Preliminary Report on the 1995 Ridgecrest Earthquake Sequence in Eastern California

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The Ridgecrest earthquake sequence began on 17 August 1995 with a M_L 5.4 earthquake. As of October 3, 1995, the Southern California Seismic Network (SCSN) had recorded over 4,500 events in the sequence, with eight events of $M \geq 4.0$. These earthquakes are occurring along the eastern edge of the Indian Wells Valley along a small stretch of the thoroughgoing Eastern California Shear Zone (ECSZ). Previous large events within the ECSZ include the 1992 (M_W 7.3) Landers earthquake sequence and the 1872 (M 7.6) Owens Valley earthquake. The only large earthquake to occur near Indian Wells Valle, was the 1946 Walker Pass (M 6.0) earthquake on an unknown fault in the Sierra Nevada mountains to the west. The ECSZ transfers some of the relative motion between the North America and Pacific Plates away from the San Andreas fault to the western Great Basin of the Basin and Range province.

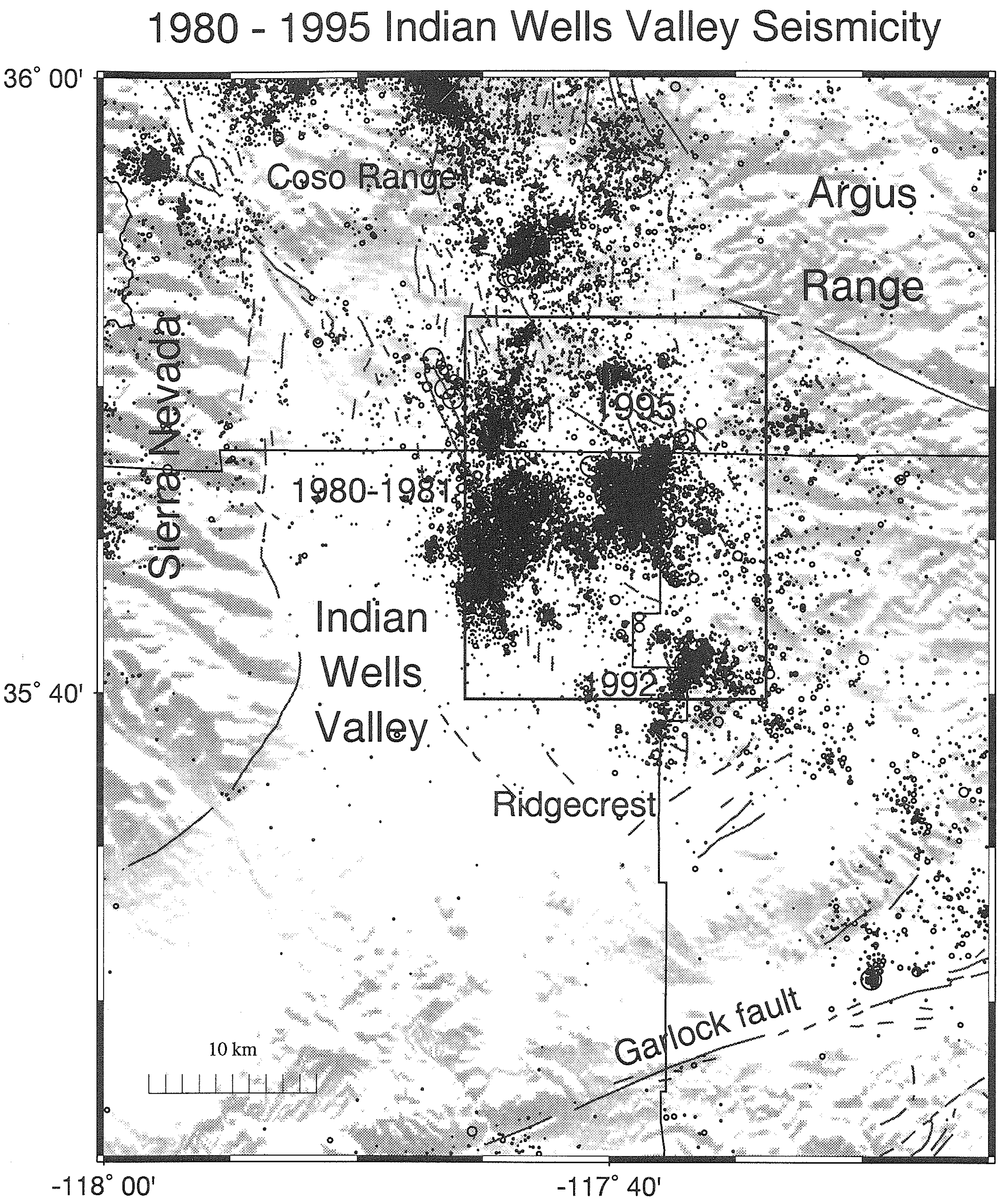
The Indian Wells Valley is flanked by the Coso Range to the north, the Argus Range to the east and the Sierra Nevada to the west. The valley floor is cross-cut by a northerly-trending mosaic of fault segments that merge towards the north with the frontal fault of the Sierra Nevada or the rupture zone of the 1872 earthquake. In the south, this mosaic of segments diffuses into a broad zone of faulting that disappears before it is cut off by the west-striking Garlock fault. The mosaic of fault segments consists of north-to-northwest striking as well as a lesser number of northeast-striking faults, most of short length, of less than a kilometer up to 10 km length (Figure 1).

