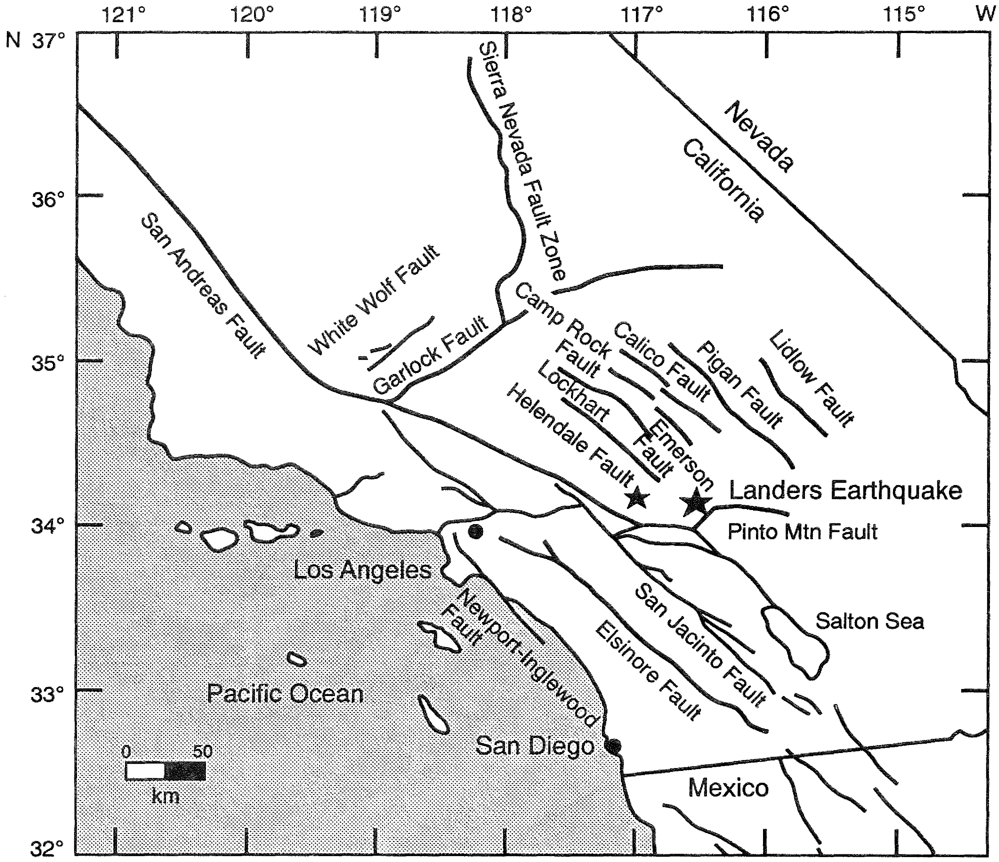

Figure 1. Active fault map of southern California, showing principal cities and epicentres of Landers and Big Bear earthquakes.

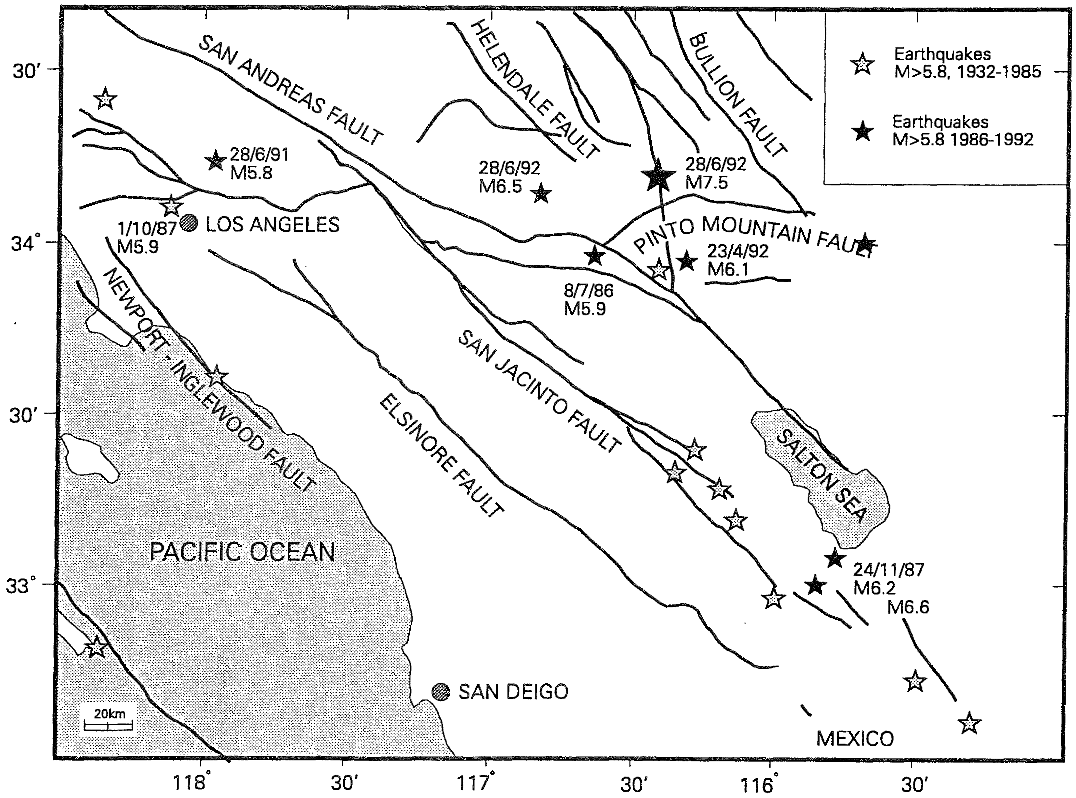

Figure 2. Location of principal earthquakes (M > 5.8) in southern California from 1932 to 1985, and 1986 to 1992.