During the last three decades the seismicity of this region has been characterized by swarms of earthquakes, some of which have lasted more than 12 months. These swarms typically have thousands of small earthquakes, with the largest earthquakes in the magnitude range of 4 to 5. The swarms tend to migrate in space. For instance, the fourteen-month-long swarm in 1980–1981 migrated from north to south over a distance of 12 km, with temporal bursts in activity. The largest earthquake to occur in the valley itself was a M_L 4.9 event in April, 1982. It caused some ground cracking (Roquemore and Zellmer, 1983) on two short fault segments.

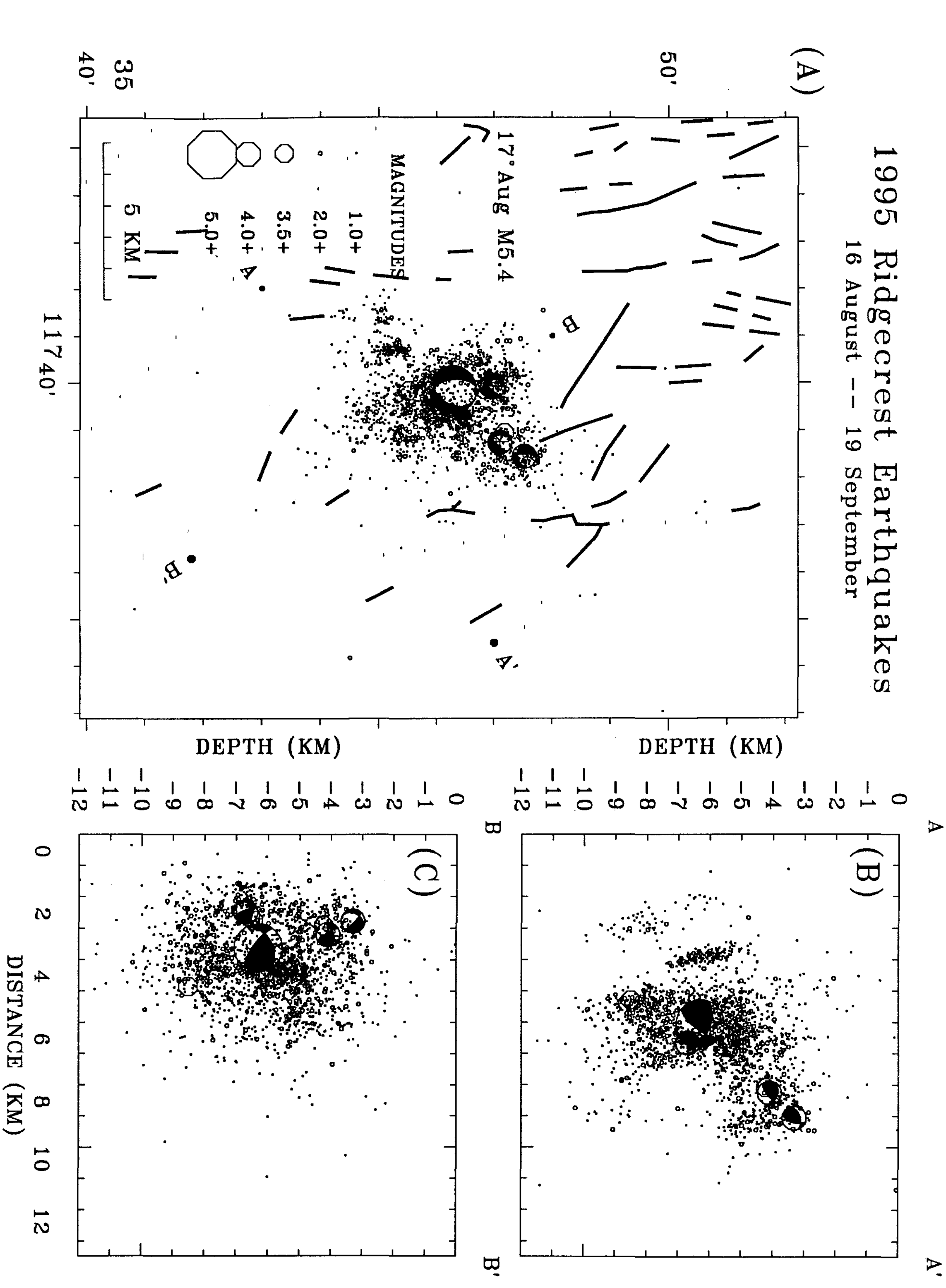
THE M_L 5.4 EARTHQUAKE OF 17 AUGUST 1995

The M_L 5.4 Ridgecrest earthquake that occurred on 17 August 1995 was located 11 miles north of Ridgecrest, on the county boundary between Kern and San Bernardino Counties. The focal depth of this event was shallow, or 6 km deep, as is common in this region. This event was felt widely in southern California. The first motion focal mechanism of the M_L 5.4 earthquake had a dominantly normal-faulting mechanism (Figure 2). The focal mechanism derived from regional surface waves, however, showed a more dominant strike-slip component (H. K. Thio, written communication, 1995). This difference in the focal mechanism derived from the two independent data sets suggests that the event may have begun with normal faulting and quickly evolved into right-lateral strike-slip faulting.

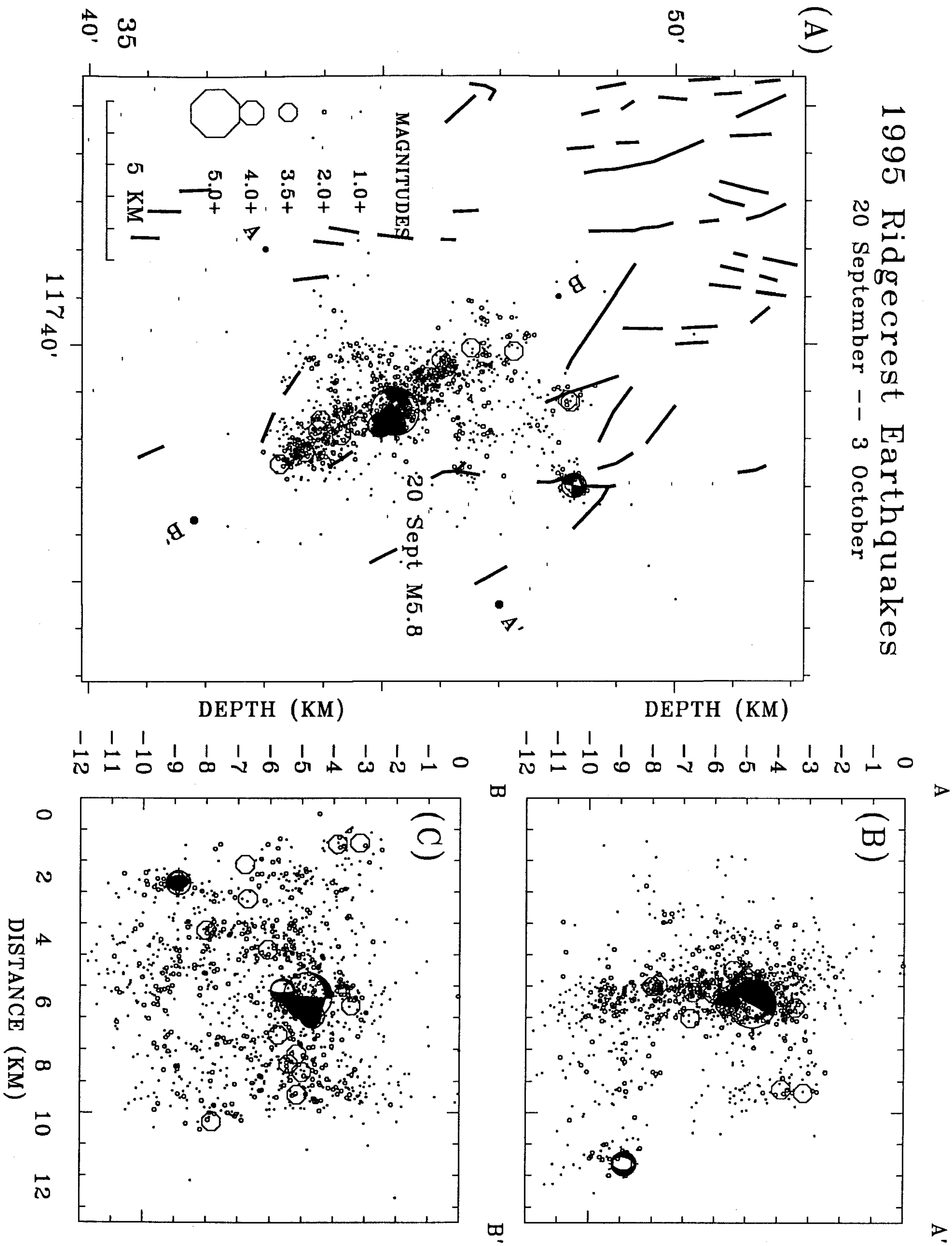
The SCSN station coverage in the region is good with about 10 km average station spacing. To obtain accurate hypocenters we inverted arrival time data from 250 earth-



▲ **Figure 1** Overview of seismicity in Indian Wells Valley recorded by the Southern California Seismic Network from 1980 to 1995. Symbol size is scaled with magnitude. The swarms of 1980–1981, 1992, and the 1995 sequence are labeled with the year. The box indicates the location of Figures 2 and 3. The straight lines are the county boundaries.



▲ **Figure 2** (A) Map of the epicenters from 16 August to 19 September, 1995. Symbol size is scaled with magnitude. Mapped Holocene faults are also shown. The M 5.4 earthquake and M > 4 aftershocks are indicated by their lower hemisphere focal mechanisms. (B) Strike-normal cross section and (C) strike-parallel cross section.



▲ **Figure 3** (A) Map of the epicenters from 20 September to 3 October, 1995. Mapped Holocene faults are also shown. The M 5.8 earthquake and M ≥ 4 aftershocks are indicated by their lower hemisphere focal mechanisms. (B) Strike-normal cross section and (C) strike-parallel cross section.

quakes in this sequence for an improved velocity model and a set of corresponding station delays. We used the VELEST program (Kissling *et al.*, 1994). The final locations were calculated using HYPOINVERSE (Klein, 1985) and focal mechanisms were determined from first motion polarities using FPFIT (Reasenberg and Oppenheimer, 1985).