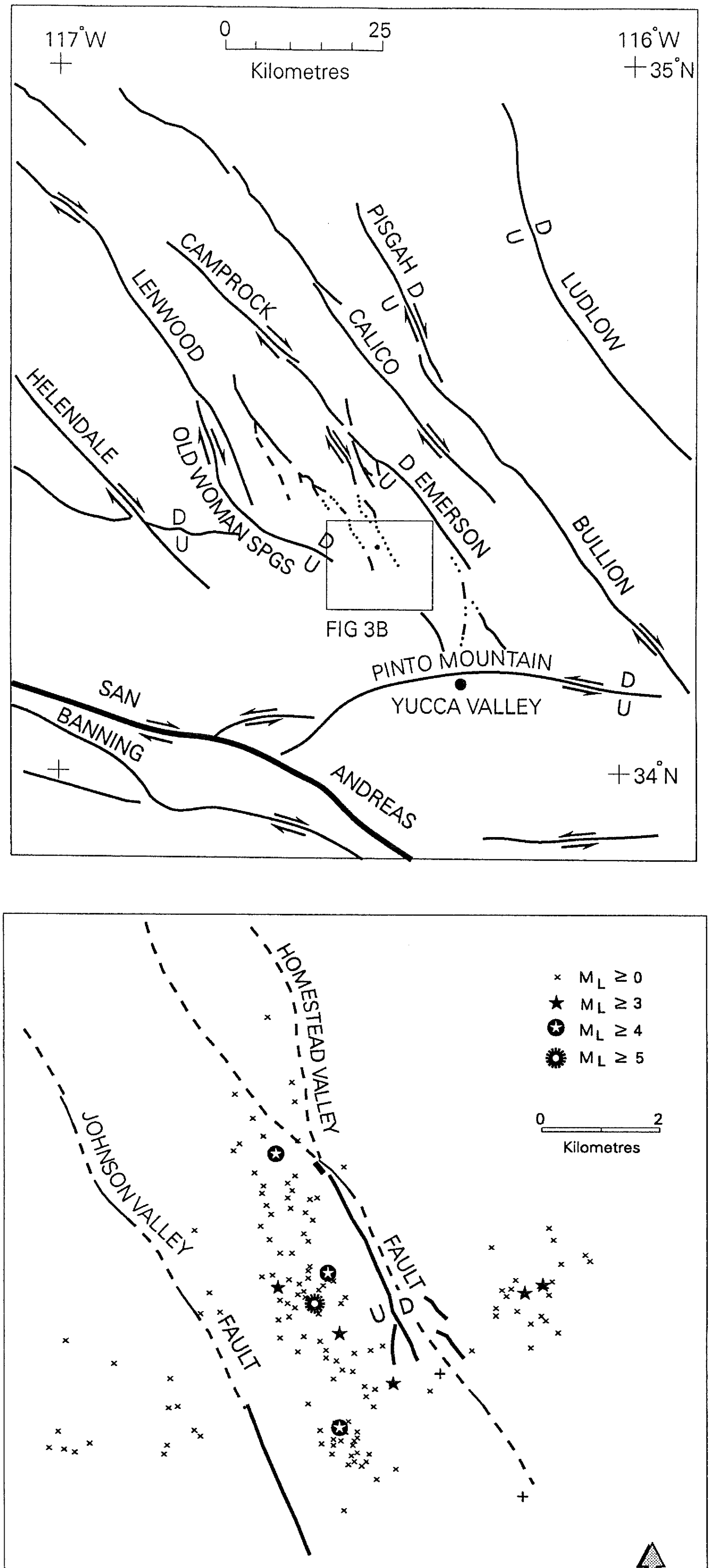

Figure 3. Relationship of 1979 Homestead Valley earthquake to active faults of the Mojave block (3A), and detail of the aftershock zone in relation to triggered slip on the adjacent Johnson Valley and Homestead Valley faults (3B). After Stein and Lisowski (1983).

At 8.04 am a M_s 6.5 event occurred 10 km southeast of Big Bear Lake, about 40 km west of the mainshock at Landers (Fig. 1). This event has sometimes been considered an aftershock, but it occurred on a different structure at a high angle to the orientation to the Landers aftershock zone. The Big Bear earthquake is therefore better considered a separate but related earthquake sequence. The Big Bear event had a focal depth of 10 km and a left-lateral strike-slip mechanism (strike=045°, dip=70°, with a minor reverse component).

Both earthquakes have had a normal temporal and magnitude distribution of aftershocks. In the first 2.2 days following the Landers mainshock there was one aftershock of M6.0 (counting the Big Bear event as a separate mainshock), 9 events of M5.0 or above and 59 events of M4.0 or above.

Following the Landers and Big Bear earthquakes there has been a remarkable increase in the level of seismicity throughout the western USA, eastward of the San Andreas Fault system. In the three weeks since the Landers and Big Bear earthquakes there has been a five-fold increase in seismicity at Long Valley caldera in east-central California; Yucca Mountain, Nevada, experienced a M5.9 event; a M5.2 event occurred in the northern Mojave Desert; Carson City, Nevada had a M5.0 event; and seismic activity increased at two of the Cascade volcanoes in Oregon. While none of these occurrences is remarkable in itself, the joint probability of all these events happening by chance is extremely remote. This observation has led to speculation in the US that more major earthquakes in eastern California and Nevada can be expected.

As to the effect of the Landers and Big Bear earthquakes on the increased or decreased likelihood of a major earthquake on the San Andreas Fault, there is no consensus. From a purely kinematic point of view it is conceivable that right-slip on the roughly north-striking faults that ruptured in the Landers earthquake may have unloaded the San Andreas Fault to the south of San Gorgonio Pass, while left-slip faulting on a northeast trend in the Big Bear earthquake may have loaded the San Andreas north of San Gorgonio Pass (Fig. 4). There is no consensus as to whether it is increased or decreased loading that will precipitate a San Andreas rupture, but it is clear that the Landers and Big Bear earthquakes will have influenced future activity on the San Andreas Fault.