In the next 5 weeks the M_L 5.4 earthquake was followed by over 2,500 aftershocks, 3 of which were $M_L > 4$ aftershocks. The first of these larger aftershocks occurred on the same day, while the two later ones occurred on August 29 and September 11. The spatial distribution of the immediate aftershocks suggests that the M_L 5.4 earthquake occurred on a north-northwest-striking fault. The two later $M_L > 4$ aftershocks occurred to the northeast of the mainshock and were followed by events forming a northeast lineation, suggesting that they activated a separate northeast-striking fault (Figure 2). In addition, a vertical north-striking group of aftershocks to the southwest of the mainshock hypocenter suggests that three separate faults might be involved in this part of the sequence (Figure 2).

THE M_L 5.8 EARTHQUAKE OF 20 SEPTEMBER 1995

The M_L 5.8 earthquake occurred about 2 km to the south-southwest of the epicenter of the M_L 5.4 earthquake at a focal depth of 5 km. It had a strike-slip focal mechanism with a north-northwest striking nodal plane, aligned with the strike of the aftershock distribution. The aftershocks form a 7-km-long distribution that defines an almost vertical plane in the depth range of 3 to 11 km (Figure 3). The strike of this distribution coincides with that of the M_L 5.4 event so the M_L 5.8 mainshock may have occurred on a southeastward extension of the M_L 5.4 earthquake's fault.

Over 1,900 aftershocks have been recorded in the two weeks since the M_L 5.8 mainshock. The largest was a M_L 4.9 event on September 24. This event had a focal mechanism significantly different from the other events, with left-lateral strike-slip faulting on a north-striking plane (Figure 3). This mechanism and the location of the event, six kilometers to the northeast of the main part of the sequence, suggests that a fourth fault was activated in this event.

This sequence has shown significant temporal variability in its distribution in time, space, and magnitude. The locations of the sequence events have migrated with time, extending from the original aftershock zone to both the northeast and southeast. Each of the larger events ($M > 4$) has been accompanied by a burst of smaller earthquakes, but the M 3 aftershocks have also shown a notable temporal clustering. This clustering has led to a significant variability in the b-value of the sequence with time. The original aftershocks to the M_L 5.4 event had a moderately high b-value of 1.13 ± 0.07. In the first day of aftershocks to the M_L 5.8, the b-value went down to 0.90 ± 0.08 (the average for Californian aftershocks), but since then it has returned to a higher value ($1.10 \pm .10$).