Fault Rupture

Seismological data strongly suggest the rupture in the Landers earthquake was unidirectional from south to north. I will describe some aspects of the fault ruptures in the same order. Fault ruptures extend from about 8 km southeast of Yucca Valley to the north and NNW for about 80 km (Fig. 5). There are a few gaps (notably just to the north of Yucca Valley), and there is considerable overlap of traces.

1. *Johnson Valley Fault:* Fault traces begin about 5 km north of Yucca Valley, and follow, in a general way, California Highway 247. Traces are marked by small en-echelon, left-stepping, cracks. There are traces both west and east of Highway 247 suggesting either, very distributed deformation, or perhaps a bifurcation of the fault. About 3 km north at Pipes Wash there is a well-integrated trace with as much as 3 m of right-lateral displacement. This point appears to be very close to the epicentre. Northward the traces generally follow the mapped position of the fault (Dibblee, 1967) which is marked by uplifted remnants of older alluvium on its eastern side. About 5 km north of Pipes Wash, an exposure of the fault plane showed that the 1992 break was along a pre-existing fault. The fault plane dips 75°W, strikes 005°, and the east side is upthrown by about 0.4 m. Thus, at this site the fault has a minor normal component.

   To the north for another 8 km, the fault rupture is characterised by left-stepping, en-echelon traces, usually upthrown to the east, and numerous fences, roads, and rows of telephone and electricity poles show that the right-slip movement was reasonably constant at 2.5 to 3.0 m (Fig. 6). This sizeable amount of right-slip continues north of the region to the transfer fault (in the area of the 1979 Homestead Valley earthquake aftershock zone) where the Homestead Valley Fault diverges (Fig. 5).

   South of Yucca Valley, a c. 8 km-long trace extends as far north as housing estates in the southeast part of Yucca Valley. As much as 0.2 m of right-slip has been seen on this trace (M. Rymer, pers comm). This trace is along strike of the Johnson Valley Fault but separated by the roughly east-striking Pinto Mountain Fault (Fig. 1). The author knows of no estimate of total slip on the Pinto Mountain Fault, and if it is only small then it is possible the active trace southeast from Yucca Valley is a continuation of the Johnson Valley Fault.

   An interesting feature of the trace southeast of Yucca Valley is the presence of appreciable (several centimetres) of afterslip measured over a period of several days after the earthquake. In contrast, no more than several millimetres has been measured on any other 1992 trace. It seems possible, but uncorroborated, that this southeastern trace has developed largely by afterslip in association with the numerous aftershocks occurring there.

2. *Transfer Fault A:* This fault connects the Johnson Valley and Homestead Valley Faults and follows a northerly trend along the aftershock zone of the 1979 Homestead Valley earthquake as mentioned above. The fault is composed of left-stepping, en-echelon traces that are often overlapping. At the northern end, close to the Homestead Valley Fault, the fault is composed of at least two traces, oriented about 030°-040°, demonstrating the en-echelon nature of the trace. Individual strands of this fault have as much as 2.5 m of right-lateral movement, and are upthrown to the NW by as much as 1.0 m.

3. *Homestead Valley Fault:* Approximately 15 km of this fault broke in 1992, coincident for about the southern 3 km with the triggered slip of the 1979 event. Left-stepping, en-echelon scarps with right-lateral movement that varies from about 1.0 m in the south to as much as 4.0 m in the central and northern section characterise all but a 3 km long south-central section where the traces have a strong reverse component (Fig. 5). As with all of the traces of the 1992 faulting, the zone of deformation along the Homestead Valley Fault is wide, commonly in excess of 100 m and sometimes as much as 400 m. This may be due in part to the presence of thick unconsolidated surficial deposits.

4. *Transfer Fault B:* At the northern end of the rupture on the Homestead Valley Fault a broad zone of deformation extends in a northerly fashion to the southern end of the rupture on the Emerson Fault. We did not inspect this fault and only know of its character from conversation. Michael Rymer (USGS) reports several strands of faulting, one with about 1.5 m of right-lateral movement. The trace that crosses the bedrock ridge to the west of the Emerson Fault is considered part of the transfer fault because we saw older strands of the Emerson Fault continue SSE along the edge of the bedrock ridge to the south of the 1992 rupture.

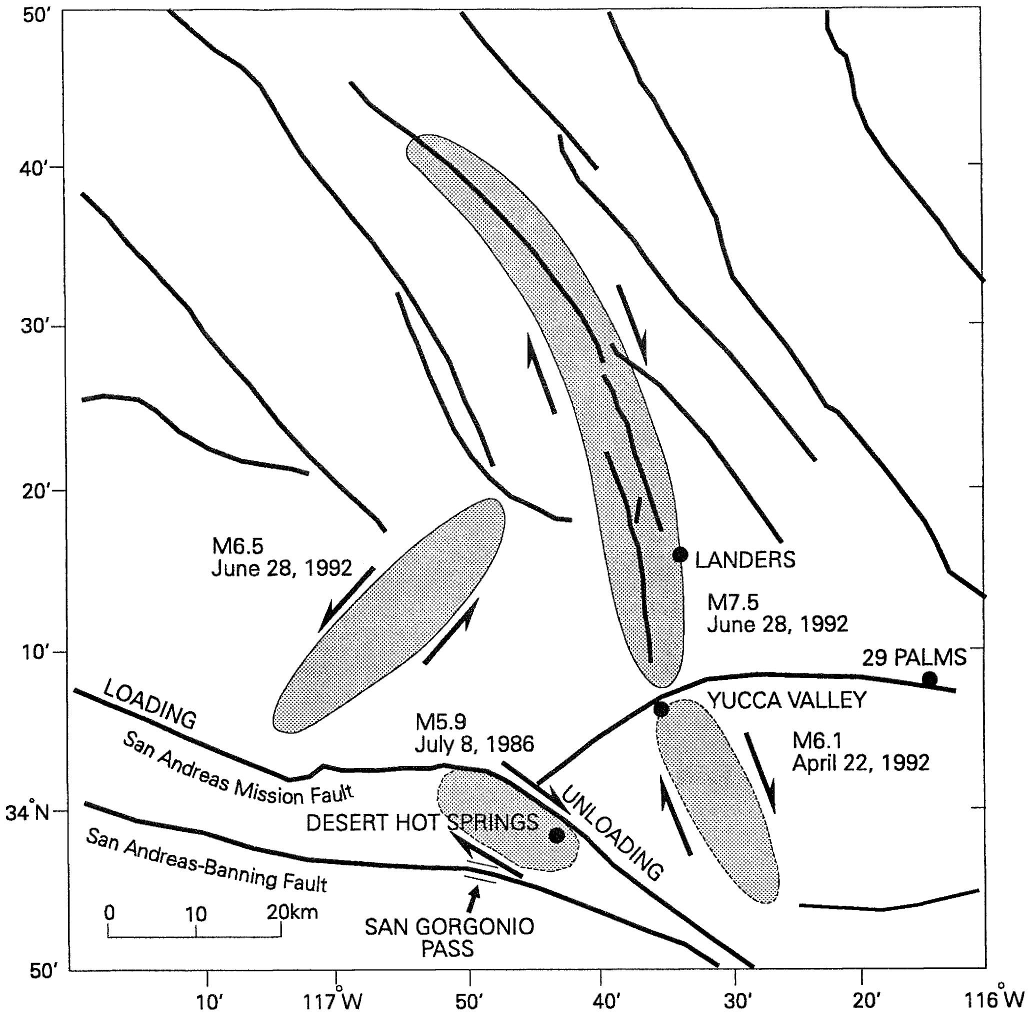

Figure 4. Aftershock zones, along with sense of slip of major earthquakes in the southern Mojave and San Andreas fault zone. Along the San Andreas northwest of the Bear Lake zone increased loading has probably occurred, while in the section of the San Andreas between the Bear Lake and Joshua Tree zones there may have been decreased loading.

5. *Emerson Fault:* This strand of the 1992 faulting is about 25 km long and contains the maximum right- lateral displacements that occur in the vicinity of Bessemer Mine Rd. (Fig. 5) and reach 4.5 m right- lateral movement with about 1.0 m of vertical displacement (Figs.7 & 8). The second subevent of the 1992 earthquake sequence occurred in this area. About 10 km NNW of Bessemer Mine Rd., fault rupture caused severe damage to a 110kV electricity pylon that straddled the fault. Three metres of right-slip was recorded on the gravel service road alongside the pylons. A second pylon route across the fault 2 km to the NNW was not damaged, both because no pylons straddled the fault and because the amount of right-slip had decreased to about 0.8 m.

6. *Camp Rock Fault:* A minor transfer zone takes the west-side up northern Emerson Fault across to the east-side up Camp Rock Fault. A prominent bedrock ridge is located on the east side of the Camp Rock Fault, opposite to the situation at the northern end of the Emerson Fault. Only minor displacements were observed along the 8-9 km of the Camp Rock Fault that ruptured in 1992. Displacements reach a maximum of about 0.3 m right-lateral movement, with just a few centimetres of vertical movement on multiple, left- stepping, en-echelon traces. It is this ubiquitous left-stepping of traces suggestive of right-lateral shear that distinguishes the ruptures on the Camp Rock Fault from cracking related to strong ground shaking. Traces on the Camp Rock Fault closely follow subtle older scarps along the edges of older, uplifted remnants of older alluvium. However it seems unlikely that earlier movement on the Camp Rock Fault was as small as the 1992 rupture (the 1992 rupture could not produce the fault geomorphology present), and the 1992 rupture may best be considered triggered slip.

With the exception of suggested triggered slip on the Camp Rock Fault, and substantial afterslip on the fault trace southeast of Yucca Valley, the amount of strike-slip displacement was fairly uniform (usually ± 1 m) for each of the faults. Only in the last 1-2 km at the ends of traces did the amount of displacement die away. On faults with average strike-slip displacement of 2.5-3.0 m there was commonly variation of about a metre over distances of 10's to 100's of metres. Sometimes this variation resulted from the distribution of shear across a wide zone of cracking. These cracks, which in places absorb a significant amount of shear, will disappear quickly and would not be recognised in a paleoseismic investigation of a fault, without extensive trenching in suitable materials.