GEOLOGICAL FIELD INVESTIGATIONS

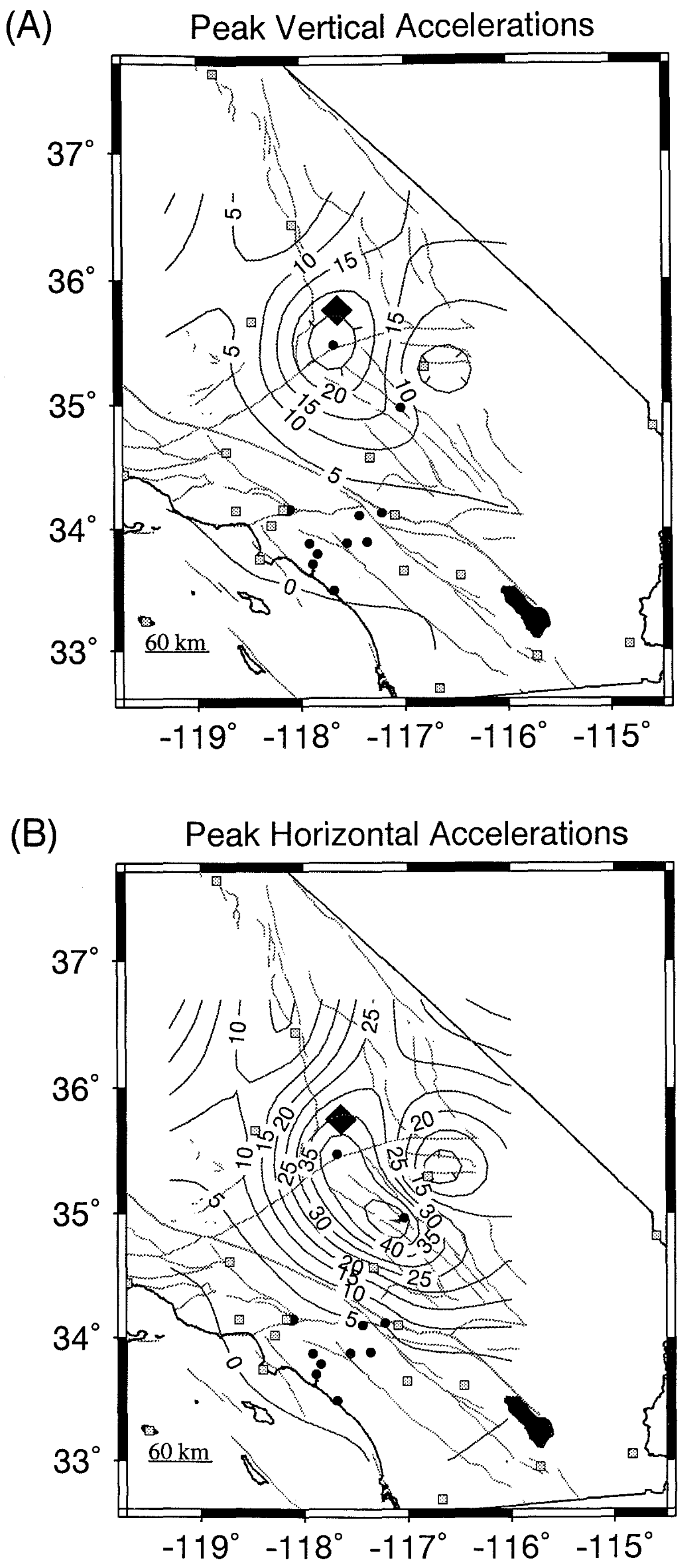
The Ridgecrest earthquakes may have caused triggered slip on fault segments within the Airport Lake fault zone (Roquemore and Zellmer, 1986), outside of the epicentral and aftershock areas. A short (3 km) north–south fault segment, located approximately 3 km to the northwest of the epicentral region experienced surface cracking possibly related to surface rupture in both the August 17 and September 20 events.

The epicentral region of the August 17 and September 20, 1995 Ridgecrest earthquakes was investigated for potential surface rupture. Following the August 17 event a highly fragmented line of surface cracking was located along a mapped fault segment within the Airport Lake fault zone. The Airport Lake fault zone is a broad zone of north–south striking normal and oblique slip fault segments. The cracks were generally 1 to 2 meters long and separated by several meters over a total length of less than 1 km. Two parallel cracks separated by about 50 cm formed along some of the segments. Other segments showed en echelon patterns. Close inspection of the cracking revealed evidence of up to 2 mm of right-slip as observed in pebbles pulled away from their matrix on the opposite side of the cracks. The areas closest to the epicenter and areas to the east where the fault plane (determined from seismicity) would project to the surface were also investigated but only randomly oriented cracks interpreted to be caused by shaking and settlement were observed.

Following the September 20, 1995, M 5.8 earthquake, the region was again investigated for surface rupture. The same fault segment within the Airport Lake fault zone experienced more extensive cracking. In this event, the cracking developed into a continuous en echelon pattern over a length of 2.5 km. Evidence for surface rupture was observed in several locations along the pre-existing fault scarp. A maximum vertical displacement of 1 cm was measured near the middle of the rupture zone. Also near the middle of the rupture zone, a maximum of 8 mm of right-slip was measured. The rupture crossed several types of materials including channel fill, eolian sand, and dense lacustrine deposits. As in the August 17 earthquake, the area nearest the epicenter and to the east was investigated for surface rupture, but only cracking interpreted to be caused by shaking and settlement was observed.