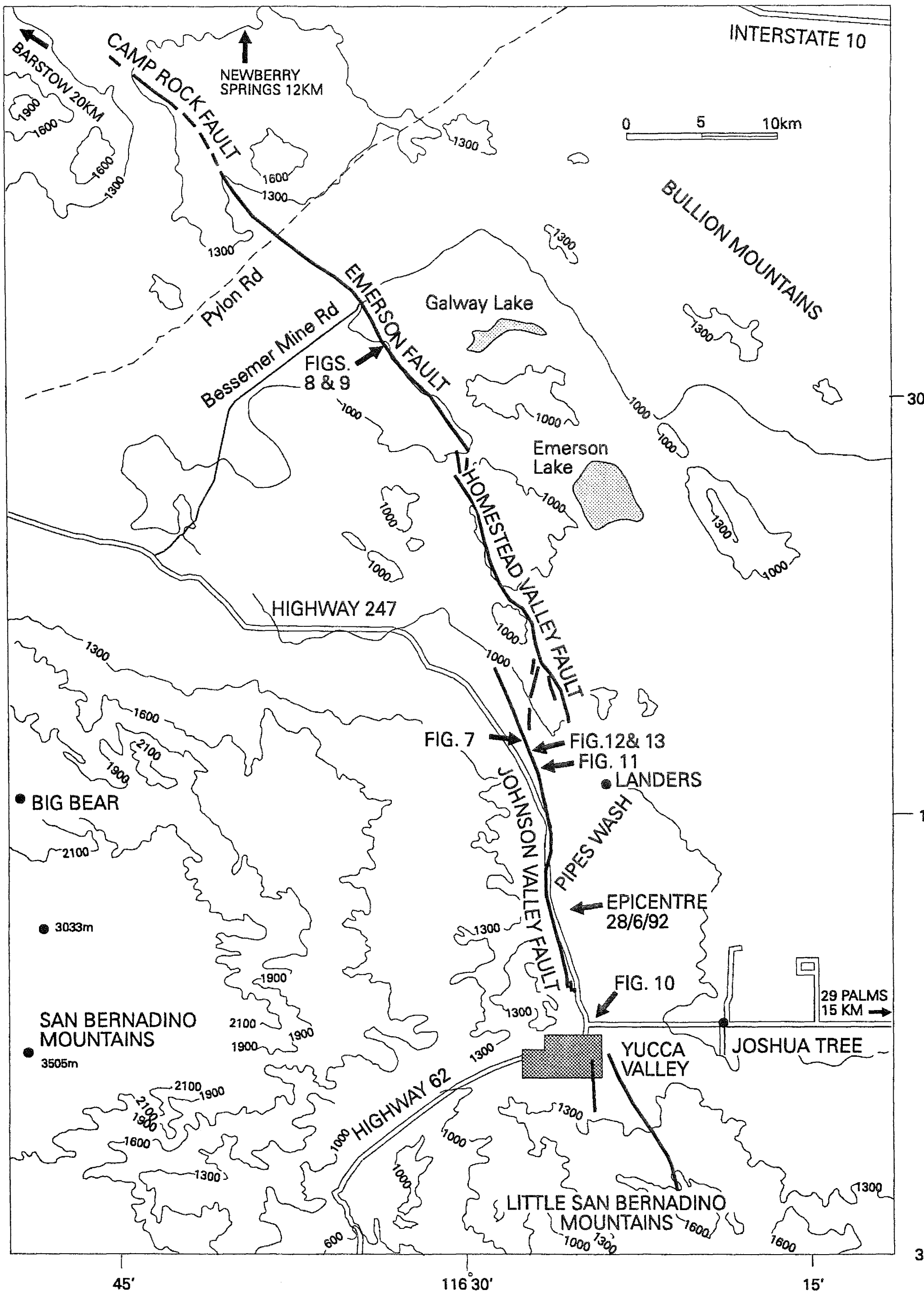

Figure 5. Distribution of surface faulting accompanying the Landers earthquake. The location of principal towns, the earthquake epicentre, and additional figures are shown. Contours up to 2400 m have been generalised from contours (40 foot) on U.S.Geological Survey 1:250,000 scale topographic map. Note the predominance of northwest-trending ridges, most of which are adjacent to active strike-slip faults.

Engineering Aspects and Shaking Damage

1. *Damage to housing and services*

The Landers and Big Bear earthquakes resulted in the death of a 3 year-old boy in Yucca Valley when a cinder-block chimney collapsed through the roof of a family home. At least 24 serious injuries and at least 324 minor injuries were reported. A newspaper account about two weeks after the earthquake placed the damage at about US$100 million. Much or probably most of that damage was to residential buildings in the Big Bear Lake area, Barstow, Newberry Springs, Landers, Twentynine Palms, Joshua Tree, and Yucca Valley (Fig. 5). The financial cost of the earthquake has been amazingly low for a M7.5 earthquake—entirely due to the lack of heavy industry in the epicentral region, and essentially no habitation in about 75% of the region where strong ground motions would have occurred.

When the author arrived in Yucca Valley about two weeks after the earthquake there was very little evidence of the earthquake damage. Commercial activities in the town were thriving, especially at motels and restaurants because of the influx of scientists and engineers, and temporary relocation for local people evacuated from their houses. In Yucca Valley the supposed collapse of a bowling alley was widely reported by the media. However, only the light framing wall at one end of the building collapsed (Fig. 9)and substantial steel roof beams performed well. Some false-ceiling panels fell, but overall it seemed unlikely that serious injury would have occurred had the building been occupied at the time of the earthquake. The two large supermarkets in Yucca Valley suffered major stock losses, with most goods falling from shelves. No structural damage occurred, however. One store was open for business at 2pm on the day of the earthquake (9 hrs after the mainshock), and the other store opened within a few days.

Substantial residential damage was reported from the resort town of Big Bear, located only about 10 km from the epicentre of the M6.5 Big Bear earthquake. Initially all roads in that area were closed by landslides or ground cracking, three houses burned, seven were reported to have collapsed (although the author couldn't get confirmation of this), and many chimneys were toppled.

Electricity and telephone services were initially cut to at least 500,000 residents across the Mojave, but were quickly restored in most places. Water, sewerage and telephone (where underground) services were cut to a considerable number of residents within areas affected by fault rupture and severe ground cracking.

When the reconnaissance team inspected the area about two weeks after the earthquake there were many houses in a zone along the fault traces that remained evacuated. Some had been declared unsafe because of structural failure, while at others the lack of water, gas, electricity, and sewerage services appeared to be delaying reoccupation. The housing stock in the region is diverse in terms of construction and quality. Most houses appeared to be of light timber framed construction, built on a reinforced concrete pad. These buildings survived the earthquake well with no collapses even when fault traces with as much as 2-3 metres of lateral movement ran beneath the houses, severely torquing them. The foundations were not usually cut very deeply into the soil, which itself is of a loose, granular nature. Trailer homes did not, in general, survive as well. Most are mounted on rows of concrete or wooden piles, and I suspect not very well secured to the floor bearers. We saw many instances of these homes having been tipped from their pile foundation (Fig. 10), or else differential movement of the ground having caused severe distortion to the structure. Those trailer homes on a concrete foundation performed rather better, but major damage was still common because of the flimsy framing, low strength wall materials, and lack of diagonal wall bracing.

The most severely damaged house we saw provided a graphic example of the effects of energy focussing on hilltops. The house was built in the 1950's with timber framing on a concrete foundation. The trace of the Johnson Valley Fault (which sustained 2.5-3.0 m of right-slip at this locality) ran about 60 m west of the house. The hilltop was criss-crossed with a network of fractures but none of these had large displacements. This structure must have been very close to the point of collapse. It is fortunate that this house was unoccupied at the time of the earthquake, because although it did not collapse, the disruption to internal fittings and appliances was extreme (Fig. 11 & 12).

2. *Strong ground motions*

Preliminary peak horizontal ground acceleration records from southern California reach a maximum of 1.55g at a station about 50 km west of the epicentre. A site about 140 km north of the epicentre recorded 0.57g, while a site at Pasadena, about the same distance west of the epicentre recorded 0.31g, reflecting a strong north-south ellipticity to the ground motions.

Within the epicentral area close to the surface fault breaks, building damage was generally consistent with MM7 intensity with only local incidences of MM8 and rarely MM9 intensity. MM7 intensity seems remarkably low for the epicentral area of an apparently very shallow, M_s 7.5, earthquake. As data are further analysed it will be particularly interesting to see if the high PGA values recorded some distance from the epicentre can be reconciled with the generally low level of building damage in the epicentral area.

Conclusions

1. The author's visit to the epicentral area of the Landers earthquake was extremely valuable as a geologist to see, first-hand, the expression of a substantial rupture of a right-lateral strike-slip fault. This style of faulting characterises much of the central part of New Zealand, including the Wellington Fault.

2. Although the magnitude and probably the length of fault rupture associated with the Landers earthquake are what can be expected on the sector of the Wellington Fault that cuts through Wellington city (Van Dissen *et al.* ,1992), the occurrence of rupture across several faults is not analogous to our current understanding of the Wellington Fault. Additionally, the fault ruptures in the Landers earthquake commonly occurred in a zone of shearing 100 m and sometimes 400 m wide. The principal displacement zones of strike-slip faults in New Zealand commonly appear to comprise much narrower zones, but we should be aware that significant shear can occur on small cracks away from the principal displacement zone, leading to under estimates of fault slip rates, and single event displacements.

3. The faulting associated with the Landers earthquake will raise further questions about the applicability of fault segmentation models and characteristic earthquakes on low slip-rate faults in the USA and elsewhere.

4. There was surprising little damage in the epicentral area considering the magnitude of the Landers earthquake.

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Acknowledgments

The author would like to thank the New Zealand National Society for Earthquake Engineering for funding to travel to the earthquake area to see first-hand what is a significant event in the science of earthquake geology. Colleagues at the U.S. Geological Survey shared their knowledge freely, and I would like to thank Michael Rymer, Lucy Jones and Jim Mori in particular. Geologists at Caltech have also been mapping the fault ruptures and Kerry Sieh and Charlie Ruebens provided very useful information on the extent of faulting. Steven Wesnousky from the School of Neotectonics at the University of Nevada at Reno was an excellent field companion. Alan Hull (Institute of Geological & Nuclear Sciences) provided comments on this paper and facilitated its speedy publication.

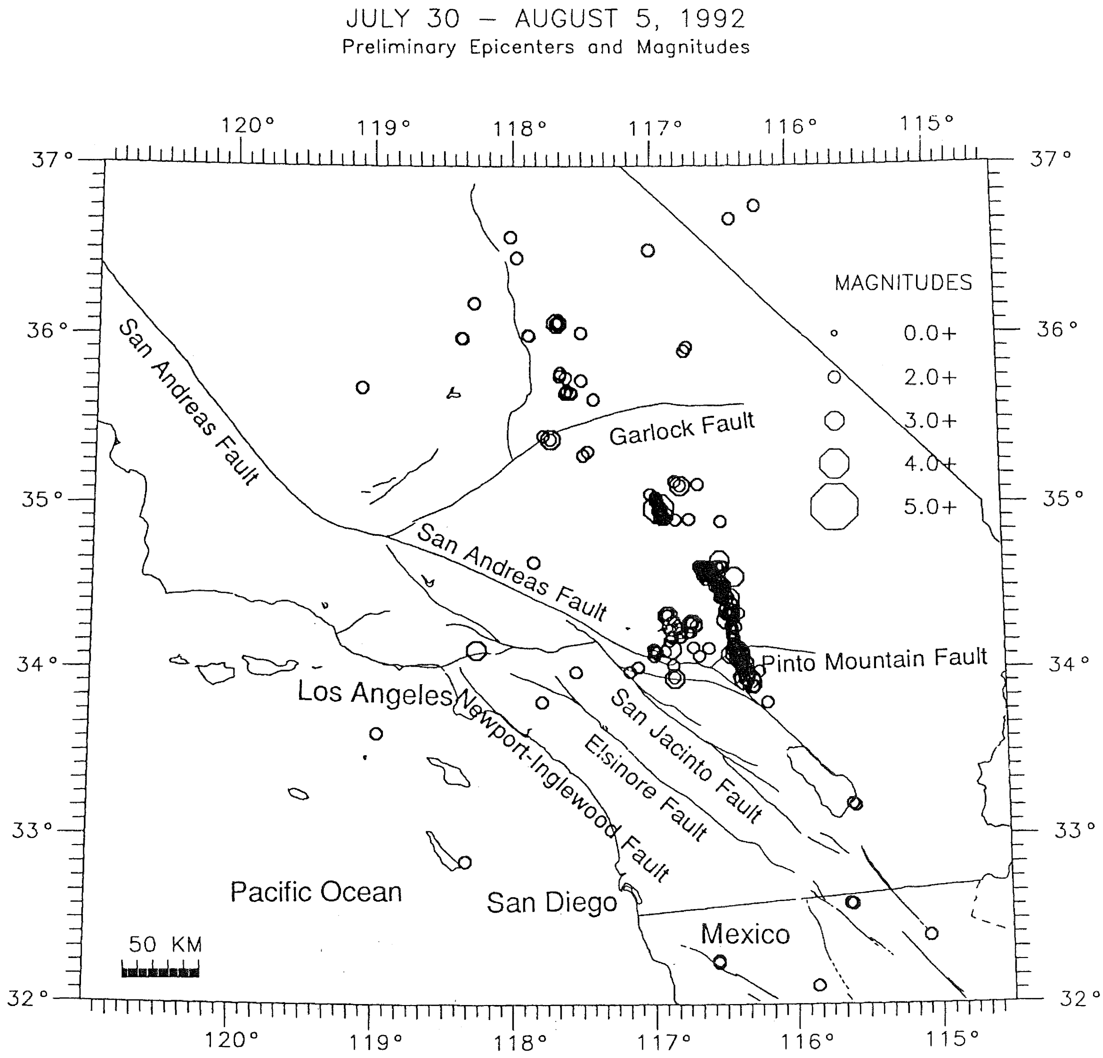
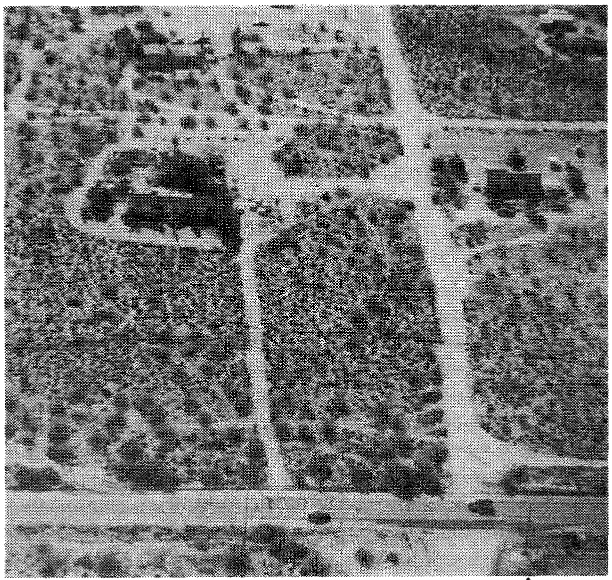