RAPID NOTIFICATION AND GROUND MOTION

The M 5.8 Ridgecrest earthquake is the largest earthquake to strike southern California since the 1994 (M_w 6.7) Northridge earthquake. It was widely felt over southern California, even though its location, in the desert 150 kilometers north of Los Angeles, meant that damage was confined to Ridgecrest and its vicinity. The Caltech US Geological Survey Broadcast of Earthquakes (CUBE) reported the location and preliminary



magnitude of both mainshocks within 3 minutes of their occurrence. This information was used by local utilities and transportation companies to determine the scope of their deployment of field crews following the earthquake. The CUBE system broadcasts earthquake information automatically via commercial paging to both belt pagers and pagers connected to computers that can display on a map the location and magnitude. Earthquake information from the SCSN that is available on the World Wide Web (`http://scec.gps.caltech.edu/`), including near-real time locations and magnitudes and the weekly bulletin, were accessed by thousands of users during August and September.

In the last few years, Caltech and the US Geological Survey have been working to improve the capability of the SCSN to provide quick estimates of the location of strong shaking to emergency management officials. Eighteen broad-band TERRAscope stations, eight analog SCSN stations with strong motion sensors, and ten new strong motion sensors, deployed as part of the Automated Monitoring of Strong Ground Motions Project (AMOES) and located at sites of the Pacific Bell Company are now operating in southern California. These stations provide near-real time estimates of strong ground shaking. The data are transmitted from the remote sites using frame relay digital technology under a California Research and Educational Foundation (CalREN) grant from Pacific Bell.

The M_L 5.8 earthquake provided the first test of the new enhancements to SCSN and CUBE for strong ground motion monitoring. Contours of measured peak horizontal and vertical accelerations are shown in Figure 4. Presumably the ground shaking was highest at the epicenter and decreased rapidly with distance. Because of the sparse distribution of high-dynamic range stations in eastern California, the contours of ground motion are not exactly centered on the epicenter. Instead large peak values caused by local site amplification affect the pattern of

▲ **Figure 4** (A) Vertical and (B) horizontal peak accelerations in cm/sec^2 from the M 5.8 earthquake (epicenter indicated by solid diamond). The ground motions are affected by distance from the epicenter and local site effects. The open squares are TERRAscope stations while the filled circles are analog SCSN stations and digital AMOES/CalREN stations with strong motion sensors.

ground motions. The contours that are well constrained in the Los Angeles to San Bernardino urban corridor also show how the sedimentary basins locally amplify the ground shaking. These new data demonstrate that emerging technologies now are becoming available to enhance the capabilities of regional networks to process and quickly distribute information about ground accelerations. The reliability of the information, however, will be strongly dependent on adequate station distribution.

DISCUSSION

The most notable features of the 1995 Ridgecrest sequence are the multiple faults involved in the sequence and the spatial migration of the aftershocks with time. This spatial migration has been characteristic of previous swarms in the general region (1981–1992 Indian Wells Valley, 1983 Durrwood, 1990; Jones and Dollar, 1986), but these mainshocks were smaller than those in the 1995 sequence. The only other recent, large, southern California earthquake with similarly migrating aftershocks was the 1992 M 6.1 Joshua Tree earthquake. That event was also in the ECSZ and was a preshock to the M_w 7.3 Landers earthquake (Hauksson, *et al.*, 1993). The 1995 sequence differs from a swarm because it had two mainshocks of M_L 5.4 and M_L 5.8, which is more similar to the 1992 Landers sequence than to previous swarms in the Indian Wells Valley.

Although the M_L 5.8 Ridgecrest earthquake is the largest recorded in this region, earthquakes of larger magnitude are possible. This region is part of the Basin and Range physiographic province and has range-bounding faults similar in length and tectonic style to those that produced the 1983 M_w 7.0 Borah Peak and 1954 M_w 7.2 Fairview Peak earthquakes (Ellsworth, 1990).

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