Figure 6. Epicentres of earthquakes in Southern California from July 30-August 5, 1992. Note the alignment of aftershocks along the NW-trending surface fault breaks associated with the Landers earthquake, and the more diffuse zone of aftershocks following the Big Bear earthquake.



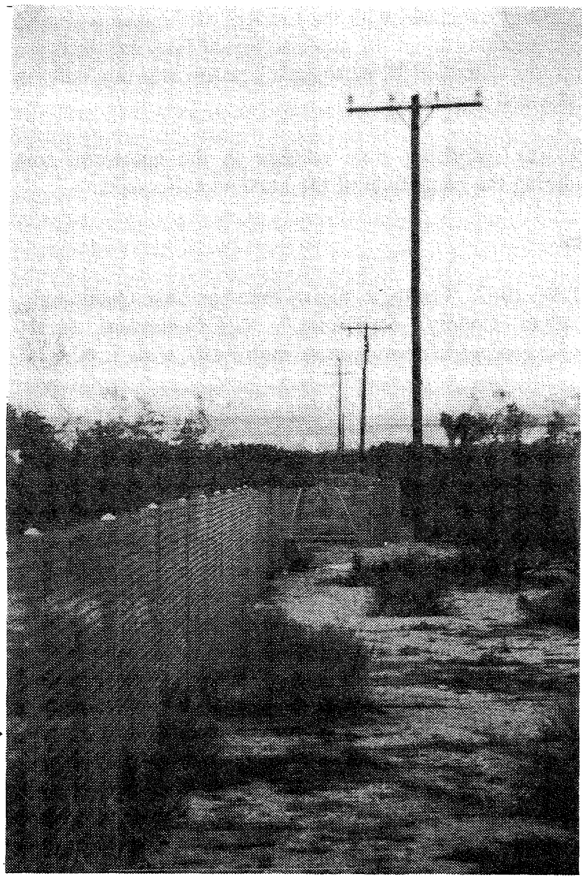


Figure 7. Aerial view of the Johnson Valley fault (7A), parallel and about 50 m east of California Highway 247 (foreground). Note the complex nature of surface faulting, and occurrence of cracks running at a high angle to the fault. Fig 7B shows a fence displaced 2.7 m right-lateral on the Johnson Valley fault in the same vicinity. At this site displacement occurred on two principal fractures in a deformation zone about 5 m wide. Location shown on Fig. 5.

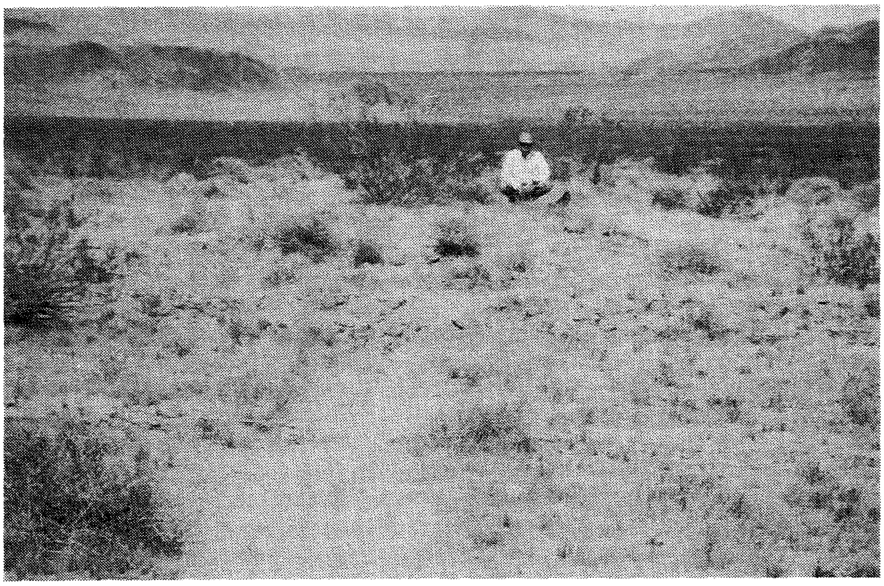


Figure 8. Off-road motorcycle track displaced by 4.5 m right-lateral on the Emerson fault. Displacement occurs across four principal fractures, most of which also have minor upthrow to the east. Photograph taken looking east; location is shown on Fig 5.

Figure 9. Aerial view of Emerson fault trace cutting across topography to the south of Bessemer Mine Rd. Right-lateral displacements of ridges and gullies in this area range from 3.5 m to 4.5 m. The trace is upthrown to the east by as much as 1.1 m locally. Location shown on Fig 5.

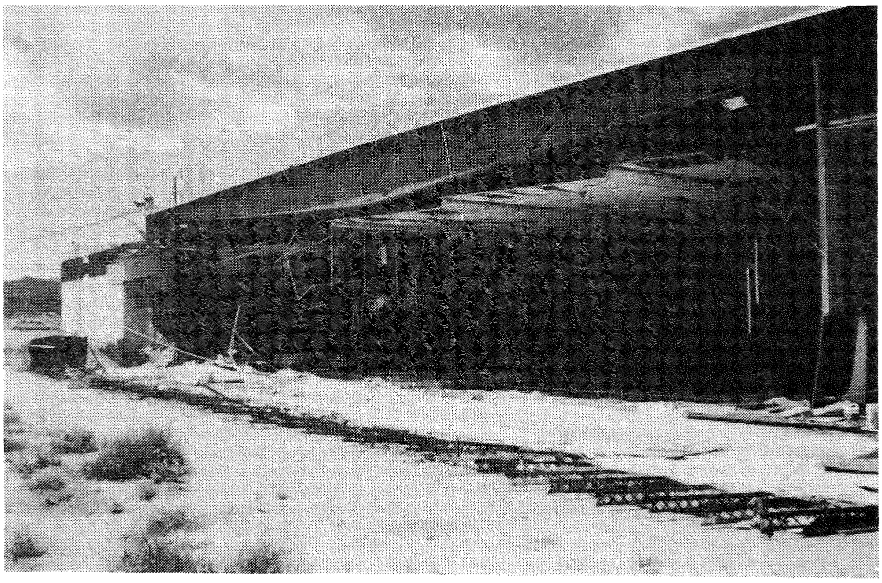


Figure 10. Collapsed east wall of the bowling alley in the eastern part of the town of Yucca Valley. Steel roof beams were not significantly damaged, but many false ceiling panels have fallen. The west wall of the building was constructed of concrete blocks that suffered only minor cracking. Location shown on Fig 5.

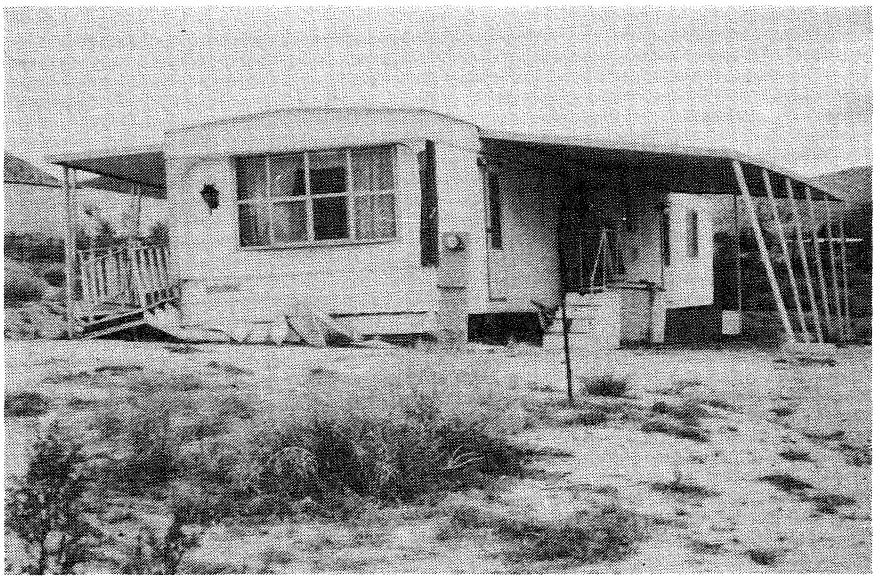


Figure 11. Damaged trailer house about 100 m west of the Johnson Valley fault. The trailer was apparently poorly tied to its wooden pile foundation. Location shown in Fig 5.

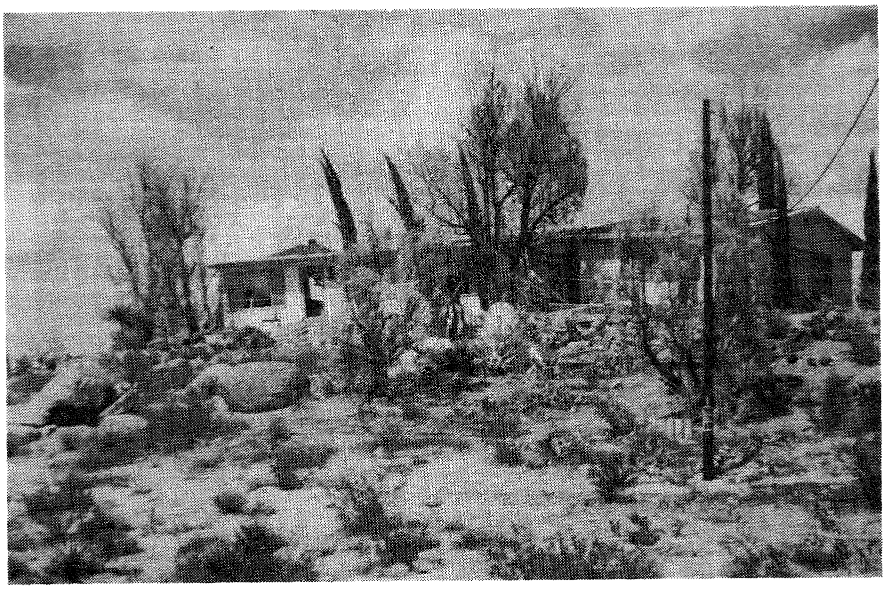


Figure 12. Exterior view of severely damaged "hilltop" house located about 60 m east of the Johnson Valley fault. Note that several trees have died (photo taken about two weeks following the earthquake) because of root damage. Location shown on Fig 5.

Figure 13. View of the interior of "hilltop" house, showing cracked concrete floor slab, extreme racking of exterior walls (about 1.5 m), and temporary bracing to stop total collapse so that possessions could be removed before demolition.